A CROP GROWTH MODEL FOR PREDICTING CORN (*Zea mays* L.) PERFORMANCE IN THE TROPICS

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ABSTRACT

The Crop Environment Resource Synthesis (CERES) maize model was verified, calibrated, and validated on data from a wide range of agroenvironments in the tropics. These agroenvironments ranged from 5° S to 20° N latitude and from sea level to 800 meters above sea level. The model assumed: (i) complete irrigation; (ii) all nutrients at optimum level except nitrogen; (iii) no weeds, pests, and pathogens; and (iv) no wind damage. Adjustments were made only on physiological basis. These adjustments were made to: (i) incorporate soil temperature as a means of computing thermal time up to the tassel initiation stage; (ii) modify maize genotype coefficients based on field data; (iii) raise optimum temperature for photosynthesis; (iv) reflect the effect of minimum temperature instead of mean temperature on grain filling ; (v) reflect the effect of nitrogen deficiency and water stress on grain numbers; and (vi) lower the nitrogen mineralization constant based on minerological and chemical properties of the soil. The model was designed to minimize the need for future model calibration when the factors currently not simulated are later incorporated into the model. CERES maize model predictions for phenological development, kernel weight, kernels per ear, and grain yield were nonsite-spcific. The model was sensitive to latitudinal differences, seasonal variation, altitudinal differences, response to nitrogen fertilizer applications and planting density. However,

unmeasured environmental and management variables caused considerable differences between simulated and observed values. These variables affected yield predictions and phenological development. The CERES maize model was able to mimic the high sensitivity of maize to temperature and solar radiation.

Evaluation of statistical validation techniques indicated that both the R and the Freese statistics required improvements. The R test accepted model predictions which were subjectively "poor" because the field experiment had a large coefficient of variation. The Freese statistics, on the other hand, showed that the CERES maize model was capable of simulating grain yields from 2,500 to 11,200 kg ha^{-1} with a critical error of approximately 1,200 kg ha^{-1}, in a wide range of agroenvironments, when a model bias to overestimate in yield was taken into account.

Phosphorus regression models were developed to determine labile phosphorus, organic phosphorus, buffering capacity, and phosphorus availability index from readily available soil test P methods and soil physical and chemical properties. These models were used to generate input data for the phosphorus simulation model. With the above changes the P model simulated maize grain yields with high accuracy.

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I. INTRODUCTION

To improve agricultural production the scientific community has to reassess and critically evaluate the tools of research. Development, testing and full scale use should be made of those tools which give the most information in the shortest time. Since their introduction during the past decade crop simulation models that consider the soil-plant-atmosphere continuum have been increasingly popular as research tools . However, there is a need to have more accurate crop growth and development models enabling improved crop systems analyses for optimizing production.

Crop growth models that are based on mechanistic principles and are driven by daily weather data enable quantitative description of the dynamic crop production system and have the greatest potential for use in both yield prediction and crop management. These models are nonsite-specific when properly tested and can have a universal application. Simulation models could describe the impact of such phenomena as weather, erosion, soil properties, and crop characteristics on agricultural production by utilizing the vast amount of experimental data available in many parts of the world. These models, therefore, could be used as means of assisting farmers in minimizing their risks.

Crop Environment Resource Synthesis (CERES) models have been developed by a multidisciplinary team of soil scientists, agronomists, hydrologists, and crop physiologists at the Grassland, Soil, and Water

Research Laboratory, Temple, Texas (Jones et al., 1983a; Ritchie and Otter, 1984; Ritchie, 1984). These models are mechanistic and user-oriented. CERES models have been developed for wheat, maize, and barley. To fully access the CERES models for tropical conditions reliable input data are essential. Preliminary testing of the CERES maize model using data from Benchmark Soils Project experiments on Hydric Dystrandept (Jones, 1982) and Tropeptic Eutrustox (Chinene, 1983) sites has brought to attention the lack of field level information about soil initial conditions and intermediate stages of crop growth.

The CERES maize model simulates growth, phenological development, soil water balance, and soil and plant nitrogen budget. The CERES model does not consider the effect of pests, diseases, and other nutrients. Climate, nitrogen, and water are the main factors driving the CERES maize model. In general, these are the predominating external factors in maize production. In many highly weathered soils of the tropics phosphorus is perhaps more limiting than nitrogen for crop production.

Jones et al. (1984a) have developed a simple soil and plant P model designed for use in the Erosion Productivity-Impact Calculator (EPIC) crop management model (Williams et al., 1983). The phosphorus model contains pools of soil organic and inorganic phosphorus, plant residue phosphorus, and plant shoot, root, and grain phosphorus. The model simulates P uptake and transformations, and is sensitive to soil chemical and physical properties, crop P requirements, tillage practice, fertilizer rate, soil temperature, and soil water content.

Although the model oversimplifies soil phosphorus transformations advantages are the model parameter can be obtained from limited soil data and the model is sensitive to soil properties. The model formulation is based on chemical and physical properties of soils from the temperate region (Sharpley et al., 1984a).

The objectives of this study are to:

1. Test the CERES maize model on Tropeptic Eutrustox and Hydric Dystrandept sites in Hawaii;
2. Check the logical and mathematical correctness (verification) of the model and make appropriate changes in the model such that it simulate the field situation realistically (calibration);
3. Validate the CERES maize model on a wide range of agroenvironments in Hawaii, the Philippines, and Indonesia;
4. Evaluate the model qualitatively and statistically;
5. Develop regression equations based on soils from the tropics as means of generating accurate and readily available input data for the phosphorus model; and
6. Test the modified phosphorus model on Benchmark Soils Project experiments in Hawaii.

II. LITERATURE REVIEW

2.1 Simulation Models for Agricultural Management

Some fundamental problems of agricultural and environmental research are knowing how to obtain knowledge of specific processes within a complex system of interacting and interdependent phenomena, and then, utilizing such knowledge to obtain a comprehensive understanding of the way the system as a whole operates. Understanding of such nature is essential if experience gained under specific conditions is to be extrapolated to different locations and seasons (Hillel, 1977). In recent years, mathematical modeling and simulation techniques, relying on the use of high-speed computers, have been developed to provide a comprehensive and quantitative description of the behavior of dynamic crop growth simulation or plant process models.

By 1969 the modeling approach was well established in agriculture with two leading groups of crop modelers presenting papers at a symposium on "Potential Crop Production" organized at the Welsh Plant Breeding Station in the United Kingdom. The group of Acock, Thornley and Warren Wilson; and the Wageningen group of de Wit, Brouwer and de Vries have provided a continuing stimulus to crop model building ever since. In March 1981 in the "Workshop on Crop Simulation" held at the University of Florida, about forty papers were presented. In the same workshop, held in March 1984 at the University of Nebraska, over forty papers were presented; and in April 1984 in the "Advanced Research Workshop on Wheat Growth and Modelling" held at the University of Bristol in the United Kingdom, about twenty-five papers were presented.

Crop modeling is now established as a valuable research tool in delineating the constraints and exploring the opportunities of increased productivity in crop plants (Legg, 1981). Crop growth models have started to emerge as operational models within the agronomic scientific community.

2.1.1 Advancement in computer technology

To meet the increasing demand for food, agriculture requires a high level of management. The use of computer simulation may appear to be out of reach for agriculturalists in less developed countries (LDCs), however, the reduction in cost of computers and breakthroughs in software technology may provide a way of transferring new information about agriculture in LDCs. The developments in software technology have resulted in computers with the ability to mimic human thought processes including reasoning and learning (Artificial Intelligence). Artificial Intelligence is the ability of the computer to utilize stored information in some worthwhile (goal-directed) manner. One example of Artificial Intelligence is the advanced weather forecasting model capable of "learning from experience" with automatic adjustments to statistical parameters made as data on weather patterns accumulates.

Thus, with improvements in systems analysis techniques and digital computers, quantitative prediction of crop response to physical environment is now practical. Simulation models can describe the impacts of such phenomena as weather, erosion, soil properties, and crop characteristics on agricultural production by utilizing the vast amount of experimental data that have been collected in many parts of

the world (Williams et al., 1983a, b; Kniesel, 1980; Williams and Nicks, 1981). These models allow farmers to test assumptions about the value of economic inputs like water, fertilizers, or pesticides.

2.1.2 Principles and processes of modeling

A fundamental principle of model-building is that the type of model to be constructed depends on the use to be made of it, i.e., it should represent those facets of the real system relevant to the model-uses (Dent and Blackie, 1979). A mathematical model is a quantitative description of a system. It is an analogue which is generally more convenient to use for study and exploring than using the system itself. Models are always simpler than reality but interpretative models must be comprehensive and not exclude possible effects. Effects not included in the model will not be found in the results (Legg, 1981). A model is an integral part of systems research acting as a guide to experimental studies; a method whereby the results of such work are accumulated and assessed; and a platform to guide the development of new systems or to assist decision making in existing systems (Dent and Blackie, 1979). The development of mathematical models is one of the most powerful means known for sorting and describing complex systems. It provides a way to evaluate and analyze the various interactions going on within an ecosystem.

In the physical sciences, a component could be taken from a complex system, place it in a controlled environment and its response to various inputs studied. In general, one is able to accurately predict

what the component will do when placed in the system from its responses in a controlled environment. However, most of the components of a biological system respond much differently, if at all, when removed from the system.

Model development

Fundamental to any development of models is the need from the onset to identify the user. When the user has been identified, one should also determine the scope of the model application. This permits one to address the objective, and hence the model strategy, which includes such issues as the kind and type of data needed and perhaps more importantly, the types of data that will be accessible for real time assessment (Sakamoto and LeDuc, 1981). Therefore, models are built at various levels of sophistication for various purposes. These purposes include: summarizing results, interpolative prediction, extrapolative prediction, and interpretation. Different techniques are appropriate for each purpose. For summarizing results and interpolative prediction, empirical models may be adequate. For extrapolative prediction and interpretation mechanistic models are needed (Bell, 1981).

The steps involved in developing a general simulation model are summarized in Figure 2.1. The figure shows that the steps in model building are not mutually exclusive, and iteration and feedback among the steps is considerable. The major problem in developing models of agricultural systems is the lack of directly suitable data. The mere attempt to develop models can play an useful role in terms of

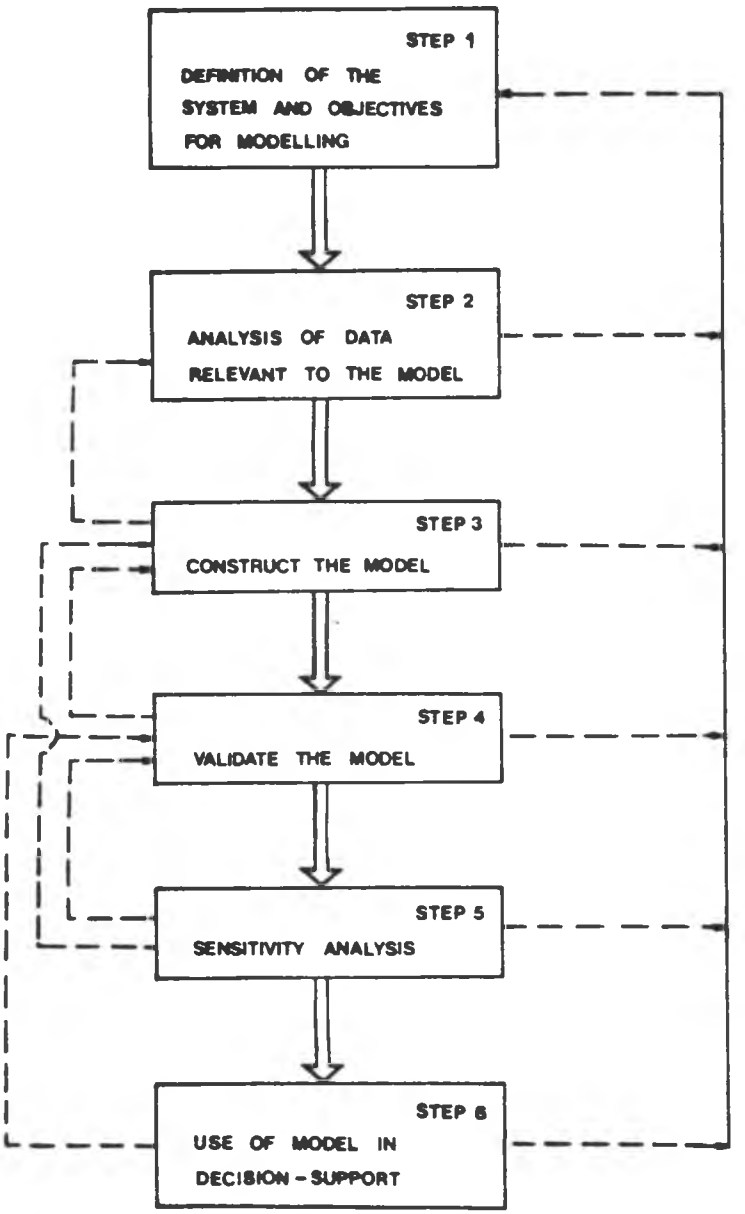


Figure 2.1 The basic steps of system simulation.
Source: Dent and Blackie (1979).

highlighting the sort of information that is lacking (Wright, 1971). There is no doubt that crop simulation models could be substantially improved if they were based on increased and more effectively utilized data. Crop simulation models could benefit from an improved data base (i) as aid in model development; and (ii) in providing input data for executing crop simulation models (Wallach et al., 1982). The first stage in constructing a crop growth model is to promote systematic and clear thinking about the system under study. This concept as achieved diagramatically is shown in Figure 2.2. The next step involves separating the system into its component parts. The components only represent the relevant features of the reality which will be modeled (Dent and Blackie, 1979). At this stage the modeler has to determine the spatial scale to which the model is to be applied. Models developed from a small area or plot and applied to large areas may show a reduction in accuracy (Sakamoto and LeDuc, 1981). The next step in the model development process is checking the mathematical and logical correctness of the simulation model against the design criteria on which it was founded. This is the verification procedure.

The next two steps in the model-building process: model validation and sensitivity analysis, are the real test for the accuracy of the model. Validation involves a testing and an assessment of the model which has been developed. Sensitivity analysis involves making successive 'runs' of the model under identical environmental conditions, but with the value of a parameter changed (Dent and Blackie, 1979). A sensitive region in the model corresponds to a sensitive region in the real system. Therefore, sensitivity analysis

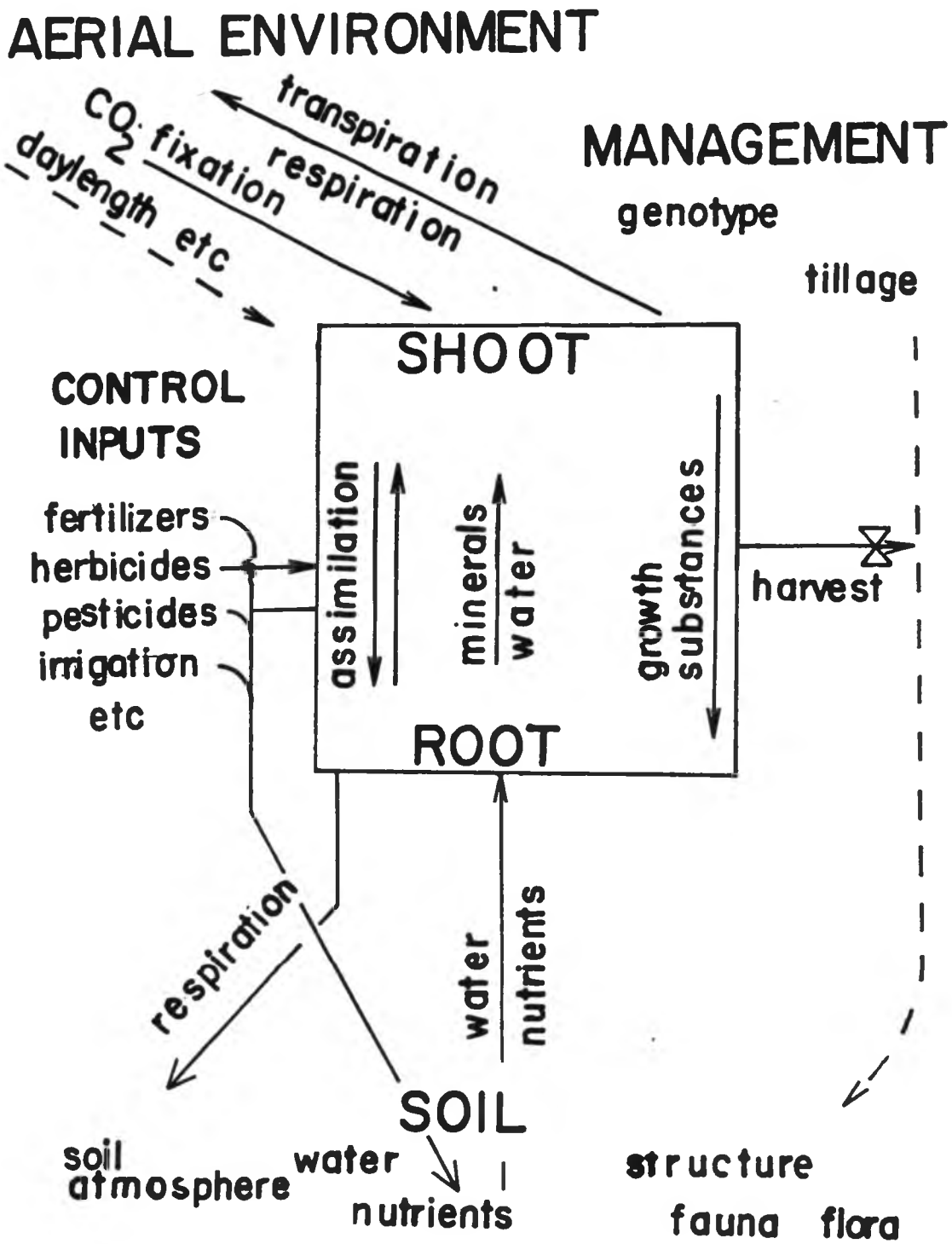


Figure 2.2 Interrelationship between soil, plant, atmosphere, and management.

helps in management of real systems by providing a close control over the systems. Larsen and Iwig (1981) have looked at using sensitivity analysis in model response to various input changes including variables, parameters and functions. The detection of the interrelationships among inputs, provides the measure of accuracy needed for input data, and indicates whether models could be simplified.

Hollinger et al. (1981) used linear regression as a diagnostic technique to identify sources of problems and the possible improvements in the Purdue corn model (Reetz and Hollinger, 1980). Their approach involved calculating the linear regression of the dependent variable(yield) on each major input in the model. The sensitivity of the yield to the input variable was indicated by the correlation coefficient. Other potential techniques that could be used to test the models are: cross validation, jackknife, and bootstrap tests (Sakamoto and LeDuc, 1981).

Too often the coefficient of determination is used as the most important indicator in the evaluation of the model. However, if most of the variability is explained by the trend term a model with R^2=0.99 will have little use. Trend explains a major part of the variability and one may come up with an improper conclusion such as the weather was unimportant. There is little difference in the process used for model testing from that used in experimental research, and the model hypothesis is accepted or rejected through validation tests.

2.1.3 Types of models and their uses

Empirical and mechanistic models

There are basically two approaches to modeling: best-fit modeling approach (regression models) and mechanistic approach. In the best-fit modeling approach, field data are taken and a mathematical expression describing a multidimensional response surface is developed through high speed "curve-fitting" to fit the observed data. The basic difficulty with this approach is that invariably the field experimenter did not measure all the significant factors, and since some factors are not known, the model response of the system may remain random. Multivariate regression models are used widely for the important task of yield prediction in variable climates (Nelson et al., 1978; Pitter, 1977; Thompson, 1969). Variables in static models (no concept of time) are integrated seasonal total yield, rainfall, and temperature. Sophistication is improved by introducing some concept of time, e.g., the calculation of developmental rate as a function of temperature (Shaw, 1964) and by sharpening the environmental parameters, e.g., use of a soil moisture balance rather than rainfall as an input (Baier and Robertson, 1968).

In the mechanistic approach it is assumed that everything observed in a complex agrosystem can be described based on a few basic biophysical postulates or laws. This approach requires a search for mechanisms that could possibly account for what is observed. Biophysical laws, theories and hypothesis are assembled and cast into appropriate mathematical form for each subsystem of the agrosystem to be modeled. The characteristics for this form of models are: the

environmental input variables, the fundamental constants of the system, and the mathematical form of the equations. Thus, a mechanistic model is one which is based on an understanding of underlying physical, chemical and biological processes that affect the phenomenon being investigated. Mechanistic models contribute to scientific understanding since their parameters often have some meaningful scientific interpretation; provide a basis for extrapolation; and provide a better representation of response function (Box et al., 1978; Chanter 1981). A mechanistic approach is justified (a) whenever a basic understanding of the system is essential to progress or (b) when the state of the art is sufficiently advanced to make a useful mechanistic model easily available (Box et al., 1978). However, the difficulties of the mechanistic approach are that the hypotheses, theories, or established laws are often non existent.

Most agrosystem models are developed using both methods, e.g., the best fit models are used where little is known about the system. Detailed mechanistic models are available on infiltration and movement of water in soils (Stroosnijder et al., 1972; van Keulen and van Beck, 1971), including in some cases the influence of expanding root systems (Landsberg and Fowkes, 1978). Radiation intercepted by foliage can also be simulated with sophisticated light distribution models (Cowan, 1968), and microweather within the vegetation can be simulated by coupling such models into net radiation budgets (latent and sensible heat exchange and radiation balance) and eddy transport models (Shawcroft et al., 1974). Submodels for the ecosystem parts can be simplified in various ways. BACROS model (Brouwer, and deWit, 1969;

deWit et al., 1970, 1978) retains considerable explanatory detail in the environmental and photosynthesis modules while using only rudimentary plant growth sections. In contrast, SUBGOL (Ficks et al., 1973, 1975), CERES maize and wheat models (Jones et al., 1983; Ritchie and Otter, 1984) employ simplified environmental modules while expanding on plant growth and development.

Both the statistical regression and process-oriented models require simplistic approaches and utilize statistical analyses. Currently the statistical methods are the most effective for giving practical advice but they have the following limitations (Nye et al., 1975, Dwyer et al., 1981; Chanter, 1981): (a) they apply only to the particular range of conditions of soil, climate and crop under which experiments were made. The results cannot be extrapolated beyond this range with certainty, unless a site-specific parameter is included in the model; (b) the statistical correlations that emerge from the data do not test any theories about the individual mechanisms involved. Although they may suggest where theories are to be sought; (c) the curvilinear relationship between growth and a single factor may be examined, however, the relationship between growth and other relevant factors may become extremely complex when growth depends nonlinearly on many factors; (d) similarly statistical models simplify the interactions in the natural environment and physiological processes, and thus may not contribute to the understanding of the system; and (e) problems of non-normality and unequal variances which are characteristics of most biological systems can often be quantified with simulation experiments.

Stochastic Models

In order to build a realistic simulation model it is essential that stochastic elements be included (Mihram, 1972). This is especially important in management oriented applications, where the outcome of the decision is unknown until some future date. Therefore, the models with decision-support roles should include stochasticity so that the model may reflect the degree of understanding of the real system. The essential feature of stochastic models is that they consider random elements and therefore give outputs in the form of probability distributions. This is in contrast to deterministic models where the predicted values may be computed exactly. Although at the molecular level all processes are ultimately stochastic, the vast number of molecules usually involved means that the results are effectively deterministic (McQuarrie, 1967). The same is true at higher levels of organization, so that in many populations and crop processes, deterministic models of mean behavior are usually adequate (Jones, 1981). One way of studying variations is to introduce distributive or stochastic generators into only selected processes.

Other than empirical models, the types of model which involve random processes at some stage may be subdivided into: (a) true stochastic models, that is models which include randum operators within the model itself. Rainfall simulators provide examples of this type of model with both stochastic elements and input probability distributors (Nicks, 1974); and (b) models with stochastic initial boundary conditions or with stochastic input driving variables. Several models have been developed recently that produce stochastically generated

weather data for use as input to deterministic models of agricultural processes (Arkin et al., 1980; Richardson 1981; Larsen and Pense, 1982; Williams and Nicks, 1983). The changes that occur with time are partly determined by the values of the exogeneous variables in each time period. Therefore, realistic values for exogeneous variables must be provided to the model for each time period. The time series of exogeneous variables used in the model should be representative of the environment taking into account of known patterns, and interactions amongst variables (Dent and Blackie, 1979). Such a series may be obtained either (i) by using historically recorded time-series data for an exogeneous variable in the anticipation, that for this variable, the past is a reasonable indication of what might be expected in the future; or (ii) by providing information structures in the model which are capable of generating representative time-series data. The precipitation model utilizes both of the above procedures. The precipitation model is a first-order Markov chain. Thus the model must be provided with probabilities of receiving precipitation and then it uses skewed normal distribution (Williams and Nicks, 1983), gamma distribution (Larsen and Pense, 1982), or exponential distribution (Richardson, 1981) to determine the amount of precipitation.

2.1.4. Sense and nonsense in modeling

The advantages of plant growth simulation modeling are: (a) it enables the study of systems where real life experimentation would be either impossible, inordinately costly or disruptive (Wright, 1971); (b) it permits the study of long-term effects since the time horizon

over which a model is run is within the control of the model builder; (c) it compels those concerned with building the crop growth simulation model to examine the system objectively and consequently undertake a thorough and critical review of knowledge concerning the system (Dent and Blackie, 1979), and (d) models serve as management and organization tools. The common assumption is that the primary purpose of a model is to provide a means of prediction and will be of little benefit until the final model has been developed and verified. However, it can be seen that there are many significant results that can come from simply attempting to model a system during the entire research program. Crop growth models can have a significant impact on the farmer's decision problem. This impact is likely to come about through the scientific models' impact on laboratory and field research rather than as a "crystal ball" for the farmer.

However, in agricultural scientific community crop growth modeling faces some opposition. Passioura (1973), believes that comprehensive mechanistic models are not testable in practice. It is a waste of time and money to simulate crop growth. One of his suggestions was that a little clear thinking about systems problems would contribute more to the advancement of our science than complex models. Loomis and co-workers (1979) stated that as one learns from reductionist research, the need and opportunity for integrative research becomes greater. There is no other means as powerful for the integrative physiology of plants as crop modeling.

Passioura (1973) also stated that the digital computer has given us the chance to deal with the complexity of a modeling system where "the result is work of art, sometimes good, sometimes bad, but almost always giving us, the creators, a feeling of euphoria ..." This is not only true in crop modeling but true of trend fitters in regression modeling (Sakamoto and LeDuc, 1981). Some modelers use comparison of model predictions with results from independent experiments as a basis for calibrating or "tuning" their models by empirical adjustments of parameters to bring model performance into correspondence with standard behavior. Calibration may create a model useful for mimicking reality but is a dangerous practice for explanation (Loomis et al., 1979).

Current models

Recently, such agricultural simulation models as EPIC (Williams et al., 1983a, 1983b); SOYGRO (Wilkerson et al., 1983); CERES wheat and maize (Jones et al., 1983; Ritchie and Otter, 1984); SORGF (Mass and Arkin, 1978), and TUBERS (Sands, 1983, 1984) have been developed to describe crop growth under field conditions. These models have been developed using readily available meteorological and agronomic data. The data needed for validating these models may be readily generated by field experiments. Some of these models have been validated (SORGF, CERES-wheat, EPIC) or are in the process of validation (SOYGRO, CERES-maize). Thus, these comprehensive models have nullified the criticism brought about by Passioura (1973).

2.2 Simulating Effect of Environment Genotype, and Management on Maize Production

Dynamic (time-based) models of crop growth that assess the importance of climatic, plant, soil properties, and farm management practices are needed as a means of assisting farmers in minimizing their risks. In crop modeling, the three most important weather variables which have to be considered as they may limit plant growth and development are light (or solar radiation), moisture, and temperature. DeWit et al. (1970), Duncan (1975), and Reetz and Hollinger (1980) used complex physiological models to consider the effect of these weather variables on crop growth and development with hourly to daily time steps from planting to maturity. Statistical multiple regression models, such as those by Thompson (1969), have made use of monthly averages of temperature and total precipitation to predict average crop yield. Models intermediate between the physiological and multiple regression approaches have also been developed (Jones et al., 1983; Stapper and Arkin, 1980).

2.2.1 Maize growth response to temperature, photoperiod and genotype

Temperature affects the growth of plants in many ways, from root growth, nutrient uptake, and water absorption from the soil, to photosynthesis, respiration, and translocation of photosynthate. The effects of temperature on crop growth are much more variable and intricate than are those of water. Several consideration that need to be evaluated include (i) the lower threshold temperature for crop

growth, (ii) the desirable daily temperature range or temperature difference, (iii) the optimum temperature for growth, (iv) the upper limit of temperature for growth, and (v) how the above relate to a specific variety (Hargreaves, 1983).

Various maize (Zea mays L.) models such as CERES maize (Jones et al., 1983a), CORNF (Stapper and Arkin, 1980), SIMAIZ (Duncan, 1975), Purdue corn model (Reetz and Hollinger, 1980), and CORNGRO (Tschescke and Gilley, 1979) consider that temperature is dominant in controlling development. The major parameter determining phenological stages for many crops and varieties is temperature-related (Richardson and Leonard, 1980). Maize has an optimum temperature range of 25-30°C. Temperature often determines the time required to reach a given stage in plant development. The most common term applied is growing degree days above a minimum and below a maximum temperature; the growing degree hour concept is a refinement (Hargreaves, 1983). This heat unit concept is used extensively to account for temperature effects on maize development in models which attempt to predict crop development and yield. Some models also take account of the effects of photoperiod on crop development (Coligedo and Brown, 1975a; Jones et al., 1983a).

Gunn and Christensen (1963) showed that the number of accumulated heat units from planting to silking remains relatively constant for a given corn variety grown in different environments, while calendar days varied widely. Various studies have shown that degree days methods were more accurate and less biased than the calendar days in predicting silking and physiological maturity (Gilmore and Rodger, 1958; Gunn and

Christensen, 1963; and Daughtry et al., 1984). Temperature and photoperiod are known to affect leaf number, although magnitude of response varies with varieties. The leaf number and temperature response of the two varieties studied by Warrington and Kanemasu (1983a) was strongly curvilinear. The leaf number was highest at both cooler (16/6°C day/night) and warmer (38/33°C) temperatures and lowest at mean temperature near 18°C (18/18°C). Because of this nonlinearity, leaf numbers observed under differential day/night temperature regimes were sometimes quite different from those observed under constant day/night temperatures but with identical mean temperatures. Their observation also explained the controversy of whether leaf numbers increased with increase in temperature (Duncan and Hesketh, 1968; Coligado and Brown, 1975b; Hunter et al., 1977) or decreased with increase in temperature (Stevenson and Goodman, 1972; Hunter et al., 1974).

Photoperiod response of maize

Most maize varieties are sensitive to photoperiod, hence most tropical lines cannot be used as parents in temperate climates and vice versa. Both temperature and photoperiod significantly affect the number of days from planting to tassel initiation (Francis et al.,1970; Hunter et al., 1974; Warrington and Kanemasu, 1983b). Long photoperiod (20 hours) and low temperature (20°C) independently increased the number of days between planting and tassel initiation. Increase in photoperiod also lengthened the time between tassel initiation and silking (Warrington and Kanemasu, 1983b). However, the photoperiod

response varies with varieties, hence there are reports where the time interval between tassel initiation and silking was not affected by photoperiod.

Similarly depending on maize genotypes a decline in sensitivity to photoperiod can occur at high temperatures (Hunter at al., 1974; Coligado and Brown, 1975b) or the sensitivity to photoperiod remain unaltered by temperature (Warrington and Kanemasu, 1983b; Stevenson and Goodman, 1972). Hunter and his coworkers (1974) reported temperature x photoperiod interaction during grain-filling period. Photoperiod is also known to affect leaf number (Warrington and Kanemasu, 1983a; Hunter et al., 1974).

Farmers do not have much control over temperature and photoperiod. They can adjust planting dates and plant suitable varieties to maximize the effect of temperature and photoperiod on plant development and thereby greatly increase production.

2.2.2. Water availability

Water and temperature are the more important determining factors in crop yield models and production variability regardless of location and year (Hargreaves, 1983). Yield is determined by moisture needs, which are influenced by temperature, radiation, the amount of water available, and the time and manner of availability to the crop. Even in humid parts of the world because of periods of insufficient rainfall, water stress commonly occurs. The processes of photosynthate

production and transpiration are closely linked (Boyer and McPherson, 1975). Thus, photosynthesis is limited when water stress occurs due to closing of the stoma and reduction in other activities in the plant.

Methods for predicting influence of plant water stress on crop production range from mechanistic prediction of details of growth of plant parts to statistical predictions of nationwide yields (Hanks and Rasmussen, 1982). Thus, it is possible for farmers to use these models to minimize their risks due to water stress. The simplest models require knowledge of total water available, such as irrigation, rain, and stored water, to predict yield using statistical methods. These methods are site and season specific, but give general guidelines and are widely used. The next step in complexity was to evaluate the relative amount of water actually used by a crop - not just available for use. For example Equation (2.1) developed by deWit (1958) is widely applicable (Fisher and Turner, 1978). However, Equation (2.1) was not appropriate for humid regions of the world.

$$Y = MT/E_o \qquad (2.1)$$

where Y = crop yield, T = transpiration, E_o = potential evapotranspiration of free water during the measurement period, and M = crop factor. The equation takes care of some of the climatic influences. Tanner and Sinclair (1981) modified Equation (2.1) so it became more applicable to different climatic regions.

Stewart et al. (1977) proposed means of estimating yield from measured ET (evapotranspiration) values, thereby eliminating the need to determine T. Many methods have been developed over the years to estimate ET. Jensen (1973) and Dorrenbos and Pruitt (1975) proposed:

$$ET = K_c ET_m \quad (2.2)$$

where K_c= crop coefficient and ET_m = potential evapotranspiration using a reference crop or one of many climatic equations. The value of K_c is dependent on the kind of crop as well as local climatic and irrigation management conditions. Evapotranspiration models have been developed for sorghum and soybean (Kanemasu et al., 1976), corn (Rosenthal et al., 1977), and wheat (Kanemasu et al., (1977). The approach has been similar in all cases. ET_m is estimated using the approach of Priestly and Taylor (1972), as modified by Jury and Tanner (1975):

$$ET_m = a[s/s+g]R_n \quad (2.3)$$

where a = crop- and location-related constant, s = slope of the saturation vapor pressure curve at a weighted average temperature, g = psychrometric constant, and R_n is daily net radiation. R_n is computed from empirically determined relationships of crop leaf area index (LAI) and stage of growth (Hanks and Rasmussen, 1982).

Stapper and Arkin (1980) developed a maize model that is based upon the simulation of leaf area, photosynthesis, evapotranspiration, and temperature. The water balance model in the CERES (Ritchie and Otter, 1984) is more complex. Yet input data required to 'run' the model is not difficult to generate. These mechanistic models require computers for solution. Soil, climatic, and crop information are used to predict water use as a function of time and can thus estimate stress as a function of time or growth stage. One of the plant factors that determines water requirement is the leaf area index. Conversely, water

availability (as well as temperature and nutrient supply) affects leaf area development. The effect of soil compaction is also taken into account when water uptake and root growth are simulated (Ritchie and Otter, 1984).

2.2.3 Solar radiation and plant density

Although other factors are believed to be more limiting on crop growth and production, yield frequently increases linearly with increase in radiation and leveling off at some value that depends upon the crop, climate, soil fertility, and other conditions.

The yield of corn grain per unit land area is also highly dependent upon plant population, plant distribution, and growth characteristics of the varieties adapted to the area. Increasing plant population is a method for maximizing interception of incoming solar energy in crop species. Greater amounts of energy are absorbed by plants under combinations of narrow rows and high population (Aubertin and Peters, 1961). Results of Jong et al. (1982) and Lee (1983) showed that solar radiation was the main climatic factor affecting yield with the changes in planting dates. They reported highest grain yields for March to August (summer) plantings and much lower yields for November to January plantings.

The optimum population for corn grain yield ranged from 30,000 to 40,000 plants/ha in North Dakota (Alessi and Power, 1975) and 49,400 to 123,500 plants/ha in Hawaii (Chung et al., 1982). Rutger and Crowder (1967) reported a hybrid x population interaction for grain yield. It has been reported that as plant population was increased, stalk

diameter and ear weight decreased significantly (Genter and Camper, 1973). Therefore, the yield of individual plants is reduced resulting in a lower harvest index with increasing population density (Genter and Camper, 1973; Deloughery and Crookston, 1979).

2.2.4 Response to N fertilizer application

Major roles of N in plant growth include (i) components of the chlorophyll molecule, (ii) component of amino acids, the building blocks of proteins, (iii) essential for carbohydrate utilization, (iv) components of enzyme, (v) stimulative to root development and activity, and (vi) supportive to uptake of other nutrients (Olsen and Kurtz, 1982). The latter two roles notably enhance water use efficienty (Olsen et al., 1964). The quantities of N found in different crops vary greatly with species and environments in which the crops are produced. There are also variations in N concentration among parts of a given plant, rapid changes in N concentrations of plant parts occur with stage of growth, differences in concentration imposed by climatic variables, varied N concentrations with deficiency or excess of another nutrient in the plant, and changing N levels in plant parts due to disease or pest attacks. The sufficiency level of N in maize (ear leaf at silk) ranges from 2.76-3.5% N while less than 2.25% N is considered deficient (Jones, 1967).

Effective management of N is complicated by its mobility. Nitrogen fertilizer is subject to losses via NH_3 volatilization, denitrification, and leaching and it may be augmented by rainfall and biological fixation. In contrast to most other plant nutrients no

mechanism for long-term storage of plant-available N exists in soils. Although NH_4^+-N is held against leaching in the cation exchange complex, it is readily transformed microbially to NO_3^- which is subject to leaching and denitrification (Olsen and Kurtz, 1982). N fertilizer has relatively low residual value so that the N- supplying capacity of the soil cannot be permanently increased by massive applications of fertilizer N. Thus, fertilizer N is applied on a crop-by-crop basis rather than for a rotation or a crop sequence. Recently, an added concern had been the emission of nitrogen to receiving water bodies, both surface and ground waters. Hence the N-soil-plant-water-atmosphere system needs evaluation.

N models

Estimating nitrogen fertilizer use efficiency by the corn crop or nitrogen leaching beyond the root zone involves consideration of the many sources and sinks of nitrogen, and the flow pathways of both water and nitrogen. Such prediction may be done conceptually, taking a more simplified qualitative approach, or mechanistically, taking a more detailed quantitative approach. For the more quantitative modeling objectives, the aim is to simulate the physical, biological, and chemical processes and conditions. The literature contains numerous mathematical equations describing N mineralization - immobilization, nitrification, urea hydrolysis and other physical, biological, and chemical mechanisms involving both nitrogen and water.

One of the earliest N transformation models was reported by Dutt et al. (1970). Empirical rate equations were obtained by carrying out multiple regressions on experimental data from batch-type or incubation

studies. Mehran and Tanji (1974) took both mechanistic and empirical approach and assumed first-order kinetics for all transformations. Beek and Frissel (1973), Seligman and van Keulen (1981), Godwin et al., (unpublished), and Jones et al. (1983b) all have developed complex nitrogen simulation models. The nitrogen model used in the CERES models (Jones et al., 1983a; Ritchie and Otter, 1984) is perhaps the -state-of-the-art N model. This N model developed by Godwin and coworkers is based on the PAPRAN model (Seligman and van Keulen, 1981) and work of Standford and Smith (1972), Standford and Epstein (1974), Burns (1980), and Mengel and Barker (1974).

The soil organic N in their model is divided into (i) fresh organic N, consisting of N in decomposing crop residue and microbial biomass and (ii) stable organic N, consisting of N in stable organic matter. The soil inorganic N is present as NO_3- and NH_4-N. Depending on the fertilizer type, fertilizer nitrogen is partitioned into nitrate and ammonium fractions. Mineralization from fresh organic nitrogen is dependent on residue type (carbohydrate-like, cellulose-like, and lignin-like), soil temperature, soil moisture factor, and carbon to nitrogen ratio. Temperature and moisture factors also influence the mineralization of N from stable organic matter. The gross rate of N immobilization depends on the minimum of N available for immobilization and the demand for N of the decaying fresh organic matter. Soil water factors and temperature factors also influence the rate of oxidation of ammonium nitrate (nitrification).

Crop uptake of N is controlled either by plant demand or soil supply of nutrients. Plant demand is the difference in the actual plant N and the content of the same biomass at optimum N concentration. The potential plant N uptake is estimated as mass flow of NO_3^--N in the transpiration stream. Actual uptake of N is the minimum of potential uptake and plant demand. Crop growth on a day is a function of intercepted photosynthetically active radiation and the minimum of temperature, water, and N stress factors. The stress factors vary nonlinearly from 1.0 at optimal N concentration to 0.0 when N is half the optimal.

The CERES models and perhaps all other simulation models currently do not take into account the spatial variability of the soil and plant properties required as model inputs and also existence of anaerobic and aerobic conditions when simulating denitrification (Frissel and van Veen, 1978). The spatial variability in soils is of importance in explaining nitrogen losses from soil and site-to-site variation in yield, and in choosing the optimum agronomic practice. In weathered soils phosphorus is perhaps more limiting for maize production than other nutrients. In the next section effect of P management on crop production is presented.

2.3 Simulating Phosphorus Response

2.3.1 Forms of P

A full description of phosphorus cycling in soils and plants is complex and requires understanding of chemical, physical, and biological processes influencing the various forms of P in the soil profile. As an input to a model, it is necessary to have measurements of biologically available P in the soils. Solid phase phosphorus comprises organic and inorganic phosphorus. The soil fractions P considered most important for predicting biologically available P are (i) the P in the soil solution, and (ii) labile P or that quantity of soil P in rapid equilibrium with solution P.

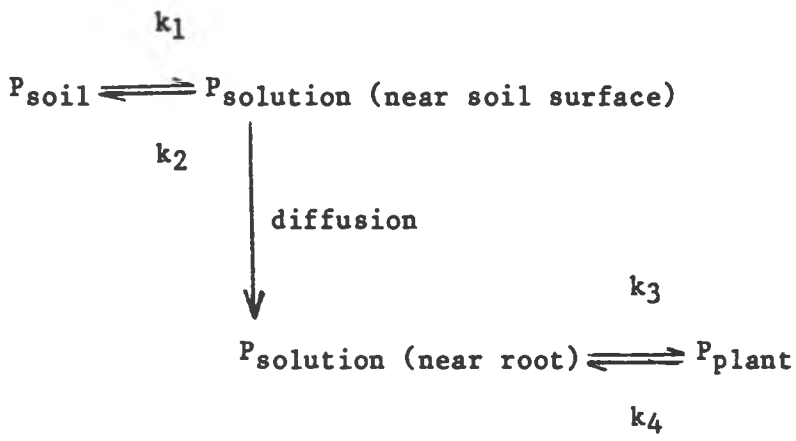
Labile P has been determined using the isotopic dilution technique (Russell et al., 1954), adsorption/desorption isotherms (Holford and Matingly, 1976), anion exchange resin (Cooke and Hislop, 1963), or chemical extractants (Thomas and Peaslee, 1973). Soil solution P may be determined by measuring water soluble P or from adsorption/desorption isotherms (Olsen and Sommers, 1982) The inorganic P in soil is further fractioned into 3 major forms: Ca-, Fe-, and Al- P (Thomas and Peaslee, 1973). The selection of any particular chemical extraction procedure is dependent on which of the above P forms are dominant in the soil.

The organic forms of phosphorus are of importance in fertility because, they are an indirect source of the soluble forms. Phosphates, as well as nitrates are produced when soil organic matter is decomposed. After liberation, soil reactions sooner or later make the

phosphate a part of the adsorbed and acid soluble forms. The level of the available P forms already present, and not the amount liberated from the organic matter during growing season, determines the fertility of the soil for that season. No direct method for determination of organic phosphorus has been described. The indirect methods are: 'ignition' and 'base extraction'. In ignition method, organic phosphate is mineralized by ignition of the soil, and measured by the difference in inorganic P extracted from comparable ignited and unignited samples. In the 'extraction' technique total and inorganic P are determined in the extracts and organic P is obtained by difference (Williams et al., 1970).

2.3.2 Assessing P availability

A major problem encountered in the soils of the tropics is the inordinate amounts of fertilizer P needed to meet the crop requirements. In agronomic studies, the usefulness of any parameter of soil P depends on the extent to which it can account for the variation in yield and P uptake with variations in soil P. The P availability is dependent on the supply characteristics of soils and the ability of roots to absorb P from soil solutions. The availability of soil P is influenced by the intensity factor (I), the quantity factor (Q), the capacity factor ($\Delta Q/\Delta I$), as well as rate and diffusion factors (Dalal and Hallsworth, 1976). The supply of phosphate to the plant is as follows:



The system simplifies to the following factors: quantity (P_{soil}), rate (k_1/k_2), intensity ($P_{solution}$), and diffusion (Gunary and Sutton, 1967). For plants in active vegetative growth, k_4 is likely to be negligible and the rate of uptake from solution, k_3 is likely to be limited only at high phosphate concentrations. The immediate source of phosphate to plant roots is the soil solution which is replenished in most soils by adsorbed P. In addition to concentration of P, the rate of P uptake depends on the rate of movement of P to the root surfaces by the process of diffusion and mass flow of water. At the low concentrations of P usually observed in soils, diffusion is the main process of transport to the roots (Barber, 1962; Olsen and Watanabe, 1963, 1966; Lewis and Quirk, 1967; Olsen et al., 1962). The two main parameters that describe the plant availability of soil P are therefore the concentration (more appropriately activity) of P in soil solution (an intensive parameter) and the quantity of adsorbed P (an extensive parameter). The relationship between these variables, termed the buffer capacity,

defines the change in quantity of adsorbed P per unit change in concentration of solution P.

The fundamental problem in evaluating the plant availability of soil P by means of a soil test, whether it be an intensive or extensive parameter is that neither alone gives information on buffering capacity, which controls the resistance of both concentration of the soil solution P and quantity of the adsorbed P to change when P is added to or removed from the system (Halford and Mattingly, 1976). The short term changes (measured in weeks or several months), in the intensities and quantities of labile P and the buffer capacities of a soil is a function of the previous P fertilization and the inherent adsorption properties of each soil. Long term changes (over at least 2 years) are affected by additional processes which convert absorbed P into non-labile forms (Mattingly, 1965).

In the measurement of quantity, intensity and kinetic components it is essential that no major change is induced in the chemical constitution of the soil by the applied experimental procedure. Ideally, a P soil test would take into account both intensity and quantity. In practice, however, soil tests characterize either the intensity or the quantity factor. The suitability of a soil test for predicting the P status of a soil can be evaluated by correlating the P extracted with plant growth parameters such as yield, P uptake, and P concentration or with estimates of labile P (Kamprath and Watson, 1980). The estimation of labile soil phosphate for modeling purposes must be a simple procedure (readily carried out), as distinct from the more comprehensive and time consuming determinations associated with

more fundamental studies. The resin technique (discussed later) reflects both the quantity and intensity/kinetic factors of P status and it is also a simple procedure (Hislop and Cooke, 1968).

The intensity factor

The concentration (activity) of P in solution is an estimate of the intensity of P nutrition. Since P in solution is extremely dilute, it must be continuously renewed; if not concentrations will decrease rapidly as soil P is used by plants. A high flux of P to roots is possible, even when P concentrations are low, if solutions bathing root surfaces are quickly and continuously renewed with P. In general, this required a short diffusion path and a large cross sectional area through which ions may diffuse (Fox, 1981).

The parameters of intensity factor in general are poorly correlated with P uptake and grain yield (Dalal and Hallsworth, 1976). The intensity factor may be important only in early stage of plant growth. Gunary and Sutton (1967) showed good correlations of combinations of the log of the P concentration in solution and a quantity factor (L-value) with short and long-term uptake of phosphate. The log P concentration in solution measures an intensity/kinetic complex that takes account of intensity, rate and diffusion factors. The concentration of P in the soil solution is estimated by : (1) water extraction (Kamprath and Watson, 1980), (2) 0.01M $CaCl_2$ extraction (Aslyng, 1964), (3) water displacement (Whelan and Barrow, 1980).

The extraction procedures differ in certain details such as: extraction period, soil to solution ratio and period of incubation before extraction. P in the soil solution or extracts has been

expressed in several ways: (1) elemental or molar concentration, (2) molar activities of specified phosphate ions, (3) chemical potential of phosphate ion, (4) orthophosphoric acid potential, and (5) monocalcium phosphate potential (Olsen and Khasawneh, 1980).

The quantity factor

The quantity factor has been defined as the quantity of solid phase P that acts as a reserve to replenish the loss of P from soil solution (Olsen and Khasawneh, 1980). For normal agricultural soils, the quantity factor is as important, or even more important than the intensity/kinetic complex. However, with the enriched soils, exhaustion occurs less readily, and hence importance of the quantity factor is much less than intensity/kinetic complex. This situation appears to be equally true for initial and long-term uptake (Gunary and Sutton, 1967). The quantity factor has been divided arbitrarily into 3 categories: (1) forms which are in rapid equilibrium, (2) forms which are in slow equilibrium, and (3) forms which are not in equilibrium with soil solution P (Corey and Schulte, 1973). The relationship between intensity-and quantity factors is as follows (Larson, 1967):

$$\text{soil solution P} \overset{\text{rapid}}{\rightleftharpoons} \text{labile P} \overset{\text{slow}}{\rightleftharpoons} \text{nonlabile P} \longrightarrow \text{fixed P}$$

Thus labile P, readily exchanges with solution P, and when P intensity is decreased, solution P is quickly replenished by P from the labile pool (Mattingly, 1965).

Various methods have been used to assess the quantity factor of a soil. These are: (1) P isotope exchange, (2) anion exchange resin P,

(3) adsorption-desorption processes, and (4) chemical extraction. A number of these methods are discussed in more depth later in the review.

Buffer capacity

Buffer capacity of a soil is the change in quantity of sorbed P (ΔQ) per unit change in intensity of P (ΔI). Buffer capacity determines the resistance of both Q and I when P is added or removed from the system. In most soils Q/I relations are linear at very low solution concetrations (<1 mg P/l) and nonlinear at higher concentrations (Barrow, 1974). The buffer capacity is calculated from the linear part of the Q/I plot. The buffer capacity of the soil P system may be described by the P sorption isotherm. A sorption isotherm is a curve relating the amount of a substance sorbed at an interface to its concentration at equilibrium in the medium in contact with the interface (Bache and Williams, 1971).

As P is added to or removed from the soil system, the buffering capacity will decrease or increase (respectively), the magnitude of change depending on the original position on the sorption isotherm. As the high energy surface gets saturated the buffer capacity diminishes (Holford and Mattingly, 1976). In a soil in which high energy surface is significantly under saturated with P, most of the buffer capacity is provided by adsorption properties of this surface because of its much higher P affinity. The buffer capacity generally increases with increase in clay content of the soil, with depletion of organic matter and increase in short range order minerals (Sanchez and Uehara, 1980). The buffer capacity of acid soils is influenced by the amounts

of hydrated oxides of Al and Fe, and of calcareous soils by the amount of exchangeable Ca and $CaCO_3$.

Maximum or limiting buffer capacity is used to overcome the problem of a constantly varying capacity. Holford and Mattingly (1976) used maximum buffer capacity as a characteristic for defining the P adsorption properties of soils because it integrates both intensive and extensive components of adsorption and is independent of P saturation. Peaslee and Phillips (1981) obtained two- to three- fold variation in magnitude of buffering capacity when they compared four methods, viz., adsorption, sequential desorption, resin desorption, and ^{32}P exchange, for determining buffer capacity of two soils. Of the four methods, only adsorption did not rank the two soils in the same order as the other three methods did.

2.3.3 Rapid P Sorption

Numerous studies have described the rate and/or extent of rapid adsorption of fertilizer P on soils by adding varying amount of P to soil suspension and then analyzing the amount of P remaining in solution over time (Barrow, 1978, 1980a, 1980b, Fox and Kamprath, 1970; Rajan and Fox, 1972). The behavior of labile phosphate in soils is dominated by sorption and desorption processes (Mattingly, 1965).

It is impossible either to define rigorously or to measure unequivocally the amount of solid phase phosphate in equilibrium with the ambient solution. The use of the radioactive isotope, ^{32}P, has confirmed these difficulties rather than solved them, because the continuing slow rate of isotopic exchange, and the effects of

experimental variables, such as the ratio of soil weight to solution volume, the vigor of shaking (Barrow and Shaw, 1979), and the ionic nature of solution used during P adsorption (Rajan and Fox, 1972, 1975), emphasize that there is no single valued amount of isotopically exchangeable phosphate. Further, much of the phosphate added to a soil is sorbed irreversibly; only a proportion of that sorbed remains readily isotopically exchangeable, and this proportion decreases with time (Russell et al., 1954). Many of these problems also reoccur with other P extraction techniques. Thus, some arbitrariness is unavoidable because of the complex nature of soil phosphate reactions. Factors affecting P content and availability in soil include: organic carbon, kind of organic matter, carbonates, pH, and clay content, iron oxides, exchangeable Ca, and active Al components, soil age, parent material, climate, management history at the site, and probably other factors.

Isotopically exchangeable soil P

Attempts have been made to define the total amount of phosphate which is capable of releasing phosphate ions to the soil solution as the quantity of phosphate capable of undergoing exchange with radioactive phosphate or isotopically dilutable phosphate (Dalal and Hallsworth, 1977). This can be estimated in the laboratory by an isotopic dilution technique, when the quantity is referred to as the E value (Russel et al., 1954; Amar, 1962), or by measurement of plant uptake in greenhouse experiments, L value (Larsen, 1952). There are two assumptions involved in determining the E- and L- values. First, all of the activity added to the system remains in isotopic equilibrium

(Eq. 2.4) and secondly, the final specific activity of solution P (or plant P) is the same as that of surface P.

$$^{31}P_{surface} + ^{32}P_{solution} \rightleftharpoons ^{32}P_{surface} + ^{31}P_{solution} \quad (2.4)$$

Thus:

$$^{32}P_{surface}/^{31}P_{surface} = ^{32}P_{solution}/^{31}P_{solution} \quad (2.5)$$

In an attempt to attain such equilibrium, soil suspension may be shaken for some time prior to the addition of carrier-free ^{32}P and surface exchangeable P calculated by means of equations that are arrangements of Equation (2.4) i.e.,

$$^{31}P_{surface} = ^{32}P_{surface} * ^{31}P_{solution}/^{32}P_{solution} \quad (2.6)$$

The total amount of phosphate in the soil (solid phase plus soil solution) which can undergo isotopic exchange is called labile phosphate (Talibudeen 1957). Labile phosphate (E) is often determined by the direct method of equilibrating soil with a solution of ^{32}P - labelled orthophosphate, assuming that the phosphate ions in solution exchange with the solid phase phosphate and ^{32}P becomes diluted throughout the total exchangeable pool in the soil. The fundamental equation for isotopic dilution is:

$$y/(E+x) = y_t/x_t \quad (2.7)$$

Here y= amount of ^{32}P added per g of soil; x= amount of carrier P added with the ^{32}P (per g soil); y_t, x_t=amount of ^{32}P and ^{31}P per g of soil, respectively, in equilibrating solution at time t (White, 1976). Rearranged, the equation as used by Russell et al. (1954) is obtained:

$$E = yx_t/y_t - x \quad (2.8)$$

Identical expression:

$$E = x(S_i/S_t - 1) \qquad (2.9)$$

has been used by Amer (1962), Mekhael et al. (1965), Amer et al. (1969) and Olsen and Sommers (1982). The terms S_i and S_t represent the specific activity of the added phosphate and of the equilibrium solution at time t, respectively. If carrier-free ^{32}P is used for measurement of labile P, then Equation (2.8) reduces to:

$$E = yx_t/y_t = y/S_t = x_t/f \qquad (2.10)$$

where f is the fraction of total activity remaining in solution at time t.

However, the radioactive ^{32}P cannot clearly distinguish between labile and nonlabile P and if the ^{32}P is not well distributed, a longer time required for the reaction makes the task of separation more difficult. Lamm (1961) found that the L- value changed with time. Gunary (1963) found a slow rate of isotopic dilution due to uneven distribution of ^{32}P on and in soil crumbs. The laboratory procedures for the determination of the isotopically exchangeable pool of phosphate has not proved as valuable tests of soil phosphate as was originally anticipated. Their failure has been attributed to lack of equilibrium between added isotopic phosphate and surface phosphate (Russell et al., 1954), fixation of the radioactive phosphate in non-exchangeable sites, or to variations in the extent to which different soil components would release adsorbed phosphate to the soil solution (Amer et al., 1969). One reason for some of these difficulties has been the failure to recognize the fact that the

phosphate fixing capacity of most soils in the natural state is far from being satisfied.

In high phosphate fixing soils the radioisotope P which is added will largely be adsorbed on the surface without the concomitant release of ^{31}P, thus disturbing the isotope equilibrium, and leading to an overestimation of the isotopically exchangeable pool (Russell et al., 1954, Amer et al., 1969; Dalal and Hallsworth, 1977). The above is particularly so when carrier-free ^{32}P is used. Methods involving use of 0.2 ppm P carrier solution or the inverse dilution technique may give satisfactory labile P measurements in low- and medium-phosphate-fixing soils (Amer et al., 1969).

In the inverse dilution technique a small amount of radioactive P is added to the soil solution and then the exchangeable pool measured with nonradioactive phosphate solution (Mekhael et al., 1965; Amer et al., 1969). On theoretical grounds this technique gives the best estimate of the isotopically dilutable pool of phosphorus (Dalal and Hallsworth, 1976). Expression for determining labile P by inverse dilution is:

$$(E + x)S_t = ES \tag{2.11}$$

or

$$E = x\,[S_t/(S - S_t)] \tag{2.12}$$

where S and S_t are specific activities before and after equilibration with inactive P. The very small quantity of ^{32}P added would not significantly increase the quantity of exchangeable phosphate held on the soil. Moreover, the inverse dilution technique does not require that all added ^{32}P remain in isotopic equilibrium, since the labile P

value is calculated from the specific activities of soil solution before and after the addition of ^{31}P. However, the errors due to uncertainties in the measurement of the specific activity in solution is increased, since measurements are made twice. The final specific activity may be overestimated and E value underestimated (Equation 2.12) if ^{32}P labelled solutes exist in solution where they are detected by isotopic counting but are not quantitatively detected as orthophosphate by colorimetric analysis (White, 1976).

Anion - Exchange Resin P

The anion-exchange resin method does not directly measure the soil - P factors, but the P extracted by a resin, shaken in a soil-water suspension is the result of them. The resin functions as a plant root with a very high capability for P uptake. Depending on the type of resin, the resin simulates the plant root, by releasing chloride, bicarbonate or sulfate ions for the anions extracted. The results from the resin method have often been found to correlate well with plant P uptake (Amer et al., 1955; Cooke and Hislop, 1963; Hislop and Cooke, 1968; Vaidyanathan and Talibudeen, 1970; Sibbesen, 1978). However, the method is not in widespread routine use, probably because of the analytical procedures presented by Amer et al (1955) and Hislop and Cooke (1968). Furthermore, there is no standard procedure.

Various experimental studies have shown that the following factors may influence the amounts of P extracted by the resin method: (i) relative volumes of soil, resin, and water; (ii) available surface area of soil and resin (governed by particle size); (iii) temperature of the suspension; (iv) duration and vigor of shaking; and (v) type of resin

(Hislop and Cooke, 1968). Thus, precautions must be taken to standardize these experimental factors. Sibbesen (1968) reported that for resins in the chloride and hydroxyl forms both the amount of P extracted per soil unit and the pH of the suspension varied with the type of resin and the soil-water ratio. However, the resins in the bicarbonate form stabilized the system, so that the amount of P extracted and the suspension pH were almost independent of the type of resin and the soil-water ratio.

Anion resin extraction is a better technique than chemical extraction because anion resins adsorb P from the soil without exerting a destructive influence on the soil, and the P removed by resin is analogous to P adsorption by roots (Hislop and Cooke, 1968; Sibbesen, 1978; Dalal and Hallsworth, 1976; Bowman and Olsen, 1979). On the other hand, extraction methods with acids, organic and inorganic complexing agents or alkaline solutions often extract all or part of labile P plus undefined proportions of other forms of soil P. The degree of correlation between P uptake and P determined by resin method has generally been higher than P determined by chemical extraction methods and even higher or as high as by the isotope method (Sibbesen, 1978, Bowman and Olsen, 1979). Dalal (1974) explained the phosphate desorption by anion-exchange resin using a two-constant equation. The coefficient term (rate factor) and the constant term (solution P) were significantly related with amorphous Al.

Chemical Extraction Methods

The complex nature of soil P and the failure of one well-defined chemical fraction of P to account for uptake of P by plants from a

broad range of soils have resulted in a large number of soil testing methods. The four basic reactions by which P is removed from the solid phase are solvent action of acids, anion replacement, complexing of cations binding P, and hydrolysis of cations binding P (Kamprath and Watson, 1980). The acid solutions used to extract P have a pH of 2 to 3. Acid solutions solubilize calcium phosphates and some of the aluminum - and iron phosphates (Thomas and Peaslee, 1973). Anions such as acetate, citrate, lactate, sulfate and bicarbonate replace P adsorbed on surfaces of $CaCO_3$ and hydrated oxides of Fe and Al. Fluoride ions, citrate ions and acetate ions are effective in complexing Al ions and thus releasing P from Al-P (Kamprath and Watson, 1980). Calcium is precipitated by F ions as CaF_2 and therefore P present in soils as $CaHPO_4$ is extracted (Thomas and Peasley, 1973). F ions cannot extract P from basic Ca-P and Fe-P unless F solution is acidified. $NaHCO_3$ buffered at pH 8.5 extracts P from Al-P and Fe-P due to hydrolysis of cations binding P. Extracting solutions containing OH ions utilize hydrolysis mechanisms to extract P (Tynes and Davide, 1962).

Soil properties that may determine the choice of extracting solution are soil pH and soil mineralogical properties. Thus, dilute acid extractants will be unsuitable with soils whose pH under natural conditions is 7 or higher. Similarly the soils with high clay and Fe oxide content will tend to neutralize the acid extracting solution and reduce the amount of P extracted (Thomas and Peasley, 1973; Kamprath and Watson, 1980). Hydroxide ions have little effect on basic Ca-P but will dissolve Fe- and Al-P in that order. Use of the OH ions is not

practical in soils with high organic matter contents. OH ions in these soils releases organic phosphates which are inseparable from inorganic phosphates. Thus there is no one chemical extraction method that will give satisfactory results on a broad range of soils.

P sorption isotherms

As previously defined, a sorption isotherm is a curve relating the amount of a substance sorbed at an interface to its concentration at equilibrium in the medium in contact with the interface. Sorption isotherms have been used to obtain information on both the quantity and intensity aspects of P availability (Beckwith, 1965; Barrow, 1967; Ozanne and Shaw, 1967; Fox and Kamprath, 1970; Fox et al., 1982). This approach can serve as a means for characterizing soils as to their P buffer capacity and grouping together those which are similar for the purpose of making fertilizer recommendations. The reciprocal of buffer capacity is also an important factor in diffusive transport of phosphate from the soil to the plant (Nye, 1968). P sorption curves were adequate bases for making predictions about phosphate fertilizer requirements of soils as diverse as those from Alaska, Idaho, Ontario, Peru, Hawaii, and Bangladesh (Vander Zaag et al., 1979).

The replenishment of soil solution with P from the solid phase involves P desorption (Syer et al., 1970). Thus, as far as plant nutrition is concerned, P desorption is more important. The concentration of P in solution is usually greater when P is being added to the system than when it is being withdrawn for a given level of soil P (Fox and Searle, 1978), similarly slope is steeper for adsorption isotherms than desorption isotherms. This difference in slope is

termed hysteresis and is an important factor in determining the magnitude of the residual effect. The greater the hysteresis, the smaller the residual effect (Uehara and Gillman, 1981).

One possible mechanism by which P is held onto soil colloids is presented in Figure 2.3. Phosphate ion replaces (a) the aquo - and (b) hydroxy - group to become chemisorbed to the oxide surface. The sorption process is dependent on time, temperature, supporting electrolyte and the pH of the system (Fox and Searle, 1978; Fox, 1981). The soil mineralogy and organic matter content also affect P sorption (Barrow, 1974b). Cropping that accelerates organic matter decomposition and thus uncovers sorption sites may increase P requirements of soils (Moshi et al., 1974). As soils weather (become Si-depleted), the magnitude of P immobilized increases. Similarly for soils with similar mineralogy the P immobilized increases in relation to clay content or surface area (Fox and Searle, 1978).

The complete sorption curve is, however, a cumbersome way of representing results and requires much time and work. Bache and Williams (1971) found that isotherm slopes for different soils measured at 10^{-4} M phosphate correlated very closely with those at 10^{-5} M phosphate ($r=0.977$) and at 10^{-3} M phosphate ($r=0.946$). Thus, there is some latitude for selecting the concentration at which to measure the slope. They suggested that the isotherm slope at concentration of 10^{-4} M be used as reference index.

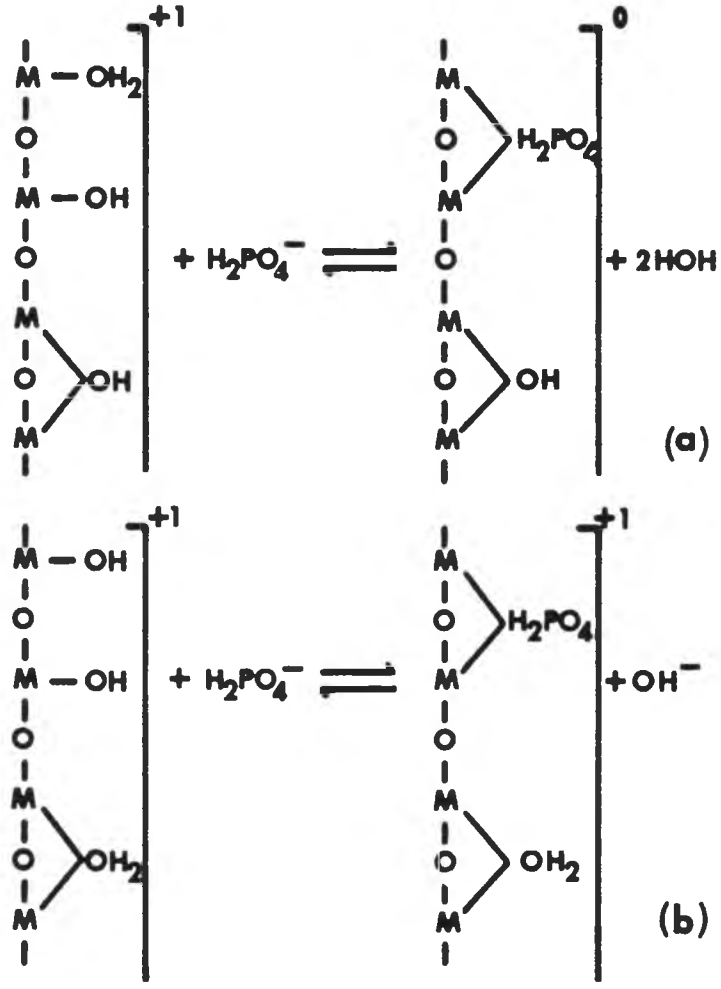


Figure 2.3 Displacement of (a) aquo and (b) hydroxy group from a metal oxide by phosphate.

2.3.4 Slow sorption of P

Slow sorption is a continuation of the fast sorption process. Hence no distinct point can be identified at which the fast sorption ends and the slow sorption begins.

Prolonged contact between phosphate and soil makes the phosphate less available to plants, more difficult to displace with other anions, and less ready to exchange with isotopically labelled phosphate (Talibudeen, 1958). This behavior can be explained by phosphate remaining on adsorption sites but becoming more tightly bound or otherwise occluded. This conversion is associated with: (i) formation of binuclear complexes between sorbed phosphate and -OH or $-H_2O$ groups (Muljadi et al., 1966; Mattingly, 1975; Parfitt et al., 1975), (ii) movement of phosphate into micro-pores (Vaidyanathan and Talibudeen, 1968), (iii) precipitation of some of the phosphate (Chen et al., 1973), or (iv) occlusion of chemisorbed phosphate in short range order minerals (Ryden et al., 1977). The influence of slow reaction on the residual effect of phosphate may determine the usability and management of soils with large phosphate requirements (Munns and Fox, 1976).

Evaluating residual effects

The residual value of phosphorus in soils is dependent upon the nature of the compounds formed when phosphate fertilizers react with soil components. The residual value is defined as the comparison between the current effect of a previously applied fertilizer and same fertilizer freshly applied (Barrow and Campbell, 1972). In soils that require a heavy initial application of phosphorus, the quantity of

phosphorus removed by the crop and lost through leaching is negligiblysmall compared to the amount that is added. The remaining adsorbed phosphorus continues to supply the soil solution with phosphorus, but at a lower concentration. Thus available P may be increased in many soils generally low in available P and possessing high buffer capacity by heavy initial P applications to an available P level which would maintain maximum yields over a period of years (Shelton and Coleman, 1968). Many studies have reported increase in available P due to residual effects (Barrow, 1974; Munns and Fox, 1976, Yost et. al., 1981).

Mattingly and Widdowson (1956) have observed that after 15 weeks growth, barley was twice as effective at using a previously applied superphosphate as it was at 6 weeks. These effects may be most marked on soils with a high capacity to adsorb phosphate and may be caused by increased root density. Because of these effects the current availability of previous application of phosphate does not necessarily have a unique value through a season. Fertilizer P applied to calcareous soils has been found to be available to plants for a long period of time. Soil fertility investigations have indicated that fertilization with P not only increases the yield of the crop fertilized but also has a beneficial effect on yields of succeeding crops (Lewis et. al., 1950; Ridley and Tayakepisuthe, 1974). In alkaline and calcareous soils residual phosphate from fertilizer P mainly accumulate as octocalcium phosphate (Olsen et. al., 1983). Large applications of P to a high P-fixing soil were rapidly converted into Al- and Fe-P (Shelton and Coleman, 1968). The degree of

saturation of the fixation capacity necessary for maintaining high available P levels for long periods of time seems to depend upon the relative proportions of fixed P in the Al and Fe forms and the rate of conversion of Al-P to reductant soluble Fe-P.

Fox and Searle (1978) have showed that the phosphorus adsorption isotherms shift to the right as the phosphorus application rate increases. The shift in the isotherms to the right can be measured many years after the fertilizer has been applied. However, with time after the application of phosphorus, the isotherms progressively return to the left, and the rate of return depends on the quantity of phosphorus desorbed through plant uptake and leaching losses as well as on hysteresis (Uehera and Gillman, 1981). High hysteresis is associated with low residual efficiency of the remaining adsorbed phosphorus. Although it is true that an ordinate initial phosphorus input will discourage development, it will be the magnitude of the hystersis factor and residual effect that will eventually determine the economic success of agricultural schemes on high phosphorus fixing soils.

Economists have generally used the point of maximum profit to be that point on a response curve where the cost of an increment of fertilizer equals the consequent increase in returns (Helyar and Godden, 1977). Thus the fertilizer is assumed to be an input yielding returns for only one production period. However, most fertilizers have residual effects. Bowden and Bennett (1975) used a residual value function to describe the decrease in residual value of phosphate fertilizer with time. Furthermore, when calculating the cumulative

residual value of phosphate fertilizer history, they assumed that theresidual values of fertilizers were additive. Cox et al. (1981) also assumed that the residual values of fertilizers were additive and obtained a good agreement between observed and predicted values. The long term rate of P release by natural accretion and/or weathering is a soil or site characteristic and is not easily affected by management. However, the maintenance requirement is. Thus, the development of management techniques to minimize P losses by leaching, runoff, unequal redistribution, erosian and product removal, are the appropriate subjects for research once a system is operating at a desired equilibrium yield level (Helyar and Godden, 1977). The systems approach to evaluate P fertilizer response will be discussed in the next section.

2.3.5 Phosphorus modeling

Empirical approach

Attempts to relate the concentration of a nutrient in soils to its effect on plant growth are largely empirical because they are linked by a very complicated series of individual mechanisms. Therefore, in order to make predictions one has to rely on statistical methods to relate concentration or treatment level to its effect. Bowden and Bennett (1975) use Mitscherlich equation for yield response in their 'Decide' method:

$$Y=A[1-B \exp(-CX)] \qquad (2.13)$$

where Y= yield per unit area, A= maximum yield per unit area, B= relative response to applied P, X= rate of nutrient applied

standardized to Mg P/ha, and C= curvature coefficient which has reciprocal dimensions to X. The optimal rate of P to apply is determined using marginal returns theory:

$$X_{opt} = \ln[ABCP_y/P_x(1+R-V)]/C \qquad (2.14)$$

where P_y= price of unit of product, P_x= the price of a unit of fertilizer, R= rate of return, and V= future value of the fertilizer for the years following the one in which the yield is derived. V has values ranging from 0-1. For any give farm situation all of the above seven parameters must be solved.

This model uses the research workers' and farmers' experience, respectively, to predict the shape of response curve (C) and to scale the response curve in terms of physical yield (A). The magnitude of B depends on the level and time of past phosphate dressings, the reserves of native phosphorus, leaching, and erosional losses, and removal of farm products. The 'Decide' approach provided fertilizer recommendations on an individual farmer basis and compels people giving fertilizer advice to face up to the problem of putting an economic value on product. Since B is related to the residual fertilizer level and the native nutrient status, Helyar and Godden (1977) expressed Equation (2.13) as:

$$Y = A[1-\exp(-C(X+I+N))] \qquad (2.15)$$

where I= depletable nutrient status and N= non-depletable nutrient status. More specifically, the constant N is the capacity of the soil to supply some nutrients to the production system in the long term without fertilizer application. The variable I is the residual value

of the depletable fraction of the native soil nutrient status plus fertilizer residuals. I+N represents the amount of "plant available" P that is contained in the soil (M):

$$Y = A[1-\exp(-C(X+M))] \qquad (2.16)$$

Mobiela et al. (1981) found a linear relationship between predicted value for plant available P (M) and soil test P (T). Thus:

$$Y = A[1-\exp(-C(X+N+bT))] \qquad (2.17)$$

where b= slope of M against T plot and N= intercept of the plot = non-depletable nutrient status. It should be noted that whereas Equation (2.16) is 'site-specific' because of the presence of M, Equation (2.17) can be extrapolated to different sites with different M values if the soil test values of these sites are known. This, however, requires the assumption that all sites have similar A and C values.

Cate and Nelson (1971) proposed that the relationship between yield and major nutrients is a linear response and a plateau (LRP) function. The LRP approach reintroduce into the response analysis the agronomic principle of 'the law of the minimum'. The fundamental implication of this 'law' is the absence of nutrient substitution. The dynamic relative yield-nonsubstitution model (Lanzer and Paris, 1981) has indicated that fertility carry over is indeed significant for P. Studies of Perrin (1976) and Lanzer and Paris (1981) have shown that functional forms which have additional advantage of explicitly incorporating agronomic principles have similar or better fits than the traditional polynomial form of the response function which was preferred because of its "good" fit.

Mechanistic approach

The models that have been reviewed in the previous section represent an over-simplification of a complex pattern of nutrient supply and demand which varies throughout the growth period. The mechanistic P models consider soil P status, plant status, growth rate and yield instead of simply soil P status and yield. The mechanistic models do have some empirically determined values or components, e.g., relative growth rate at emergence for lettuce when simulating P response (Scaife and Smith, 1973). The diffusive uptake rate of P in their model is based on the analogy with Ohm's Law (mechanistic). The proportionality constant in the model corresponding to the reciprocal of resistance in Ohm's Law, will in practice depend upon shoot/effective root ratio, and the soil water content.

Nye and Tinker (1969) assumed that uptake of a nutrient is proportional to its concentration at the root surface. Variablity in plant requirement is accounted for by a 'demand coefficient' which is inversely related to plant nutrient status, and in soil to the concentration at the root surface. Nye and coworkers (1975) reported that growth rate is basically linked to the concentration of phosphate at the root surface by two types of relationship: (i) the relationship between current nutrient status of the plant's photosynthetic tissues as measured by the phosphate concentration in the dry shoot, and (ii) the relationship between the mean P uptake per unit root surface and the phosphate concentration in solution at the root surface, viz., the mean root absorbing power. Scaife and Smith (1973) modeled the way in which plants achieve remarkable constancy of composition despite the

very wide variation in external level of supply. According to their hypothesis since the fall in concentration at root surface is caused by the plant, and could result either from a suboptimal mean soil solution concentration or from impeded transport through the soil, it is reasonable to suppose that the actual concentration at the root surface is only indirectly due to the supply position, and would be more readily predicted from nutrient stress.

The main drawback of some of these simulation models is the large number of input parameters required to run the model. The Cushman model, for instance, uses 11 soil and plant parameters to calculate flow of a nutrient in the soil toward the root by diffusion and mass-flow, and uptake of nutrient from soil solution by a growing root system. Some of the parameters used in the model (Barber and Cushman, 1981) are: initial concentration for diffusion through the bulk soil, root length when calculation began, rate of root growth, mean root radius, mean half distance between root axes and others.

Lin et al. (1983) developed a mathematical model to simulate phosphate reactions with minerals in acidic soils. Many empirical equilibrium models exist, such as, linear, Freundlich, Langmuir, two-surface Langmuir, and competitive Langmuir isotherms. Equilibrium models are viewed as limited, because they cannot be used as a continuity equation to describe the movement of phosphates in soils. The simulation model correctly predicted that high pH values, low concentrations of P in the reacting solution, and small specific area will reduce retention of phosphate. The model also effectively simulated the trend of phosphate reactions with soil minerals.

Jones et al. (1984a) developed a simple soil and plant P model designed for use in the Erosion-Productivity Impact Calculator (EPIC) crop management model (Williams et al., 1983). The P model runs on a daily time step, simulates P uptake and the transformations in up to ten soil layers of variable thickness, and is sensitive to soil chemical and physical properties, crop P requirements, tillage practice, fertilizer rate, soil temperature and soil water content. Although this model oversimplifies soil P transformations, it has the following advantages: model parameter can be obtained from limited soil data, the model is sensitive to soil properties, has a high computational efficiency, and has a high overall accuracy.

The P model accounts for the initial rapid decrease 1976; Rajan and Fox, 1972; Barrow and Shaw, 1975). This component of the model is based on empirical models of Barrow and Carter (1978) and Cox et al. (1981). Numerous studies (as discussed in previous sections) have described the rate and/or extent of fertilizer P adsorption on soil material by adding varying amounts of P to soil suspensions then analyzing the amount of P remaining in solution over time. The labile P after fertilization and P availability index in the P model of Jone et al. (1984a) is determined by the rapid P adsorption method of Sharpley et al. (1984a).

Mycorrhizal response

The effects of environmental variables on vesicular-arbuscular mycorrhizal infection in a developing root system is difficult to define precisely. This is not surprising since the growth rate of the root system itself is greatly influenced by such environmental variables. The effect of soil P may be an exception to the above. The phosphorus concentration in the host and not necessarily the P level in the soil, appear to control closely the degree of mycorrhizal infection (Sander, 1975; Graham et al., 1981). High soil P may reduce infection, which is important in supplying micronutrients (Lambert et al., 1979). The possible explanation for this is phosphorus-induced zinc deficiency. Mycorrhizal dependency, defined as the dry weight (mycorrhizal plants)/dry weight (nonmycorrhizal plants) x 100 was significantly correlated with the reciprocal of soil P (Ojala et al., 1983) Their results showed that the extraction methods whose results depend most on soil solution P concentration gave best results. For example, saturation extract P (R^2= 0.67***), anion exchange resin P (R^2= 0.57***), and 1:10 soil to water extract P (R^2= 0.51***).

Buwalda et al. (1982) used empirical model of infection of roots by vesicular-albuscular mycorrhizas to study the effect of P on the spread of infection in root systems. However, results from later experiments showed that their earlier model incorrectly assumed that the existing amount of infection has an effect upon the rate of spread (Buwalda et al.,1984). Their present mechanistic model simulates the infection of

roots by micorrhizas accurately. However, it is not known whether the model will correctly simulate mycorrhizal infection for a branched root system. Also the input data for the model may be difficult to obtain in field situation.

Current plant growth models because of the above reasons do not simulate the effect due to mycorrhiza. Therefore, the models overlook the following advantages gained from mycorrhizal association (Heylar and Godden, 1977): lower nutrient capital requirements, lower expected erosion losses (smaller nutrient pool size), and lower leaching and runoff losses (lower soil solution concetrations for a given yield level).

2.4 Crop Growth Simulation Modeling for Agrotechnology Transfer

Agricultural productivity in less developed countries should be expanded by both cultivated land acreage and yield increase per hectare. Most less developed countries lack the trained manpower, the capital, and the institutional capacity to conduct the research required to fill their needs in the short time available. Therefore, the transfer of technology is important in agricultural development of these countries. Agrotechnology transfer is the taking of an agricultural innovation from one location to another where the innovation is likely to succeed (Uehara, 1984). The basic reasons for failures in agrotechnology transfers are: (i) mismatches between the environmental requirements of technology and the environmental characteristics of the land; and (ii) mismatch between the requirements of a technology and the resource characteristics of the farmer. To succeed in a new location, the innovation must be technically sound, economically feasible, socially desirable, and environmentally safe (Uehara, 1984). Sometimes farmers do not completely invest in new high yielding varieties but retain some of the older, yet reliable varieties that they have grown for years. Therefore the considerations of the above factors are essential for accurate predictions.

In essence the success of the technology transfer rests with the individual farmer. Traditional methods of agricultural research are unlikely to solve this problem since each farmer and his farm is unique, while results from traditional methods are site-, season-, cultivar-, and management-specific (Nix, 1983). Currently used means of agrotechnology transfer are by simple observation, trial and error,

transfer by analogy, statistical methods and systems analysis and simulation (Nix, 1980). The trial and error method is impractical because of the high failure rate.

2.4.1 Transfer by analogy

In the transfer by analogy method the physical input-output data necessary for evaluation is extrapolated from experimental sites or from farm experience to analogous areas defined by vegetation, soil, and climatic classification (Nix, 1968). The Benchmark Soils Project (Silva, 1984) was based on the concept of transfer by analogy. The central hypothesis of the project was that agrotechnology can be transferred from one location to another within a given soil family.

When crop research is based on transfer of information by analogy, a network of experimental sites is a necessity although it is expensive. The analogue method is based upon existing land use and may or may not provide a basis for prediction of productivity at different levels of management or other forms of land use (Nix, 1968).

2.4.2 Statistical methods

In environments where one or two factors dominate performance, simple correlation would have useful predictive value. Similarly, by transforming raw climatic and/or soil data into more relevant indices and phenological or thermal time rather into calendar time, the predictive equations would have greater applicability. In statistical

differentiation of treatment effects where site by season interaction may account for the main variance, understanding and development of several functional relationships of growth would not be conducive (Nix, 1980).

Site specific equation

Traditional statistical methods are site specific. Site factor methods seek to relate key parameter to agricultural productivity within a given environment. The yield at a site within the region studied is described by a multiple regression equation. For example, the site specific equation for the Benchmark Soils Project experiments is of the form:

$$Y_p = b_0 + b_1N + b_2N^2 + b_3P + b_4P^2 + b_5PN \qquad (2.18)$$

where, Y_p= predicted maize yield

b_0= intercept (estimated yield when P and N are both zero in coded values)

$b_1, b_2 .. b_n$= partial regression coefficients

N= coded value of nitrogen differential

P= coded value of phosphorus differential

The above equation is essentially site specific. It is a representation of dynamic systems and is valid only for the range of site properties and for the crop studied, e.g., maize.

Non-site specific equation

If site variables are added to the above equation a non-site specific equation is obtained:

$$Y_p = b_0 + b_1N + b_2N^2 + b_3P + b_4P^2 + b_5PN + b_6NN_{ext} + b_7PP_{ext} + b_8PN_{ext} + b_9N_{ext}T \qquad (2.19)$$

where, N_{ext}= KCl extractable soil nitrogen,

P_{ext}= modified Truog extracted soil phosphorus,

and, T= minimum temperature (4 weeks before tasseling).

The yield, Y_p for one of the k experimental sites is predicted using a transfer function estimated from other (k-1) sites (Silva, 1984). The P statistic (Wood and Cady, 1981) is used to test the transfer hypothesis.

In environments where one or two factors dominate crop performance non-site specific equations will be useful in predicting agrotechnology transfer.

2.4.3 Simulation techniques

Simulation models predict the performance of any crop at any location for a given set of soil, crop, weather and management data independent of cultivar-, season-, management-, and site-specifity. A systems approach formalizes what is already known about the crop and the crop production systems. Prescribing appropriate technologies at the level of the farmer and his farm is an ultimate and attainable objective of agricultural research (Nix, 1980). This object will be fulfilled only if there is a shift in emphasis away from reductionist and analytical research to holistic and systems-based research. A systems-based research strategy centers on balanced development of two interactive components: crop models and data base.

A comprehensive simulation model will not only predict crop growth and yield but also include harvesting, processing, marketing and consumption components. Therefore technical, economic, and social

aspects which are vital for success of agrotechnology transfer are considered in simulation modeling. The International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) Project (USAID-funded) at the University of Hawaii, proposes to establish a prototype network comprised of existing national and international agricultural centers in the tropics and subtropics. The collaborators in the project would demonstrate how agroproduction technology can be transferred among research institutions and farmers' field in the less developed countries . To achieve the above goals the IBSNAT project will use system-based research strategy, i.e., utilize crop models and data base resources. The IBSNAT project would be initially developing and utilizing bio-physical simulation models to facilitate agrotechnology transfer. In its later phase the project would also consider economic and social aspects.

The objective of simulation technique is not to replace field experimentation. Simulation modeling could improve crop research both in terms of research efficiency and cost effectiveness. Presently, the development of appropriate crop models is limited by inadequate soil, crop, weather, and management data from widely contrasting environments. Nix (1980) stated two ways of generating minimum data set for crop modeling: (i) the passive approach which is least likely to disturb the traditional agricultural research strategies and (ii) the active approach involving radical revision of current strategies and aims at generating specified minimum data sets in the shortest possible time with the most economical use of land and labor resources. The passive approach aims at upgrading experiments through

additional measurements and observations to minimum data sets. The active approach on the other hand involves experiments designed with the widest possible range of genotype-environment-management interactions at few carefully chosen locations. These experiments have been described as 'omnibus experiments' (Nix, 1980). In an omnibus experiment treatments are not replicated or randomized, however, within-treatment sampling is randomized and replicated. This approach is ideal for generating very intensive data for model development and calibration.

Some IBSNAT collaborators would be using the passive approach, however, most of them would use an intermediate approach. This approach would involve setting up of new experiments (genotype, management, environment) for minimum data sets as well as for non-modeling purposes.

Networking knowledge

Systems based research as discussed earlier is multi-disciplinary team work. The systems approach involves networking, collaboration and cooperation. Development of appropriate simulation models as well as the testing of models developed in temperate region are limited by inadequate data from widely differing environments of the tropics. One of the objectives of the IBSNAT project: the setting up of networks of experiment throughout the tropics will remedy this problem (Benchmark Sites News, 1984). Networking would make research more cost-effective, reduce duplication, and disseminate research information. Networking as envisaged by the IBSNAT project would provide expertise and sharing of data by collaborators and cooperators.

Thus, appropriate crop models would be developed using systems approach. Existing crop models would be tested, perhaps modified, and validated. In this network there will be continuous transfer of knowledge as the data are generated, and crop models are developed, tested, and validated. Therefore, the benefits of networking are utilized even before the crop models become available to the users.

Database management system

Development, testing and validation of crop simulation models could be significantly improved if increased and efficiently organized data were utilized. A database management system is best designed if data are readily accessible for multiple use. Within the modeling field, the data required in developing a model is different from that required as input for executing crop simulation models. Database designed for one specific purpose or experiment would be the easiest for retrieval and storage of data for the specific case. However, it will be rigid and will not facilitate data exchange.

The database system should be very flexible: accept complex and varied data sets, be extendable to new initially unforseen types of data, and therefore be easily manipulated. Data manipulation generally involves updating the database and retrieving the required data from the database. The ultimate objective of the database system is to facilitate efficient sharing of data. Also inconsistency and redundancy of data would be avoided besides maintaining integrity and encouraging reliable data collection.

III. TESTING OF CROP ENVIRONMENT RESOURCE SYNTHESIS MAIZE MODEL

3.1 Introduction

Interdisciplinary research efforts often culminate in a better understanding of the entire system, as well as increased knowledge within specific disciplines, such as soil, crop, and environmental sciences. A synthesis or crop modeling approach is necessary to study maize (Zea mays L.) growth and yield as a system. The Crop Environment Resource Synthesis (CERES) - maize model has been developed by a multidisciplinary team of soil scientists, agronomists, and crop physiologists at the Grassland, Soil, and Water Research Laboratory in Temple, Texas.

The model simulates growth, phenological development, soil water balance, and soil and plant nitrogen budget. Preliminary testing of the model using data from experiments on Hydric Dystrandepts (Jones, 1982) and Tropeptic Eutrustox (Chinene, 1983) have brought to attention the lack of field level information about soil initial conditions and intermediate stages of crop growth. To fully assess the CERES model for tropical conditions reliable input data are essential.

In the present study the effect of N fertilizer on two different varieties were determined. This study was also undertaken to closely monitor the soil water, soil nitrogen, and plant nitrogen levels with crop growth. The overall objective was to calibrate the CERES maize model based on the present experiment as well as other experiments from

the Waipio site, Hawaii. The testing process involved : (i) comparison of actual and predicted variables and making appropriate changes in the model such that it simulated the experiment accurately (calibration), and (ii) checking the logical and mathematical correctness so the model did not predict negative yields, concentrations, etc. (verification). In the present study the model was also tested on Hydric Dystrandept sites in Hawaii. The intent of this study was to calibrate the model with two data sets obtained under very different environmental conditions.

3.2 Materials and Methods

3.2.1 Field description and assignment of treatments

A field experiment was conducted in November, 1983 to April 1984 to study the effect of variety and N fertilization on N uptake, leaf area development, maize growth and yield on the Wahiawa silty clay (clayey, kaolinitic, isohyperthermic, Tropeptic Eutrustox).

The experimental site is located in Waipio, Oahu, Hawaii, approximately 21°25' N latitude and 158° W longitude. Soil parent material is weathered olivine basalt and the physiography is nearly level upland with two percent slope. The soils are well drained with moderate to moderately rapid permeability and slow runoff. The elevation is 150 m above sea level.

A randomized complete block design with three N treatments, two varieties, and three replications was used. The plots were six by eight meters, twice the size of the conventional Benchmark Soils Project plots (Benchmark Soils Project Staff, 1982). The plot size was doubled so that there would be enough samples for the final harvest after the destructive sampling during the growing season. The three N levels selected for treatment were 0, 50, and 200 kg/ha. The maize hybrids used were 'X304C' (Pioneer Hi-Bred International) and 'H610' (=Ant 2D x B14A). A blanket application of nutrients consisting of 12.5 kg P/ha as triple superphosphate, 100 kg K/ha as KCl, 100 kg Mg/ha as $MgSO_4$, 15 kg Zn/ha as $ZnSO_4$, and two kg B/ha as Borax was applied to all plots to prevent yield reductions from inadequate levels of these nutrients.

Land preparation and planting

The land was cleared of weeds and straw. The field was then rototilled to a depth of 15 cm using a hand-operated tiller. The first application of fertilizer was broadcasted and thoroughly incorporated into the top 15 cm of the soil with a hand operated rototiller. The tillage, fertilizer and amendment application, dates of key events and chemical sources are presented in Table 3.1.

Maize seeds of hybrid H610 and X304C were planted on November 30, 1983. The seeds were planted at 7 cm depth with 75 cm row spacing and rate of 4.35 seeds/m. Planting, thinning, and harvest operations as described by Benchmark Soils Project Staff (1982) were followed.

Irrigation system

The crop was irrigated with a drip irrigation system. Each row of corn had a separate lateral line for uniform distribution and adequate application of water. Amounts of irrigation applied to each replicate were recorded separately. Irrigation was based on tensionmeter readings were less than 0.2 MPa.

3.2.2 Soil sampling and analysis

Soil samples to a depth of 110 cm were taken prior to planting, near the tassel initiation stage, at tasseling and finally post-harvest. The samples were taken at six depth increments: 0-10, 10-30, 30-50, 50-70, 70-90, and 90-110 cm.

Table 3.1 Tillage and amendments applied.

Operation	Date	Implement	Source
Tillage		11/10/83	Rake -
	11/16-17/83	Roto-till	-
	11/28/83	Rake	-
Fertilizer	11/29/83	Roto-till	Urea, blanket treatment broadcast.
	01/06/84	-	Urea-banded
	01/31/84	-	Urea-banded
Insecticides	As necessary		Sevin, diazinon
Fungicides	-do-		Diathine Z7A
Herbicides	-do-		Lasso-attrex

For preplant, tassel initiation, and post harvest soil samplings four auger samples were taken from each plot and composited into two sets of samples. Soil samples during the tassel initiation stage were taken from within corn rows (between two plants which had been harvested for growth and tissue analyses). Eight auger samples were taken per plot during soil sampling at the tasseling stage. These samples were taken within and between the corn rows. Four composite samples were then made: 2 each for within and between corn rows.

The field-moist soil samples were analyzed for NH_4^+ and NO_3^- by distillation with magnesium oxide and Devarda's alloy steam distillation method (Keeney and Nelson, 1982). Modified Truog P and anion exchange resin P determinations were done on air dried samples. Soil water content for each of the samples was also measured. For the air dried preplant soil samples organic carbon determination (Walkley and Black, 1934), pH (1:1), and total N by Kjeldahl digestion (Bremner and Mulvaney, 1982) were also done.

3.2.3 Plant observations and sampling

During crop growth, dates of phenological events were recorded for each treatment. The events considered were germination, emergence, tassel initiation, tasseling, silking, and physiological maturity. The event was considered to have occurred when at least 50% of plants or samples had reached the given phenological stage.

Determination of tassel initiation required destructive sampling. Prior to tassel initiation the growing point is rounded or hemispherical (Figure 3.1A), and at tassel initial it elongates into a

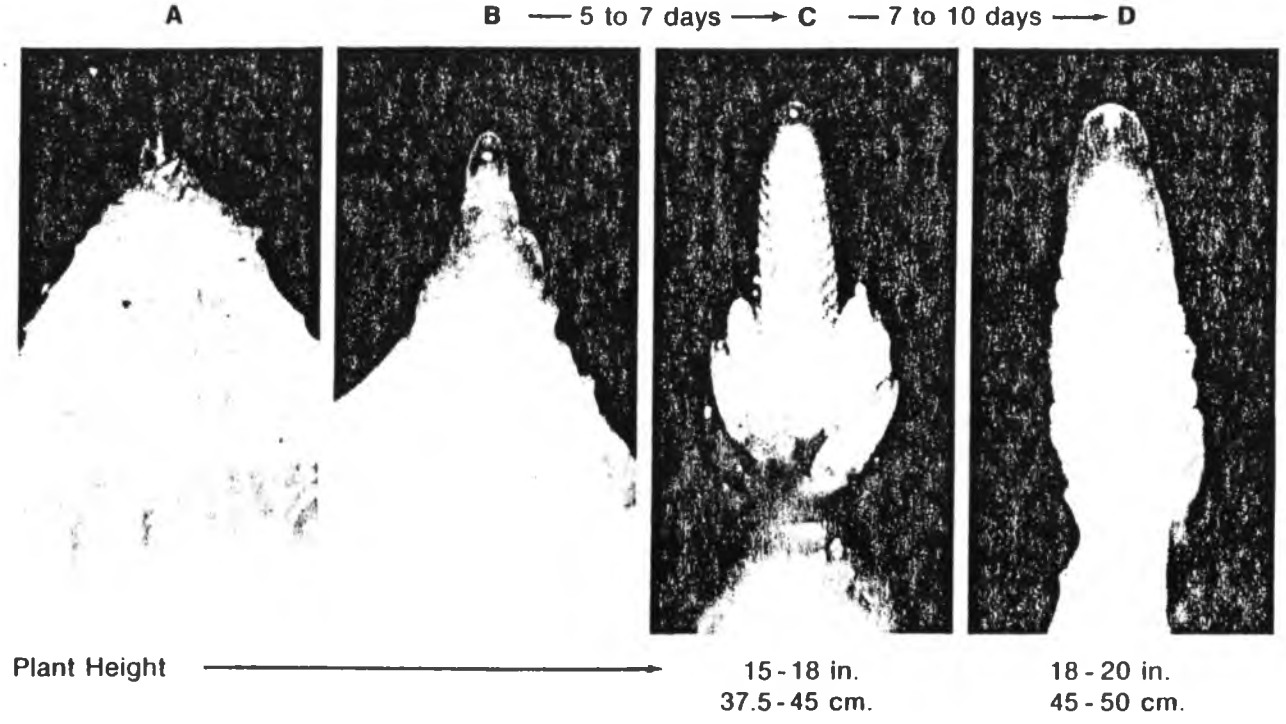


Figure 3.1 Developmental stages prior to and after tassel initiation. Source: Aldrich et al. (1978).

round-tipped cylinder (Figure 3.1B). The embryonic tassel is recognizable a few days later (Figure 3.1C). Physiological maturity determination also requires destructive sampling. Corn is physiologically mature when the 'black layer' or 'brown layer' is formed near the tip of mature kernels. It is easily observed by either cutting the mature kernel lengthwise in half or by breaking the tip of the kernel. An individual ear is mature when at least 75% of the kernels in the central part of the ear have black layers.

Eight plants were sampled from each plot five times during the course of growth. These samples were taken at tassel initiation, tasseling, and at three times during the course of grain-fill period. The plants surrounding the sampling sites were tagged so that they would not be sampled. It was assumed these plants would not be representative of the plot/treatment.

For each of the plants leaf area, dry weights of green leaves, yellow leaves, dead leaves, sheaths, stalks and ears were determined. The leaf area was determined using a Li-Cor Model 3100 Area Meter and from the product of leaf length and 0.75 of maximum leaf width (Turner and Begg, 1973). The plant samples were combined into two batches with four samples per batch. Each of the combined sample was ground and submitted for tissue analyses.

The above ground samples were analyzed for N, P, K, Ca, Mg, S, Fe, Mn, Al, Cu, and Zn. Total N was determined by the Kjeldahl method (Bremner and Mulvaney, 1982) while other elements were routinely measured with a multichannel x-ray fluorescence quantometer.

All the harvested ears were weighed. Ten ears per plot were chosen at random to determine shelled grain percentage, moisture content, and kernel weights (Benchmark Soils Project Staff, 1982). These data were then utilized to determine final grain yield. Number of kernels per ear was also measured. Elemental analyses on grain samples were then done.

3.2.4 Crop Environment Resource Synthesis maize model

The Crop-Environment Resource Synthesis (CERES) models have been developed by the Agricultural Research Service Crop Systems Evaluation Unit at Temple, Texas. The CERES models are based on the same principles and have similar structure (Jones et al., 1983a). It is designed to incorporate a minimum set of data on management, climate, soil, and cultivar. The model simulates effects of weather, soil, water, nitrogen dynamics, and genotype on crop growth, phenological stages, and final yield (Figure 3.2). The CERES maize model is based on the law of the minimum computed on a daily time step. Therefore, during the simulation, the limiting factors tend to have interactive effects. Input data required for the CERES maize model are given in Table 3.2. The main components of the maize model, viz, phenological development, crop growth, water balance, and nitrogen dynamics presented in Figure 3.2 are discussed in the following sections. A complete computer program for the model is presented in Appendix 3.1.

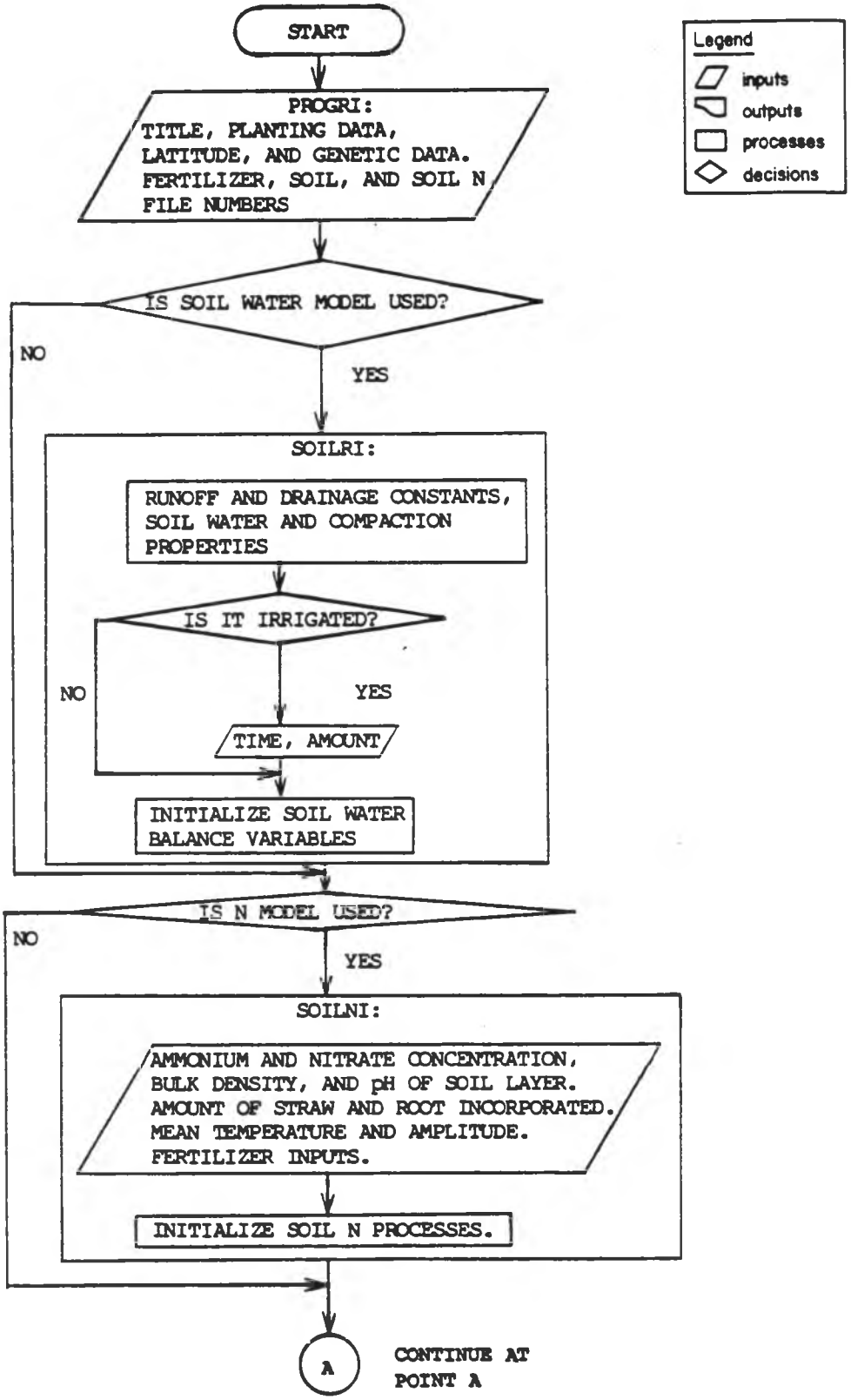


Figure 3.2 Flow diagram of the CERES maize model.

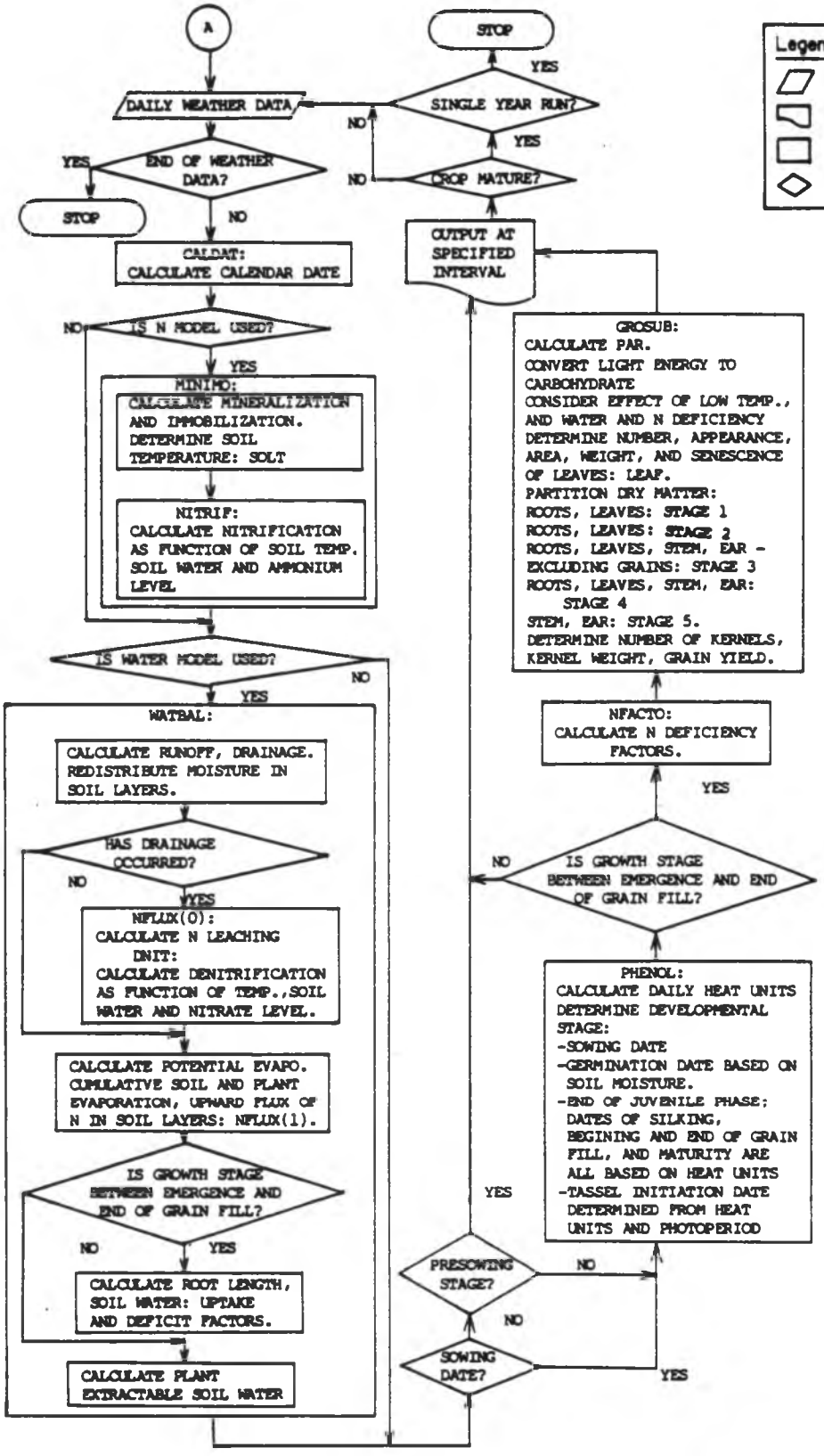


Figure 3.2 (continued) Flow diagram of the CERES maize model.

Table 3.2 Input data needed for maize growth and development using CERES maize N version.

LOCATION DATA
Latitude (deg)
CLIMATIC DATA
Daily solar radiation (cal cm^{-2} day^{-1})
Daily maximum temperature (^{o}C)
Daily minimum temperature (^{o}C)
Daily precipitation (mm)
MANAGEMENT DATA
Cultivar name
Planting date
Planting depth (cm)
Plant population (plants m^{-2})
Irrigation dates and amounts (mm)
Fertilizer N: dates, amounts (kg ha^{-1}), sources, and depth of application (cm).
GENETIC DATA
Thermal time from emergence to end of juvenile phase, P1, (^{o}C day)
Photoperiod sensitivity of tassel initiation for photoperiods >12.5 hours, P2 (days delay/hour increase in photoperiod)
Thermal time from anthesis to physiological maturity, P5, (^{o}C day)
Potential kernel number per ear, G2
Potential grain fill rate, G3, (mg $kernel^{-1}$ day^{-1})
Phylochron interval: thermal time between leaf tip appearance, PHINT, (^{o}C day)

Table 3.2 (continued) Input data needed for maize growth and development using CERES maize N version.

SOIL DATA	
Number of layers	
Depth of layers (cm)	
Soil albedo	
Soil water by layer:	initial soil water content (cm^3 cm^{-3})
	: saturated soil water content (cm^3 cm^{-3})
	: drained upper limit of soil water (cm^3 cm^{-3})
	: lower limit of extractable soil water (cm^3 cm^{-3})
	: root preference factor (Unit less 0-1)
Runoff curve number	
Upper limit of stage 1 soil evaporation (mm)	
Profile drainage rate constant (1 day^{-1})	
Soil Nitrogen by layer:	initial NO_3^- and NH_4^+ content ($mg\ kg^{-1}$)
	: Organic carbon (%)
	: bulk density ($g\ cm^{-3}$)
	: pH
C:N in roots and in straw	
Amount of straw incorporated (kg/ha) and depth of incorporation (cm)	
Temperature amplitude for the growing period (^oC)	
Mean temperature for the growing period (^oC)	
N mineralization factor, DMOD	

Table 3.2 (continued) Input data needed for maize growth and development using CERES maize N version.

OTHER INFORMATION
Title of the data set
Switch settings to initiate:
soil water balance (ISWSWB)
nitrogen model (ISWNIT)
multiple year simulation (MULTYR)
Specify output intervals for: growth (KOUTGR), water balance (KOUTWA), plant nitrogen (KOUTNU), soil nitrogen (KOUTMN), and detailed nitrogen mineralization and immobilization (MINCK).

A. Phenological development

Phenological development is affected by both genetic and environmental factors. In the CERES maize model phenological development is driven by accumulation of daily thermal time (lines 7750-7900)[1] and in some cultivars photoperiod between the end of the juvenile phase and tassel initiation, stage 2 (lines 8450-8580). In photoperiod-sensitive cultivars, photoperiods longer than 12.5 hours lengthen the period from the end of juvenile phase to tassel initiation.

In the maize model daily thermal time (DTT) is the difference between daily mean air temperature and the base temperature from tassel initiation stage to physiological maturity.. The base temperature is 10°C from sowing to emergence stages and 8°C from emergence to physiological maturity (lines 13100-14610). If the maximum temperature is below the base temperature, DTT is 0 (lines 7770-7780). If the minimum temperature is below the base temperature DTT is reduced (lines 7810-7860). In the CERES maize model, cumulative DTT for the period from emergence to end of the juvenile phase (stage 1) and linear grain fill (stage 5) are genotype-dependent.

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1 Reference to the line numbers in the program listing (Appendix 3.1).

Allocation of dry matter among plant organs during the course of crop growth is dependent on growth stages. Prior to tassel initiation all accumulating dry matter is partitioned between leaves and roots (lines 10370-10430). However, from tassel initiation to end of vegetative growth (stage 3) roots, leaves, stem and ear (exclusive of grain) grow simultaneously (lines 10440-10590). During the end of vegetative growth to the beginning of effective grain filling period (stage 4) stem and ear accumulate dry matter (lines 10600-10650). At this growth stage the crop phenology component of the CERES maize model also determines kernel number per plant and barrenness (lines 8690-8830). During linear grain fill period (stage 5) dry matter is partitioned between ear and stem (lines 10660-10900).

B. Crop growth

In the CERES maize model potential crop dry matter production is linearly related to photosynthetically active radiation (PAR) and exponentially to leaf area index (lines 10160-10240). The efficiency of energy conversion (F) decreases once the effective grain fill period has begun (lines 10190-10230). This is due to increased maintenance respiration of the crop (Jones et al., 1983 a). The actual rate of dry matter production is less than the expected rate because of non-optimal temperatures, water stress, and nitrogen deficiency (lines 10240-10260). The optimal temperature is 26°C.

Leaf growth (lines 10890-13080)

The rate of leaf area expansion is one of the components of plant growth most sensitive to environmental stresses. The leaf growth is more sensitive to temperature and drought stress than photosynthesis (lines 12580, 12750, 11240-11380). Leaf expansion is also influenced by specific leaf area to weight ratio, the maximum daily rate of extension growth of a leaf and the thermal time needed for leaf tip appearance (PHINT). In the CERES maize model, leaf senescence is hastened by drought stress, and competition for light (lines 11240-11380). Prior to silking the number of leaves that have already emerged influences leaf senescence (lines 12760-12940).

Root growth

The proportion of dry matter which is partitioned to roots decline as the plant develops (lines 10310-10600). In CERES maize model stresses such as competition for light and non-optimal temperatures tend to decrease the fraction of dry matter partitioned to the roots (lines 10260-10460). On the other hand, drought stress which reduces leaf expansion more than photosynthesis, tends to increase the fraction partitioned to the root systems. Root development in a particular soil layer is dependent on soil water content and N availability. The root preference (compaction) factor also influences root growth in that layer (lines 6680-6810). When there is a constraint or stress in a particular soil layer, compensatory root growth normally occurs elsewhere in the profile (lines 6930-6980).

Grain growth

In the CERES maize model, the number of grains per plant (GPP) is determined from biomass accumulation in growth stage 4 (SUMP) and genotype specific potential kernel number, G2 (lines 10600-10620 and 8730-8750). The grain growth rate, RGFILL, depends on a genotype specific grain fill rate, G3, and minimum temperature (lines 10680-10750). During grain filling, most of the carbohydrate is provided by concurrent photosynthesis and a small percentage can also be translocated from the stem (line 10790).

C. Soil water balance

The soil water balance routine can be by-passed in the model if soil water is non-limiting for all plant processes. The model evaluates soil water balance as:

$$SW = RAIN + AIRR - EP - ES - RUNOFF - DRAIN$$

where the quantity of soil water, SW, is the result of the input of precipitation (RAIN) and irrigation (AIRR), evaporation from plants (EP) and soil (ES), and runoff, and drainage from the profile (DRAIN).

Runoff is calculated (lines 5360-5460) by the USDA Soil Conservation Service curve number technique (SCS, 1972). Runoff curve numbers vary from 0 (no runoff) to 100 (all runoff). Runoff may occur if precipitation exceeds 0.5 mm (lines 5410-5440). Drainage and soil water redistribution are calculated in a loop which moves water down from the top soil layer to lower layers (5540-5720). Drainage takes place whenever the water content SW at any time, is between the field

saturated water content, SAT, and the drained upper limit, DUL (lines 5560-5580). The value of the soil specific conductance parameter, SWCON, is assumed to be constant for the whole soil profile because, in many soils, the most limiting layer to water flow dominates the drainage from all parts of the soil profile. The value of SWCON can vary between 0 (no drainage) and 1 (instantaneous drainage). Drainage by unsaturated flow from one soil layer to another occurs when soil water content is greater than the drained upper limit. Drainage also tends to promote denitrification and leaching of N (lines 5750-5760).

Potential evapotranspiration, ET, is computed using an equilibrium evaporation concept as modified by Priestly and Taylor (1972) (lines 5810-5840). Equilibrium evaporation is influenced by solar radiation, soil albedo, LAI, and mean daytime temperature (line 5840). The potential ET is calculated as the equilibrium evaporation times a constant, 1.1, to account for unsaturated air (line 5850). When maximum temperature exceeds 35°C, the constant is increased to account for advection; and for maximum temperature <5°C, the constant is reduced to account for stomatal closure due to cold temperature (lines 5860-5870).

The actual evapotranspiration (ET) is calculated with a model developed by Ritchie (1972) (lines 5900-6220). Modifications were made in the CERES model so when soil water content in the upper layer reaches a fixed low threshold value, soil evaporation (ES) is further reduced (lines 6230-6270). This prevents the surface soil from drying too much when roots are also removing water from near the surface. The

water balance routine also computes upward flux of water and nitrogen if a lower soil layer has more plant extractable soil water than the one above it (lines 6350-6520).

Root water absorption

The CERES maize model calculates root water absorption, RWU (cm^3 cm^{-1} day^{-1}), using a law of the limiting approach whereby the soil resistance or the root resistance dominates the flow of water into roots. The absorption rate process is a function of hydraulic conductivity, K(0) (cm day^{-1}), water potential at root surface, U_r (cm), bulk soil water potential U_s (cm), root radius, r, and radius of the cylinder of soil, c, through which water is moving (Ritchie, 1984):

$$RWU = [4\pi * K(0) * (U_r - U_s)]/\ln(c^2/r^2)$$

Using the assumptions: r=0.02 mm, difference between water potential at root surface and water potential at bulk soil = 21 cm water, $c=(\pi * RLV)^{-1/2}$ where RLV is root length density (cm/cm^3), and hydraulic conductivity is empirically calculated as $K(0) = 10^{-5}$ exp (SW-LL), the CERES model computes root water absorption, RWU (line 7050):

$$RWU = 2.67 * 10^{-3} \exp[62(SW - LL)]/6.68 - \ln(RLV)$$

Maximum flow rate, RWUMX, of 0.03 $cm^3/cm/$ day is used as the plant limited flow rate (line 3280, 7060). Finally the water balance routine computes the drought stress factor for sensitive processes, SWDF2, such

as leaf expansion and growth, and for less drought sensitive processes, SWDF1, e.g., photosynthesis (lines 7200-7260). The stress factors are a function of total root water uptake divided by actual plant evapotranspiration.

D. Nitrogen model

Soil nitrogen initialization (lines 14630-16850)

The nitrogen submodel can also be by-passed if nitrogen fertility is non-limiting for all plant processes. Firstly, the CERES N model initializes the parameters used by nitrogen related inputs (Table 3.2 and lines 15010-15230, 15240-15380).

The model assumes uniform incorporation of straw to a given depth (lines 15640-15780), whereas roots from the previous crop are distributed among soil layers as (lines 15480-15610):

$$WRN(I) = \exp(-3.0 * DEPTH/DEPMX)$$

where WRN(I) = a weighing factor for roots in layer I (unitless, 0-1)

DEPTH = mean depth of layer I (cm), and

DEPMX = depth of the soil profile (cm).

Organic matter occurs in two pools: fresh organic matter FOM and stable organic matter or "humus", HUM. The fresh organic matter in a layer FOM (I), is composed of the root and shoot residues of the previous crop, microbial biomass, and its rapidly decomposing products. The stable organic matter in a layer, HUM (I), is composed of all other organic matter in the soil and is computed as (lines 15810-15830):

$$HUM(I) = OC(I) * 1000 * BD(I) * DLAYR(I)/0.4$$

where OC(I) is organic carbon content (%),

BD(I) is bulk density (g cm^{-3}),

DLAYR(I) is depth of layer I (cm),

factor 1000 converts OC(I)* BD(I)* DLAYR(I) into kg organic C/ha, and factor 0.4 is the fraction of carbon in organic matter. The amount of N in the stable organic matter pool, NHUM(I) (kg/ha) is calculated by subtracting mineral N from total soil N (line 16010):

NHUM(I) = OC(I)/10 * DLAYR(I) * BD(I) * 1000 - [NO3(I) + SNH4(I)]

where factor 10 converts organic C (kg/ha) to total soil N (kg/ha), assuming C:N of 10, and SNO3(I) and SNH4(I) are soil nitrate and ammonium levels in kg N ha^{-1}, respectively.

Mineralization and immobilization of N (lines 16880-17880)

If fertilizer was applied on the current day [i.e. JDATE=JFDAY(J)] then fertilizer N is apportioned into nitrate and ammonium fractions (lines 17120-17330). The model assumes instantaneous transformation of fertilizer materials into the appropriate pools. The fraction of fresh organic N, FON (I), or fresh organic matter, FOM (I), mineralized in a given day, DECR (I), is given as follows (line 17610):

DECR(I) = RDECR * TFAC * MF * CNRF

RDECR is a rate constant which is a function of the ratio FOM(I)/FON(I). Depending on the ratio, the rate constants for decomposition of carbohydrate-like (RDCARB), cellulose-like (RDCELL), and lignin-like (RDLIGN) fractions of the residue is used (lines 17520-17550). The moisture factor MF, ranges from 0.0 when soil is at

half the lower limit (LL) to 1.0 at drained upper limit (DUL) (line 17440). TFAC is a soil temperature factor ranging from 0.0 to 1.0 (line 17490-17510). It affects nitrogen mineralization and immobilization, nitrification, and denitrification. The basic equations used to calculate soil temperature at the center of each layer is given in subroutine SOLT (lines 22390-22640).

$$ST_t=[ST_{T-1}+TP+DTDT + DTDZ * ZZ]/2.0$$

where ST_{t-1} = yesterday's soil temperature in the layer,

ST_t = current soil temperature in the layer,

DTDT = factor for soil temperature change as a function of time of year

DTDZ = factor for soil temperature change as a function of layer depth,

ZZ = layer depth, and

TP = temperature of the soil layer above the current layer.

The soil temperature variables are initialized in subroutine SOILNI (lines 16160-16340). The fraction of FON(I) mineralized depends on C:N ratio factor (CNRF). This factor is based on CNR(I), the ratio of carbon in FOM(I) (assuming 40% of FOM(I) is C) the N available for decay (assumed to be FON(I) plus the sum of NO_3-N and NH_4+-N (lines 17560-17600). The gross amount of N which is released (GRNOM) due to mineralization of FON(I) is (line 17620):

```
GRNOM=DECR(I) * FON(I)
```

The rate of mineralization of N from stable organic matter (RHMIN) is computed as (line 17630):

RHMIN = NHUM(I) * DMINR * TFAC * MF

where DMINR is a soil-dependent rate constant and NHUM(I) is the amount of N in the stable organic matter. For temperate soils the value for DMINR has been suggested as 0.000083 (Seligman and van Keulen, 1981), however, DMINR varies among soils. The CERES model allows an input DMOD, to correct for this variabililty. The model also assumes that 20% of the gross amount of N released due to mineralization of FON(I) is incorporated into NHUM(I) (line 17650):

NHUM(I)=NHUM(I) - RHMIN + 0.2 * GRNOM

The gross rate of N immobilization associated with the decomposition of the FOM(I) pool (RNAC) is assumed to be the minimum (AMIN1) of N available for immobilization (TOTN) and the demand for N of decaying FOM(I) (line 17660):

RNAC=AMIN1 [TOTN, DECR(I) *FOM(I) * (0.02-FON(I)/FOM(I))]

where 0.02 is the N requirement for microbial decay of a unit of FOM(I). The value of 0.02 is the product of the fraction of C in the FOM(I) (=0.4), the biological efficiency of C turnover by microbes (=0.4), and the N:C ratio of the microbes (=0.125).

The balance between RNAC and GRNOM determines whether net mineralization or immobilization occurs. The net N released from all organic sources (NNOM) is (line 17690):

NNOM(I) = 0.8 * GRNOM + RHMIN - RNAC

where the factor 0.8 represents the fraction of GRNOM which is not incorporated in NHUM(I). N mineralized from, or immobilized by, the decomposition of organic matter either adds to or draws from the SNH_4 pool. If immobilization is large and the ammonium pool cannot supply all that is required, withdrawal from the nitrate pool occurs (lines 17730-17773).

Nitrification (lines 23020-23420)

Nitrification is computed immediately after mineralization and immobilization calculations. The nitrification subroutine, NITRIF, also calculates the rate of oxidation of ammonium to nitrate on a daily basis.

Nitrification capacity is limited by supply of ammonium SANC (line 23160), soil water factor WFD (lines 23170 - 23210) and a temperature factor TF (lines 23220-23230). An environmental limit on nitrification capacity ELNC (line 23240) represents a minimum of the three factors calculated above.

The nitrification capacity index CNI is updated according to the environmental limit as (lines 23250-23280):

CNI(L) = CNI(L) * exp (2.302 * ELNC)

CNI is constrained between 0.01 and 1.10. The lower value ensures that some capacity is maintained so that nitrification can resume when conditions become more favorable. The actual nitrification rate RNTRF(L) is calculated using a Michaelis-Menten Kinetic equation as (lines 23290-23300):

RNTRF(L)=A * 40.0 * SNH4(L)/[SNH4(L) * 90.0]

The A value used in the calculation is the minimum of the water factor, temperature factor and the nitrification capacity index. The amount of N nitrified is subtracted from the ammonium pool and added to the nitrate pool (lines 23310-23320).

The reduction of nitrification capacity SARNC due to the supply of ammonium is calculated using the same function as used for SANC. The more favorable of yesterday's and today's water XW and temperature XT factors is selected (lines 23340-23350). The most limiting of these is used to modify CNI (line 23360):

```
CNI = CNI * AMIN1 (XW, XT, SARNC)
```

Nitrogen Uptake

During the course of crop growth NUPTAK subroutine (lines 18560-19570) calculates the demand for N by the crop, and the N uptake by the crop. Firstly, the model determines a weighing factor for influence of mineral N availability on daily root growth among different soil layers RNFAC(L) as (lines 18950 - 18960):

```
RNFAC(L) = 1.0 - [1.17 * exp (-0.20 * TOTN)]
```

The weighing factor, RNFAC(L), is utilized in water balance subroutine (WATBAL: lines 4800 - 7330.)

The tops N demand TNDEM (g N/plant) is calculated as follows (line 19020):

```
TNDEM = STOVWT * (TCNP - TANC) + DNG
```

where STOVWT = stover dry weight (g/plant)

TCNP = critical N concentration (g N/g dry matter) of tops

TANC = actual N concentration (g N/g dry matter) of tops

DNG = N demand of potential new growth of tops (g N/plant).

The N demand of tops therefore depends on two factors; (i) the demand due to difference between TANC and TCNP which can be either positive or negative, and (ii) the demand for N of the potential new growth. Root N demand RNDEM (g N/plant) is calculated in a similar manner (line 19030). The nitrgen demand per unit area (ANDEM) basis is determined from NDEM (sum of TNDEM and RNDEM) and planting density (line 19050). If N demand is negative or zero, no N uptake calculations are performed, and plant N concentrations are updated for any growth which may have occurred.

The maximum uptake of ammonium from a layer (kg N/ha) is calculated as a function of root length density, RLV(L), and the maximum uptake of NH_4^+ per unit root length (0.008) and a unit conversion factor (1000). The uptake is scaled down as (lines 19213 - 19271):

RNH4U(L) = RLV(L) * 0.008 * FNH4 * 1000 * DLAYR * $SMDFR^2$

The relative availability of ammonium (FNH4) is scaled from zero to unity as a function of extractable $NH4^+$ concentration the layer (line 18930) and by water availability, SMDFR (line 19200).

In the case of nitrate, potential uptake is calculated as a function of water uptake (i.e., by mass flow) at higher levels of water availability (line 19220):

RNO3U(L) = (RWU(L)/[SW(L) * DLAYR(L)]) * SNO3(L)

where RWU(L) is root water uptake as calculated in WATBAL subroutine (line 7050). RWU(L) divided by total soil water in a layer [SW(L) * DLAYR(L)] is a factor ranging from zero to one. When water availability (SMDFR) is less than 1.0, potential nitrate uptake is calculated in a manner analogous to ammonium uptake.

Nitrate available to the plant is considered to be extractable nitrate (SNO3(L)) minus 1.0 mg nitrate-N/g. The latter quantity is considered to be inaccessible to the plant. Potential N uptake (supply) from the whole profile,TRNU, (line 19300) is thus sensitive to root density, the supply of each of the two ionic species, and the ease of their extraction as a function of the soil water status of the different layers. A zero to one factor, NUF, (lines 19320 - 19350) is used to adjust N supply from whole profile (TRNU) to crop N demand (ANDEM).

The uptake of nitrate, UNO3, and ammonium, UNH4, from a layer in the root zone are computed as (lines 19380 - 19390):

UNO3 = RNO3U(L) * NUF

UNH4 = RNH4U(L) * NUF

Soil mineral N pools are then updated for plant uptake (lines 19400 - 19410). The plant N uptake is partitioned between shoots and roots. The change in tops N is based on the ratio of tops N demand to total N demand (line 19490). Root N demand is similarly calculated, but a small proportion (1.5%) of uptake is assumed to be lost due to senescence (line 19500). Shoot N (TOPSN) and root N (ROOTN) pools and their respective concentrations are updated (lines 19510 - 19550).

Shoot nitrogen concentrations are used in subroutine NFACTO to calculate three, zero to unity N deficiency factors (NDEF1, NDEF2, and NDEF4) which affect rate of photosynthesis - leaf, stem, grain, and root growth; kernel numbers; and grain N concentration, respectively.

A zero to one nitrogen factor, NFAC, is calculated (lines 20290-20310):

NFAC = 1.0 - (TCNP - TANC)/(TCNP - TMNC)

This provides an index of N deficiency in the plant. When the actual above ground (tops) N concentration (TANC) is at the critical concentration (TCNP), NFAC = 1.0 and no deficiency occurs. As deficiency increases the difference between TCNP and TANC increases, thus decreasing NFAC. Since all plant processes are not equally susceptible to N stress the three N deficiency factors described earlier are calculated (lines 20340 - 20370).

Tops critical N concentration, TCNP, is calculated as a function of growth stage (line 20250). The tops minimum N concentration, TMNC, is also calculated as a function of growth stage (line 20260 - 20270). Shoot N concentration does not fall below TMNC.

Leaching and upflux of N

When water is moving through any layer in the profile, i.e., IDRSW = 1 (line 5750) WATBAL subroutine activates the Drainage and Leaching subroutine (lines 19600 - 19890).

The model assumes that all nitrate present in a layer, SNO3(L), is dissolved in all of the water in the layer before drainage occurs:

[SW(L) * DLAYR(L) + FLUX(L)].

Thus, the amount of nitrate leached is calculated as (line 19820):

NOUT = SNO3(L) * FLUX(L)/[SW(L) * DLAYR(L) + FLUX(L)] * 0.5 * 0.8

where NOUT = nitrate leached from layer L, SNO3(L) = soil nitrate in layer L,

FLUX(L) = water moving downward from layer L,

0.5 is the fraction of solute moved with each pore volume, and 0.8 factor to account for nitrate sorption.

The upflux generally starts from lower layers and the driving force is evaporation (WATBAL subroutine). The flux of nitrate is calculated in a manner analogous to that for leaching (lines 19900-20010). Some unsaturated flow can also be in a downward direction (lines 20030-20100).

Denitrification (lines 22680-23000)

Denitrification subroutine is called from subroutine WATBAL if there is drainage in at least one layer (line 5760). If a soil layer is above the drained upper limit, DUL (line 22830) then dentrification rate, DNRATE, is calculated as (line 22890):

$DNRATE = 6 * 10^{-5} * CW * NO3(L) * BD(L) * FW * FT * DLAYR$

where the previously undefined terms are:

CW = water soluble carbon (line 22850),

FW = water factor (line 22860),

and FT = temperature factor (line 22870).

3.2.5 Testing of the CERES maize model

The CERES maize model was tested with the data generated in the present study and data from the Benchmark Soils Project. Firstly, the simulation runs were made to verify the model. This process involved changing the input values to extremes and then executing the model. The model was modified so that the program was not terminated because of division by zero and antilogarithms of negative numbers and to avoid simulated results such as negative yields and concentrations.

Nitrogen and water balance subroutines of the model were calibrated using the current experiment (WAI-F83). The water balance subroutine was also calibrated using past data, WAI-D82 (Chinene, 1983). The model was also calibrated on eleven other Benchmark Soils Project's experiments from Hawaii (Table 3.3). Only the high P treatments (+.85, +.40) from these experiments were used for simulation (Benchmark Soils Project, 1979). Currently, the CERES model does not simulate P response to crop growth.

The N fertilizer rates in these experiments ranged from 0 to 200 kg N ha^{-1}. The code N treatment as used in BSP experiments are given in Appendix 3.2. The initial soil nitrogen level of some of these sites were not available. Estimates of soil N levels were made using post-harvest soil N from the previous cropping. The simulation runs were made with the assumption that there was no water stress. This was justified because the crops were irrigated and had no documented water stress.

Table 3.3 Experiments used to calibrate the CERES maize model.

Site/block	Planting date*	Variety	Treatment
		Tropeptic Eutrustox	
WAI-F83	11/30/83	H610,X304C	N x Variety
WAI-D82	07/02/82	X304C	N x Water
WAI-A10	07/10/78	X304C	N
WAI-B10	01/03/79	X304C	N
WAI-D10	06/07/79	X304C	N
WAI-G10	05/25/82	X304C	N
MOL-A10	07/06/78	X304C	N
MOL-B10	01/09/79	X304C	N
MOL-J10	01/10/81	X304C	N
		Hydric Dystrandept	
HAL-B21	07/12/78	H610	N
KUK-A21	06/28/78	H610	N
KUK-C11	02/16/78	H610	N
KUK-C11	05/23/79	H610	N

* Month/Day/Year

3.3 Results and Discussion

3.3.1 Effect of N fertilizer on LAI, yield, and yield component

The maximum leaf area index (LAI) obtained in this study (at silking time) is presented in Figure 3.3. Nitrogen had a highly significant effect on LAI. It accounted for more than 90% of the observed variation in LAI. Similarly, it explained over 95% (R^2 = 0.95, $P < 0.001$) of the variability in grain yield (Figure 3.4). The grain yield components: kernel number and kernel weight also showed similar response (Figures 3.5 and 3.6). Nitrogen is a compound of the chlorophyll molecule and amino acids, is essential for carbohydrate utilization and also influence uptake of other nutrients. Thus the above response to N was expected.

Mean separation of the grain yields using Duncan's multiple range test indicates that there was no significant difference between the means for the two varieties of corn at the 5% level for each N level (Figure 3.4). Mean separation of LAI gave similar results except at 50 kg N ha^{-1} application where the two varieties were significant at the 5% level. On the other hand, mean separation of kernel numbers and kernel weight for X304C and H610 varieties showed that all means were significantly different at the five percent level of probability.

These results were utilized when modifying the genetic coefficients of the two varieties. As expected, X304C and H610 have similar genotype coefficients (Table 3.4). The effect of nitrogen on crop growth is discussed in later sections where model prediction is compared with actual observation.

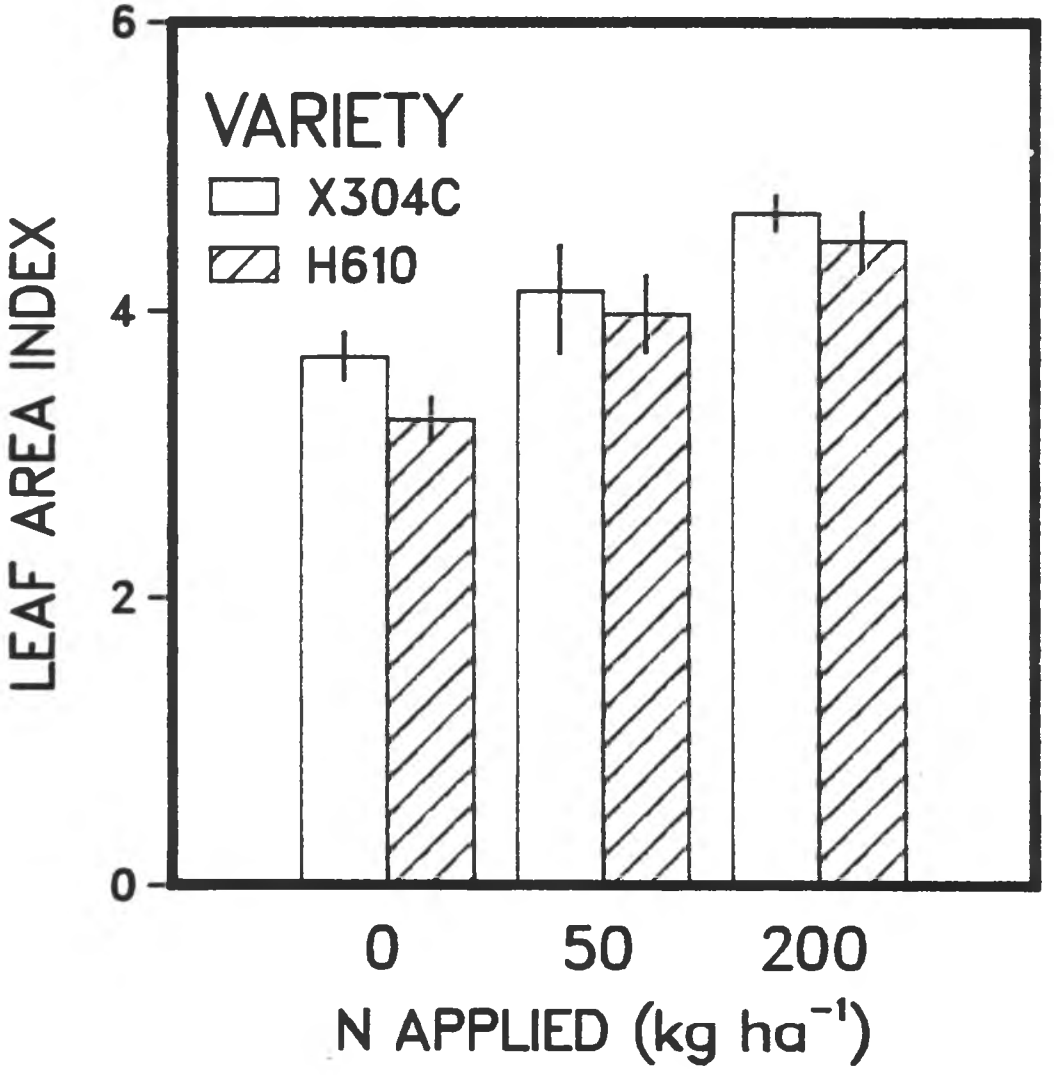


Figure 3.3 Effect of N application on leaf area index (± one standard deviation) of two maize varieties.

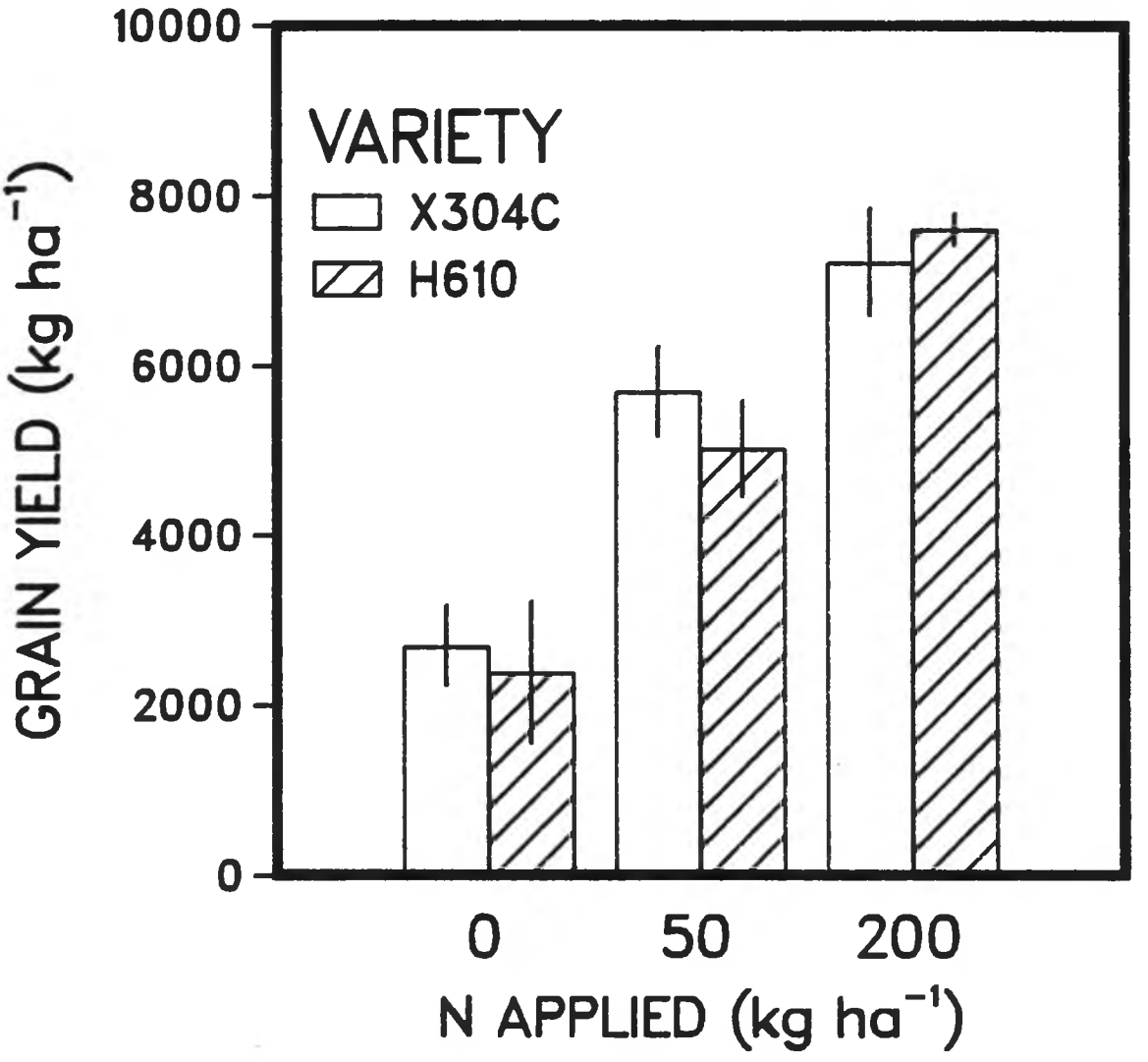


Figure 3.4 Effect of N application on grain yield (± one standard deviation) of two maize varieties.

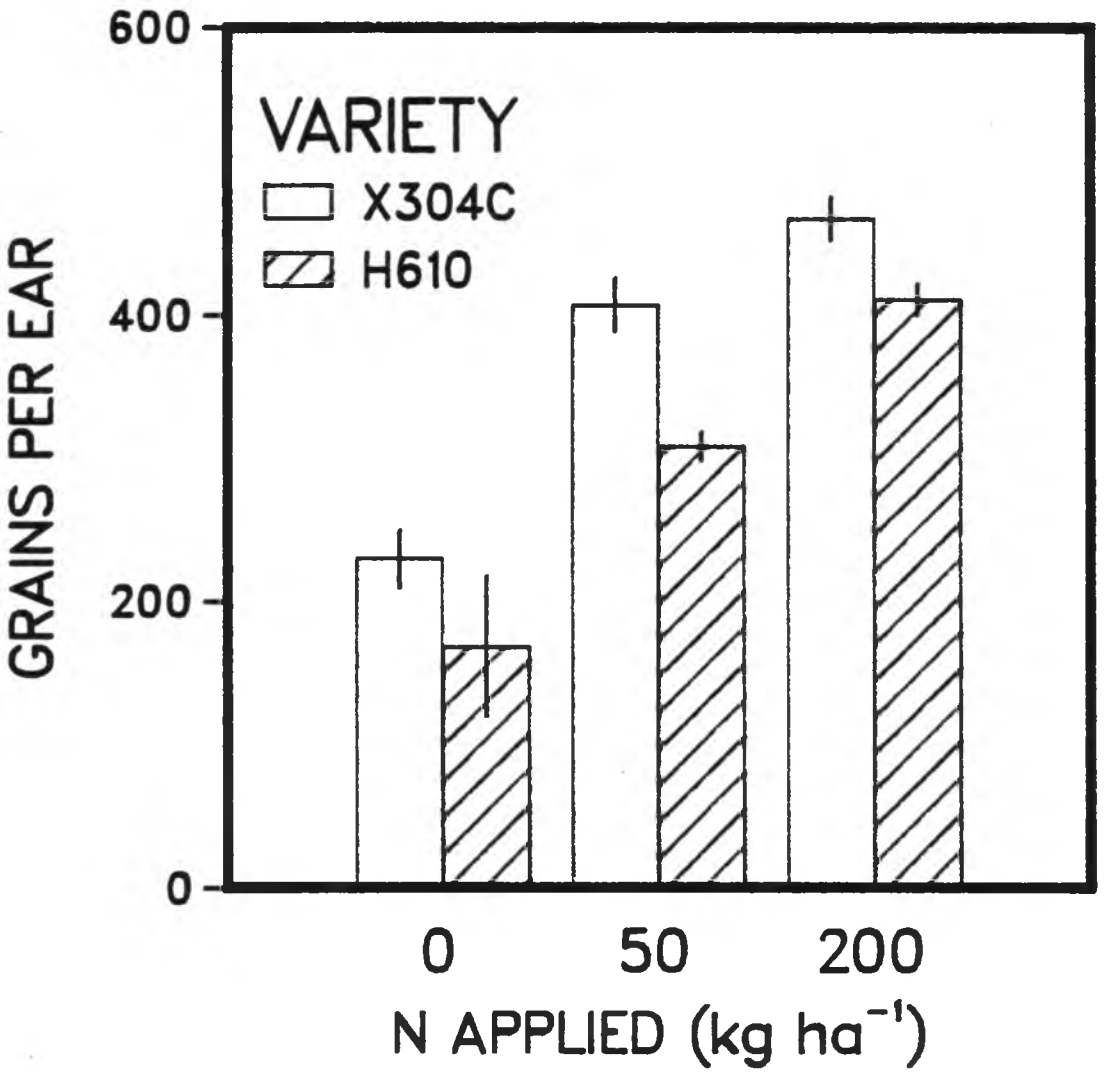


Figure 3.5 Effect of N application on grains per ear (± one standard deviation) of two maize varieties.

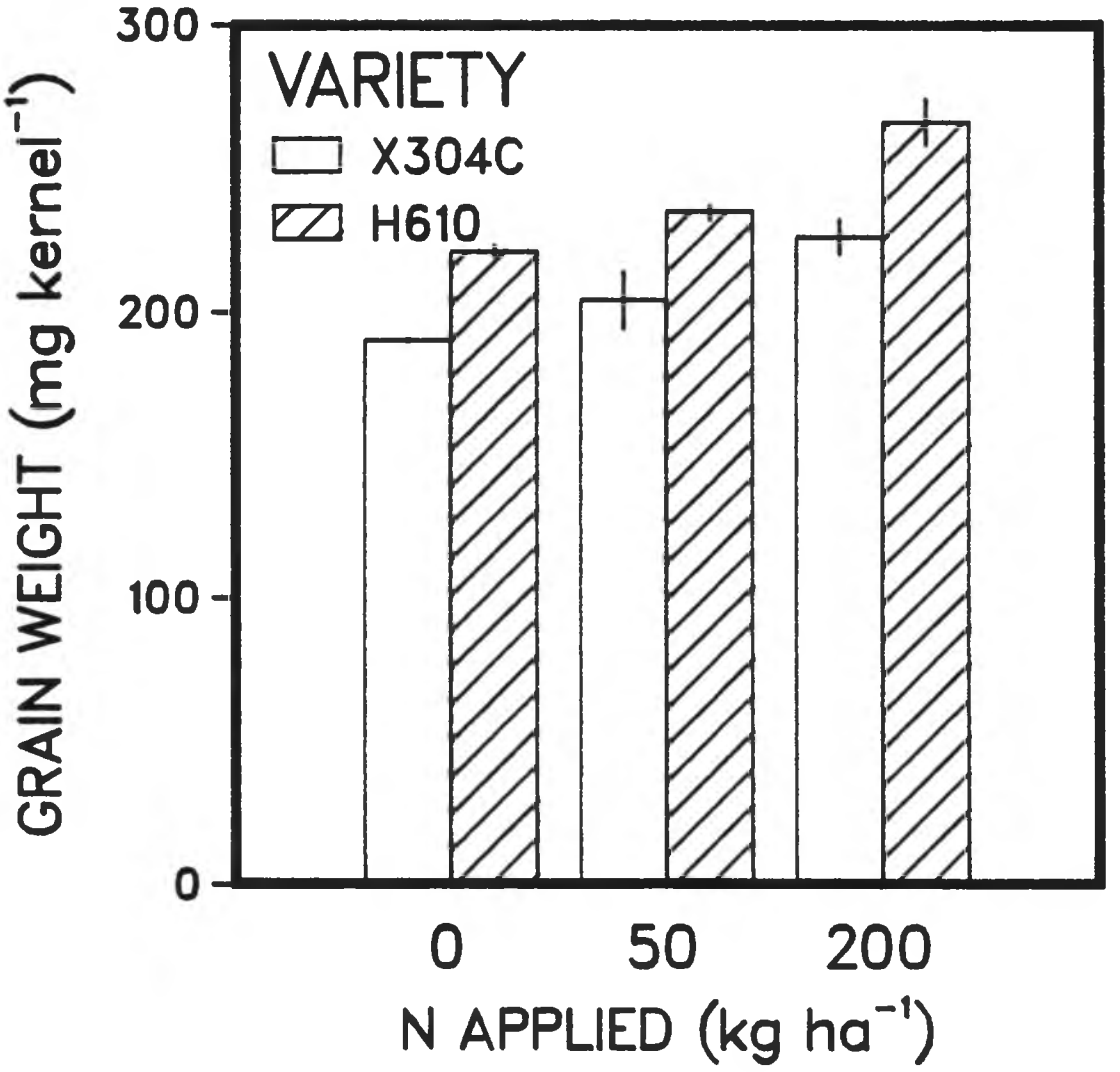


Figure 3.6 Effect of N application on kernel weights (± one standard deviation) of two maize varieties.

Table 3.4 Comparison of genotype coefficients of X304C and H610 cultivars of maize

Genetic Coefficients	X304C	H610
P1 (^{o}C-day)	340	320
P2 (days delay/hour increase in photoperiod)	0.52	0.52
P5 (^{o}C-day)	880	860
G2 (potential number of Kernels)	650	600
G3 (potential grain fill rate) mg kernel^{-1}	8.00	8.00
PHINT (^{o}C-day)	50	50

3.3.2 Model Verification

The CERES maize model was used to simulate conditions with extremely high and low input values. During severe nitrogen deficiency or drought stress the grains per ear are drastically reduced as evident from the preceding section. Modification was made such that the grain number did not fall below 50 (line 8750). Ears with fewer than fifty kernels would result in compution of the antilogarithm of a negative number (line 8780).

During N immobilization (as described earlier), if the ammonium pool cannot supply all the N that is required, withdrawal from the nitrate pool occurs. However, the withdrawl must cease once the nitrate level has fallen to zero (lines 17741-17773). Similarly, the nitrogen concentration in roots, RANC, may not fall below the specified minimum concentration, RMNC (line 11011).

With the above changes the model was adapted to run in a wide range of conditions. In the next section modifications (calibration) necessary to simulate maize growth accurately in a wide range of tropical sites is presented.

3.3.3 Model Calibration

The current experiment and past data (Table 3.3) provided adequate data sets for testing the CERES maize model under tropical conditions. Once calibrated for the differences among maize cultivars, and soils the model would be a useful tool in technology transfer. The usefulness of the model as a tool for agrotechnology transfer will be evaluated in Chapter 4.

Degree-day Computation

The driving force of the crop growth model is temperature as it affects phenological development and growth. Growth during the early vegetative stage has keen related to soil temperature by several investigators (Willis et al., 1957, Allamas et al., 1964). The growing point of corn plant is underground or near ground level for much of the first 3 to 4 weeks after planting. Thus the model was modified to use soil temperature in accumulating heat units up to tassel initation stage (lines 7751, 7871-7872).

Initially, when the model was set for wet-season (winter) plantings, the phenological events for dry season (summer) were delayed with respect to the field observation. The soil temperatures at ground level are much higher with respect to air temperature during summer than winter (H. Ikawa, unpublished data). Hence, the incorporation of soil temperature enhanced the phenological development of corn plant during the summer and improved the model prediction.

Suboptimal levels of light is another factor that may delay phenological development in the field during the wet season. This effect may be analogous to delay in physiological maturity with severe nitrogen stress. In temperate regions the degree day concept performs well because it may also be serving as surrogate a variable for solar radiation. In the tropics solar radiation and temperature may not be correlated during the growing season. Hence modification was made to account for the delay in phenological development not accounted for by the degree day concept. Phenological development was delayed when solar radiation was less than 300 langleys day^{-1} (line 7878).

Maize genotypes

The genotype specific coefficients in the model were adjusted until reasonable agreement between observed dates of tassel initiation, silking, and physiological maturity were obtained. The maize genotypes used for simulation were X304C and H610. The grain fill rate determined for varieties X304C and H610 were 6.33 mg kernel $^{-1}$ day^{-1} and 7.27 mg kernel $^{-1}$ day^{-1}, respectively (Figure 3.7). These rates do not represent the potential grain fill rate as evident from a higher rate (7.40 mg kernel^{-1} day $^{-1}$) for the X304C variety during the summer (Appendix 3.3). The potential grain fill rates for both the varities were assumed to be 8.0 mg kernel^{-1} day $^{-1}$. The higher rate was based on the heavier kernel weights observed in border rows and low planting density experiments.

The potential grain numbers were adjusted until there was reasonable agreement between the observed and predicted values. The higher grain number potential for X304C (Table 3.4) is consistent with field observations. H610 variety with lower grain number potential seems to be better adapted to cooler environments. However, the results from the present study did not show a significant difference with respect to grain yield (Figure 3.4). The adjusted genotype coefficients are presented in Table 3.4.

Photsynthesis and grain growth

The optimum temperature for photosynthesis was increased from 26° to 30° to improve the adaptability of the model to the tropics (line 10240). The optimum temperature for photosynthesis is generally in the

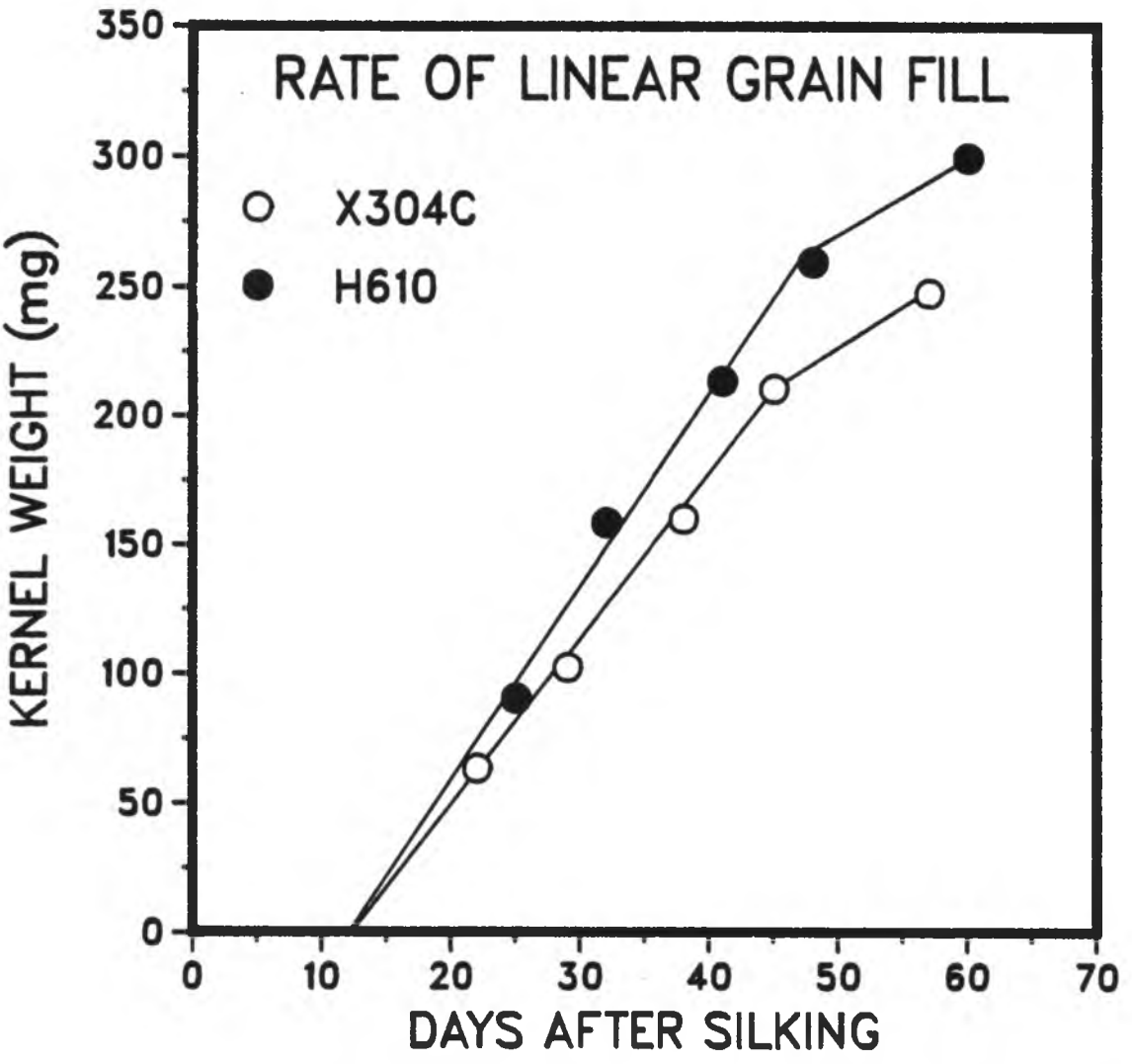


Figure 3.7 Period of linear grain filling.

range of 25-30°C. Maximum corn growth rates generally have occurred in the 28-32°C range (Coelho and Dale, 1980).

During the grain fill stage night temperature is more important than mean temperature (Shaw, 1977). Grain yields in Hawaii also have been significantly related to minimum temperature (Lee, 1983). The model was adapted to use minimun temperature instead of mean temperature to simulate grain growth (line 10691). Prior to the above change the model was overpredicting the kernel weight particularly during the cooler seasons.

Nitrogen and water stress

Both water and nitrogen stress were added as factors influencing grain number (line 8740). Although the CERES model is based on the law of the minimum on a daily time step basis, during the simulation the effect is interactive on crop growth. When a plant is facing both water and N stress, uptake of other nutrients, e.g., P, may become limiting. To correct such interactive effects and adjust the model predictions to observed values an interactive term was incorporated (line 10270).

Nitrogen Mineralization

The nitrogen mineralization rate of oxisols and ultisols was adjusted to 0.6 of the rate used for temperate soils, i.e., DMOD = 0.6 (line 15920). For Hydric Dystrandepts DMOD = 0.2. The lower mineralization constant may be attributed the complex bonding of organic matter with Fe- and Al- oxides. This effect is more marked in the volcanic ash soils with short range order minerals.

3.3.4 Comparison of observed and simulated soil water content

The water balance subroutine had been previously calibrated for the Waipio site (Chinene, 1983). Because of the changes in the CERES model since then, the subroutine was recalibrated using Chinene's data.

The model was then tested on the current experiment. The root preference factor, WR, of the soil file (Table 3.2) was reduced from 0.4 to 0.1 at 30 to 50 cm depth to account for the compacted plow layer. The predicted soil water contents were within one standard deviation of the means (Table 3.5).

In Hydric Dystrandept sites field measured drained upper limits and lower limits of plant extractable soil water were not available. These values were estimated from other soil physical and chemical properties. The water balance subroutine could not be adequately tested on these sites because actual irrigation data were not available. In these sites irrigation was assumed to occur whenever soils dried to the lower limit of extractable soil water.

3.3.5 Predicting maize performance on Tropeptic Eutrustox sites

The performance of the maize model was tested on experiments from Tropeptic Eutrustox sites after the model had been calibrated on these data.

The actual and simulated dates of phenological events are presented in Table 3.6. In general the model predictions were within two days of the actual phenological event. Field determination of such observations as 75% silking could have an error of approximately 2 days. The model, however, does not simulate the effect of nitrogen,

Table 3.5 Comparison of measured and simulated soil water content near the tassel initiation stage (Julian date 2) and during tasseling (Julian date 38).

Treatment (kg N ha^{-1})	Soil Layer (cm)	Soil Water Content (cm cm^{-3}) Julian date 2 Actual*	Julian date 2 Simulated	Julian date 38 Actual	Julian date 38 Simulated
200	0-10	0.24 (.03)	0.26	0.27 (.03)	0.29
	10-30	0.31 (.02)	0.33	0.30 (.03)	0.32
	30-50	0.37 (.02)	0.36	0.32 (.02)	0.33
	50-70	0.38 (.02)	0.38	0.36 (.01)	0.35
	70-90	0.38 (.01)	0.38	0.35 (.02)	0.35
	90-110	0.38 (.01)	0.39	-	0.37
50	0-10	0.27 (.03)	0.26	0.28 (.03)	0.28
	10-30	0.34 (.02)	0.33	0.32 (.02)	0.33
	30-50	0.35 (.02)	0.36	0.35 (.02)	0.33
	50-70	0.39 (.02)	0.38	0.36 (.02)	0.35
	70-90	0.39 (.02)	0.38	0.37 (.02)	0.35
	90-110	0.39 (.01)	0.39	-	0.37
0	0-10	0.24 (.02)	0.26	0.27 (.03)	0.29
	10-30	0.34 (.02)	0.33	0.32 (.02)	0.33
	30-50	0.35 (.02)	0.36	0.34 (.02)	0.33
	50-70	0.39 (.02)	0.38	0.36 (.02)	0.35
	70-90	0.39 (.02)	0.38	0.37 (.02)	0.35
	90-110	0.39 (.01)	0.39	0.37 (.02)	0.37

* Measured with one standard deviation.

Table 3.6 Comparison of observed and simulated phenological events for X304C variety and H610 variety.

N Applied (kg ha^{-1})		Days After Planting				
		Emergence	Tassel initiation	Silking	Begin* Grain Fill	Physiological Maturity
			Variety X304C			
200	Observed	7	35	78	89	136
	Simulated	5	35	79	95	138
50	Observed	7	35	79	-	135
	Simulated	5	35	79	-	138
0	Observed	7	35	81	-	139
	Simulated	5	35	79	-	138
			Variety H610			
200	Observed	7	34	75	87	133
	Simulated	5	32	74	89	134
50	Observed	7	34	76		133
	Simulated	5	32	74	-	134
0	Observed	7	34	79	-	133
	Simulated	5	32	74	-	134

* Determined from intercept of Figure 3.7.

water stress, and other nutrients on phenological events. Hence, the delay in silking in both varieties and the delay in physiological maturity in X304C was not simulated by the model. However, the effect of nutrient deficiency on phenological events is not well documented. For example, in the present study nitrogen stress did not delay physiological maturity equally in both varieties (Table 3.6).

Comparisons of observed and simulated dates for phenological events in Benchmark Soils Project experiments are presented in Table 3.7. The silking dates were not determined in these experiments. The days to tasseling were used as estimates for days to silking. Hence, the model's overprediction of days to silking is understandable. Results indicate that the model was able to accurately predict the prolonged vegetative growth in winter. The model also simulated the silking dates accurately for two experiments (WAI-B10 and MOL-B10) planted within a week of each other but on two different sites (islands). The model accurately predicted the eighteen-day difference in silking. In general, the results tend to indicate that the phenology component of the CERES maize model is well calibrated for Tropeptic Eutrustox sites.

Comparison of measured and simulated growth components

Leaf area was determined five times during the course of plant growth. The later three measurements were unreplicated. As expected the leaf area index (LAI) increased with increasing rate of applied N (Figure 3.3). This effect was simulated for the 3 rates of N and the 2 varieties (Figures 3.8 and 3.9). LAI prediction was overestimated

Table 3.7 Comparison of observed and simulated silking and physiological maturity dates for X304C variety on Tropeptic Eutrustox sites.

Experiment/site	Planting date		Days After Planting	
			Silking*	Physiological Maturity
WAI-D82	7/2/82	Observed	68	122
		Simulated	67	120
WAI-A10	7/10/78	Observed	60	-
		Simulated	60	111
WAI-B10	1/03/79	Observed	75	-
		Simulated	77	134
WAI-D10	6/07/79	Observed	64	-
		Simulated	63	110
WAI-G10	5/25/82	Observed	65	125
		Simulated	68	120
MOL-A10	7/06/78	Observed	59	-
		Simulated	62	112
MOL-B10	1/09/79	Observed	93	-
		Simulated	95	156
MOL-J10	1/09/81	Observed	75	140
		Simulated	83	149

* Observed dates are for 50% tasseling.

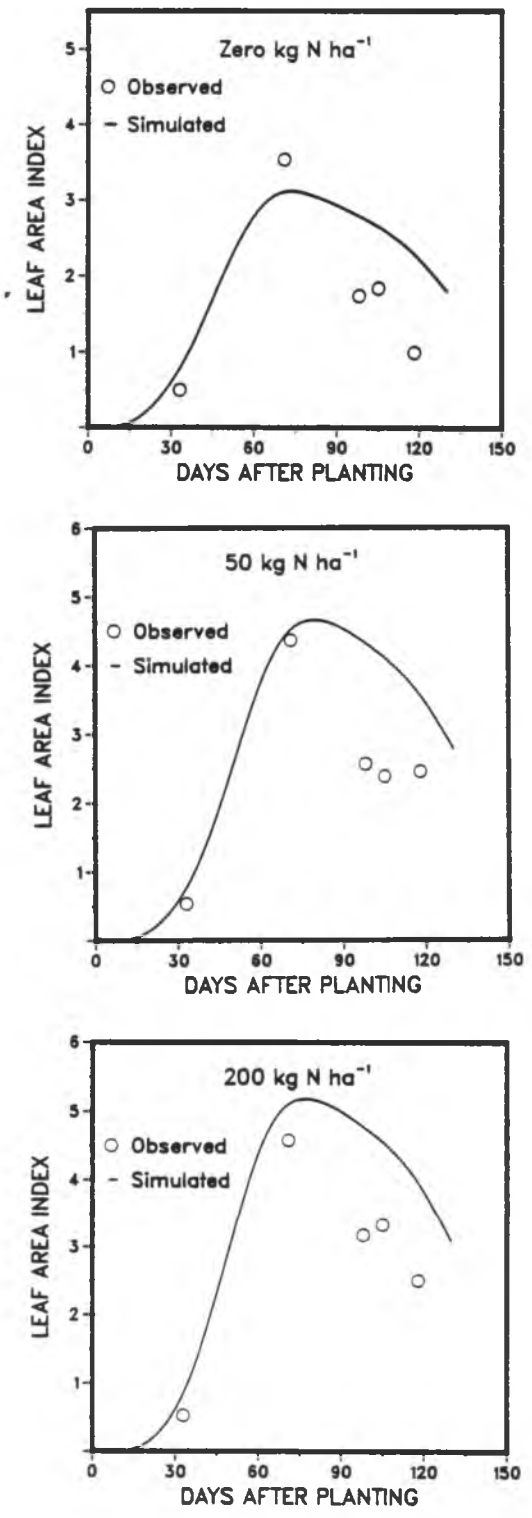


Figure 3.8 Comparison of observed and simulated leaf area index for maize cultivar, X304C at three levels of N application.

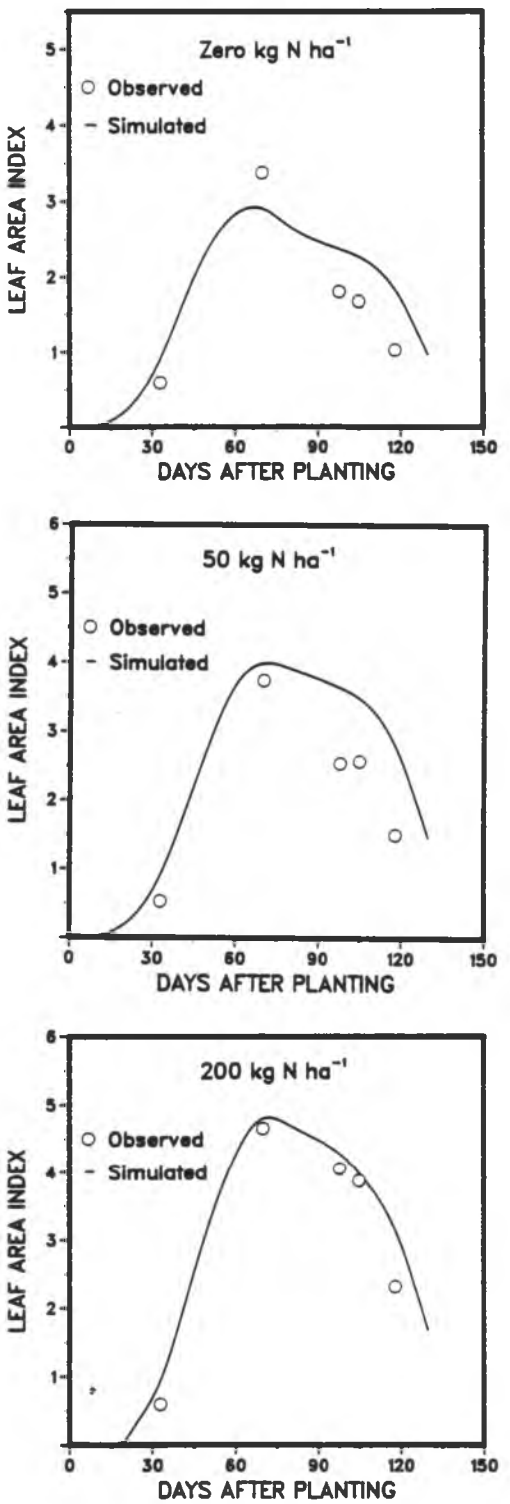


Figure 3.9 Comparison of observed and simulated leaf area index for maize cultivar, H610 at three rates of N application.

within 33 days after planting (DAP). This effect would be minimized if DAP were expressed as days after emergence because simulated days to emergence was two days before the actual emergence.

The model tends to predict the LAI at tasseling stage (71 DAP) within 10% of the observed values in most cases. The simulated LAIs were in general higher than the actual values in the later stages of crop growth (Figure 3.8 and 3.9). A similar trend was observed in the summer planting (Table 3.8). Thus, the simulated leaf senescence is less than the actual senescence in the field.

Comparisons of measured and simulated above ground biomass are presented in Figures 3.10 and 3.11. The model predictions in most cases were within 10% of the measured values. Considering the plant to plant variability in the field the model predictions are acceptable. However the dry matter produced at physiological maturity is consistently lower than the predicted. The final harvest was a few days after physiological maturity (135 DAP) and thus there was loss of leaves and plant material which the model did not consider.

The model accurately predicted the response of leaf weights to N application in both X304C and H610 varieties (Table 3.9). In general the model tends to underestimate the leaf weights in zero N treatments.

The overall or the cumulative effects of the model appear similar to the field response. Some of the anomolous predictions during the course of crop growth do not seem to affect the model's performance in predicting final grain yield and total dry matter production. This would be evident from the following sections.

Table 3.8 Comparison of measured and simulated leaf area indices for summer planting (WAI-D82).

N Applied (kg N ha^{-1})		Leaf Area Index		
		Days After Planting		
		38	66	87
0	Measured	1.3	3.9	3.2
	Simulated	2.0	4.6	4.2
29	Measured	1.7	5.0	3.9
	Simulated	2.0	5.6	5.0
186	Measured	2.1	6.8	5.4
	Simulated	2.2	6.3	5.6

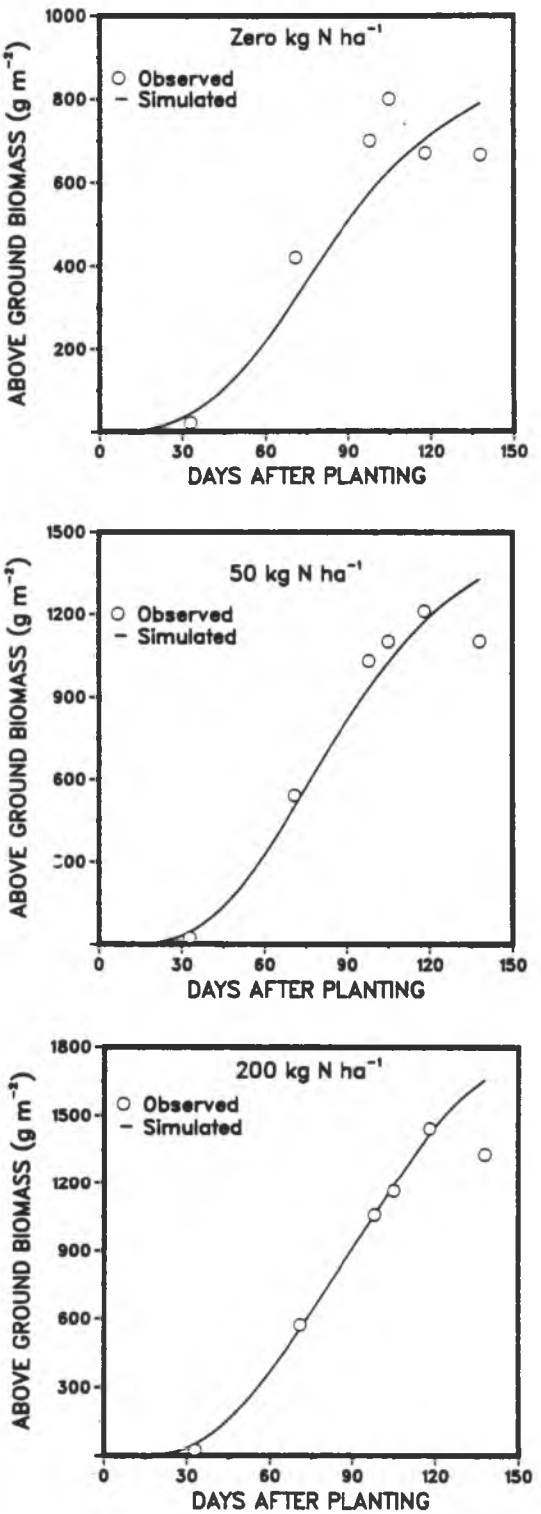


Figure 3.10 Comparison of observed and simulated above ground biomass production for maize cultivar, X304C at three rates of N application.

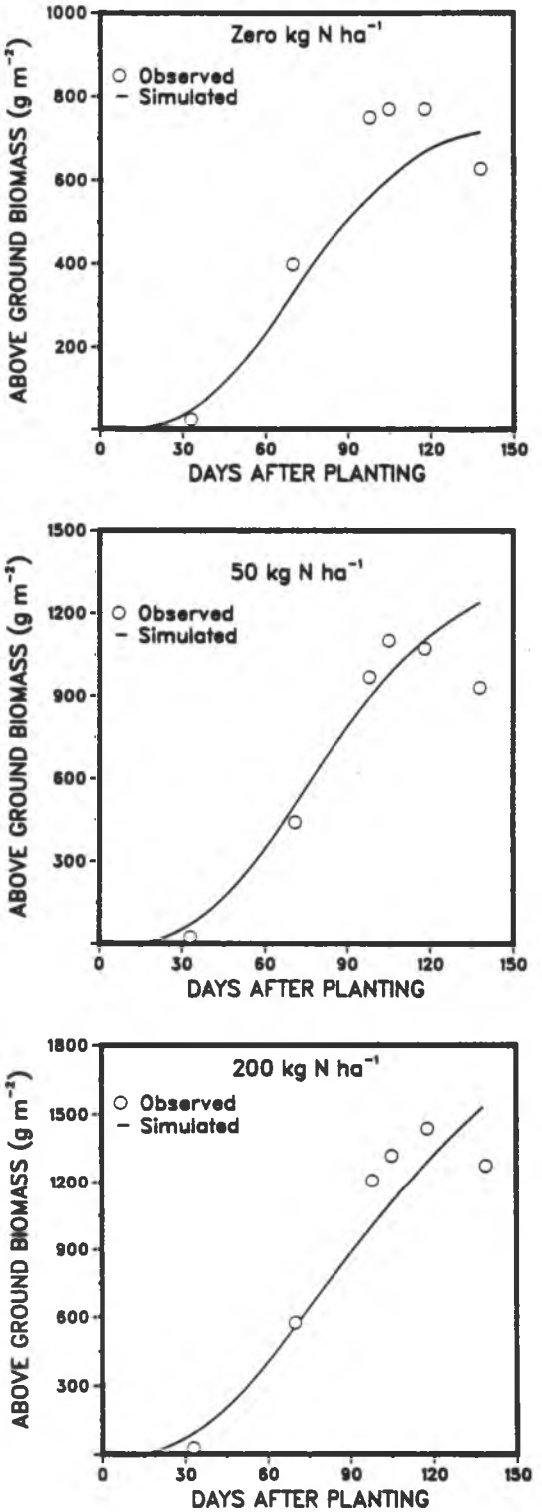


Figure 3.11 Comparison of observed and simulated above ground biomass production for maize cultivar, H610 at three rates of N application.

Table 3.9 Comparison of measured and simulated leaf weights for maize culitvars, X304C and H610 at three rates of N application.

Day After Planting		Leaf Weight (g plant^{-1}) N Applied (kg N ha^{-1}) 0	50	200
		X304C Variety		
33	Measured[a]	3.6 ± 0.7	4.0 ± 1.0	3.8 ± 0.6
	Simulated	3.9	4.1	4.1
71	Measured	39.9 ± 4.7	51.8 ± 5.0	56.8 ± 6.5
	Simulated	32.4	51.6	60.0
98	Measured	44.2 ± 1.7	54.4 ± 3.5	58.3 ± 5.0
	Simulated	33.3	54.4	61.8
105	Measured	50.4 ± 5.0	55.9 ± 6.0	60.5 ± 3.2
	Simulated	32.9	53.8	61.3
118	Measured	36.4 ± 3.0	46.0 ± 6.0	53.2 ± 6.7
	Simulated	32.1	52.5	59.7
		H610 Variety		
33	Measured	4.2 ± 0.1	3.6 ± 0.8	4.1 ± 1.0
	Simulated	4.3	4.6	4.6
71	Measured	37.6 ± 6.0	42.1 ± 7.2	56.7 ± 9.0
	Simulated	30.4	47.6	53.9
98	Measured	46.5 ± 6.5	48.2 ± 3.0	65.8 ± 4.2
	Simulated	30.4	48.9	55.0
105	Measured	43.8 ± 3.0	54.7 ± 4.0	62.8 ± 6.5
	Simulated	30.1	48.3	54.3
118	Measured	31.5 ± 6.5	43.5 ± 3.0	54.6 ± 8.7
	Simulated	29.2	46.9	52.9

[a] Measured mean ± one standard deviation of the observations.

Comparison of measured and simulated grain yields and grain components

Comparison of simulated yields for two varieties and three rates of nitrogen application in Figures 3.12 and 3.13 indicate the model overpredicted the yields at the higher N rates. For the lowest N rate the predictions were within a standard deviation of the mean. The model was not recalibrated to predict the high fertility treatments accurately.

The overestimation by the model may be due to greater susceptibility of the high treatment plants to pests and diseases. However, the presence of pests and diseases in these treatments may be less apparent than in low fertility treatments. Further, high treatment plants may have encountered other nutrient deficiencies which did not occur in low treatments since N was most limiting in these plants.

Simulation of some Benchmark Soils Project experiments with different N rates (Appendix 3.2) on Tropeptic Eutrustox are presented in Table 3.10. Most of the predicted values are within one standard deviation or within 10% of the mean yields. The versatility of the model is well illustrated from these experiments. Inspite of different locations, planting times (Table 3.3), treatments (N rate, water stress) and responses to fertilizer application the model predictions were reasonable. The overestimation at the Molokai site is due to lodging of plants. The CERES model does not simulate the effect of wind damage. The other differences are due to pests, weeds, diseases, and management.

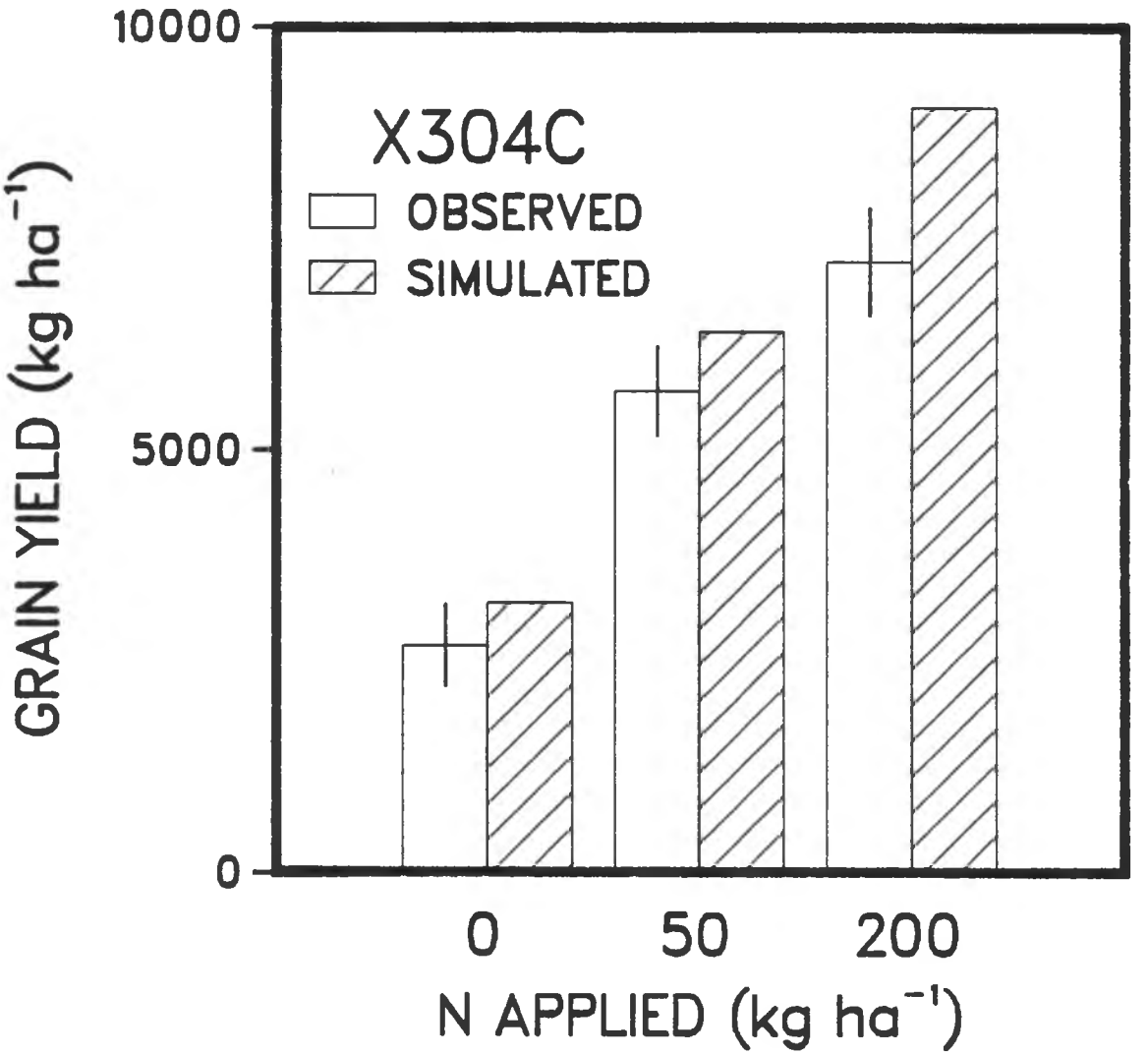


Figure 3.12 Comparison of observed (± one standard deviation) and simulated grain yield at three rates of N application for maize cultivar, X304C.

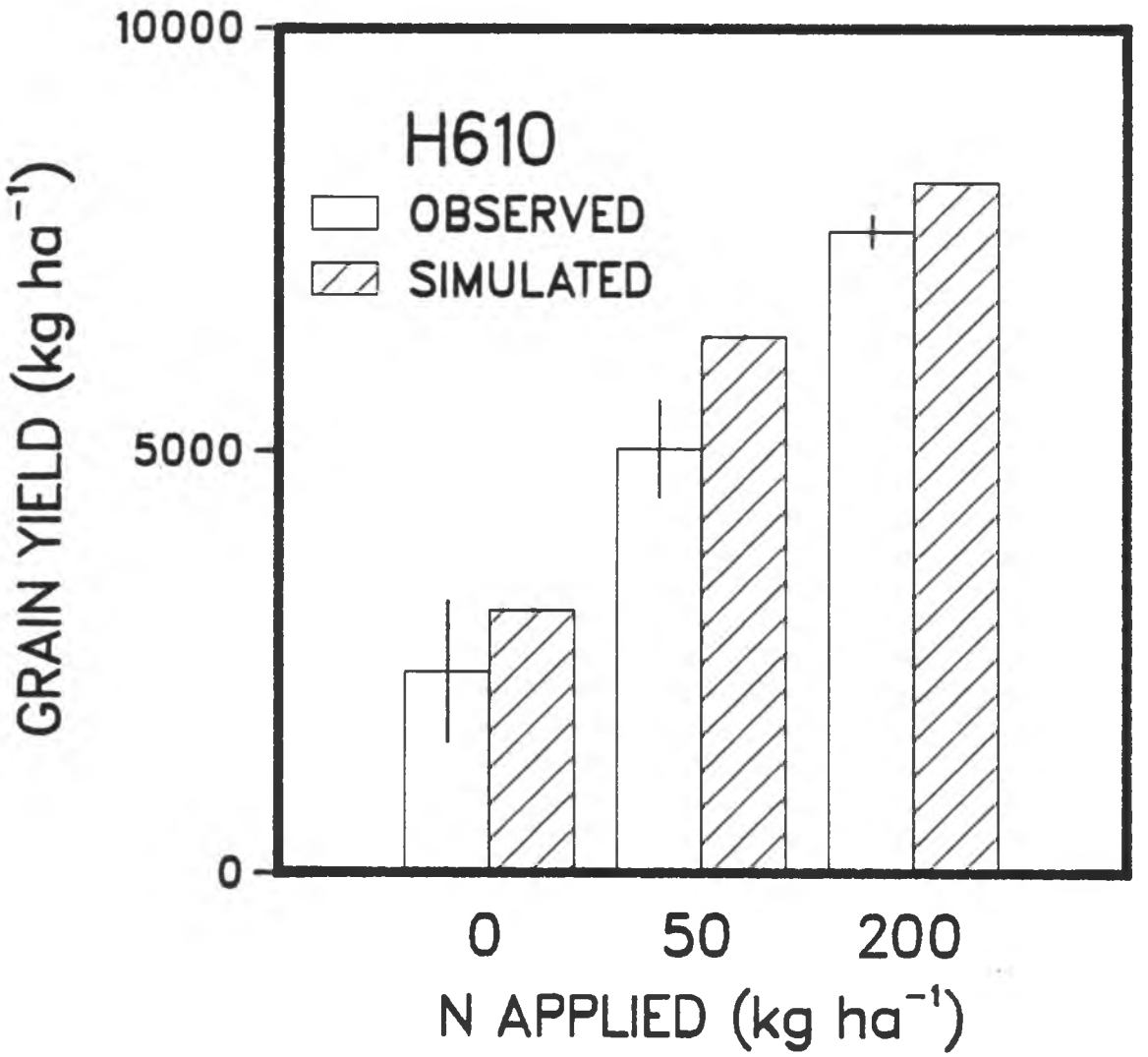


Figure 3.13 Comparison of observed (± one standard deviation) and simulated grain yield at three rates of N application for maize cultivar, H610.

Table 3.10 Comparison of measured and simulated yields in nine Benchmark Soils Project Experiments on two Tropeptic Eutrustox sites.

SITE		Coded N level (P, N)					
		Opt, 0	+.85, -.85	+.40, -.40	+.85, Opt	+.40, +.40	+.85, +.85
WAI-D82	Measured[a]	4370 ± 500	5986 ± 1000	-	-	-	10732 ± 600
	Simulated	4168*	5705*				11048*
WAI-D82W[b]	Measured	2489 ± 400	3728 ± 450	-	-	-	7982 ± 850
	Simulated	2966*	4147*				7724*
WAI-A10	Measured		9456 ± 1150	9106 ± 430	11034 ± 460	11064 ± 450	10513 ± 760
	Simulated		9147*	10084	10467	10575	10575*
WAI-B10	Measured		8454 ± 580	9365 ± 1120	9827 ± 970	10953 ± 390	11530 ± 200
	Simulated		8649*	9862*	10692*	10915*	10915
WAI-D10	Measured	5694 ± 740	6610 ± 1370	7982 ± 110	8149 ± 880	8750 ± 708	9992 ± 1850
	Simulated	6302*	7301*	8412	9601	9937	10378*
WAI-G10	Measured	4270 ± 380	6280 ± 230	7824 ± 280	9425 ± 162	9694 ± 695	9863 ± 560
	Simulated	4701	6530	8361	9636	10675	10734
MOL-A10	Measured	7090 ± 850	7960 ± 780	9266 ± 640	9930 ± 140	9580 ± 500	10460 ± 660
	Simulated	8101	8955	10067	10935	11307	11511
MOL-B10	Measured		4980 ± 1010	6090 ± 690	6985 ± 1010	8546 ± 920	8773 ± 460
	Simulated		5481*	6988	9289	9813	10159
MOL-J10	Measured	7359 ± 1020	8443 ± 720	8732 ± 680	9143 ± 1090	8875 ± 830	9320 ± 650
	Simulated	6362*	7687	9468	10715	10914	10915

[a] Mean yields ± one standard deviation of observations.
[b] Water stress experiment (Chinene, 1983).
* Simulated yields are within one standard deviation of mean yields.

The simulated values for kernels per ear and kernel weight were generally in agreement with the observed values (Figure 3.14). However, there was more scatter around the 1:1 line in kernel weight simulation than in kernel number. Grain number is a more significant component of grain yields than grain weight (Lee, 1983). The model simulates this effect in close agreement with field observation. The effect of N fertilization on grain yield, grain weight, and grain yield together with the simulated response is shown in Figure 3.15. The model tends to simulate N response to grain number and grain yield as observed in the field. However, the grain weight predictions are not very good. In general grain weight does not show marked response to N application. The grain number overestimation by the model was not corrected because it seemed reasonable to overpredict the grain numbers. The model did not consider factors such as other nutrient deficiencies, pests, diseases, and weeds that may have lowered the number of kernels in the field.

3.3.6 Testing the CERES maize model on Hydric Dystrandept sites

The model was not calibrated separately for Hydric Dystrandept sites. However, the input factor, DMOD for the nitrogen mineralization constant was reduced by one third to accommodate larger amounts of organic matter in the Andisols and the lower mineralization rate due to the chemi-sorption of the organic matter with the short range order minerals. The initial soil nitrate and ammonium levels for these experiments were determined. The soil samples, however, may not have

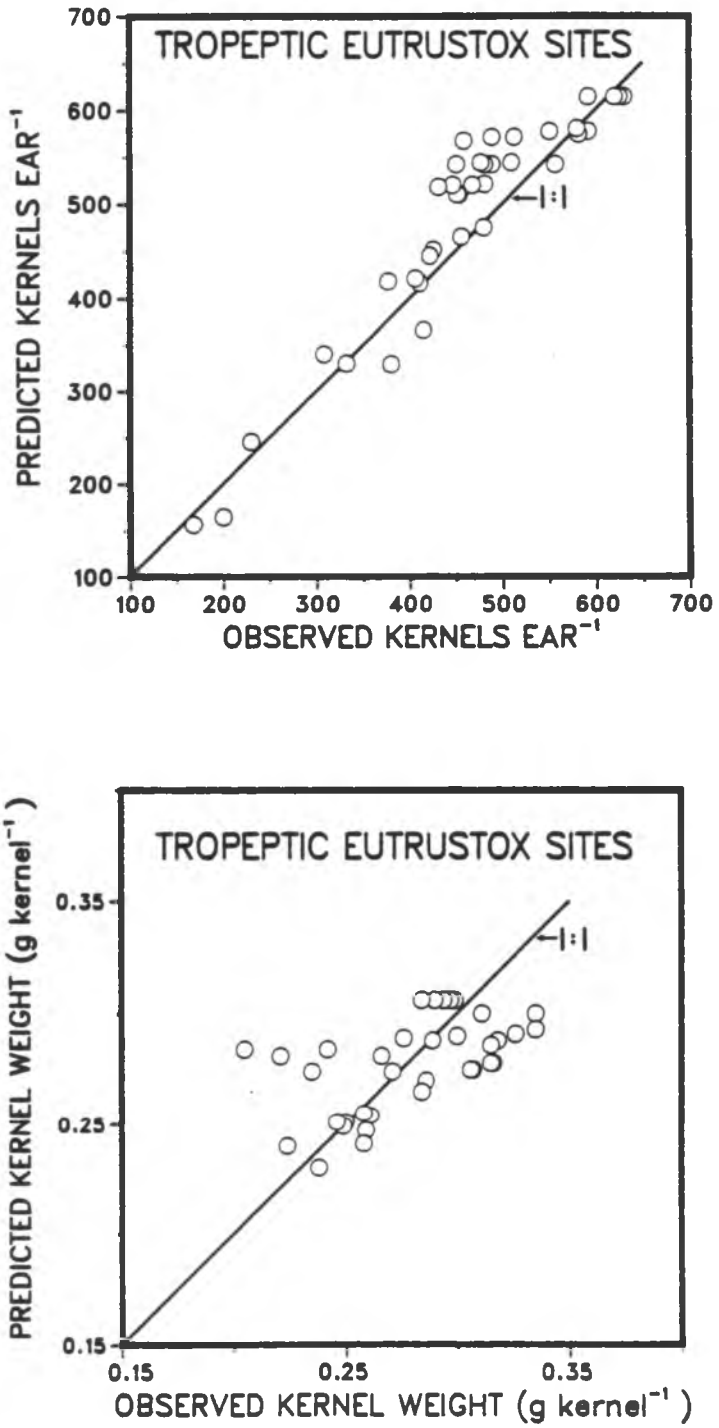


Figure 3.14 Comparison of observed and simulated kernel numbers and kernel weights on Tropeptic Eutrustox sites.

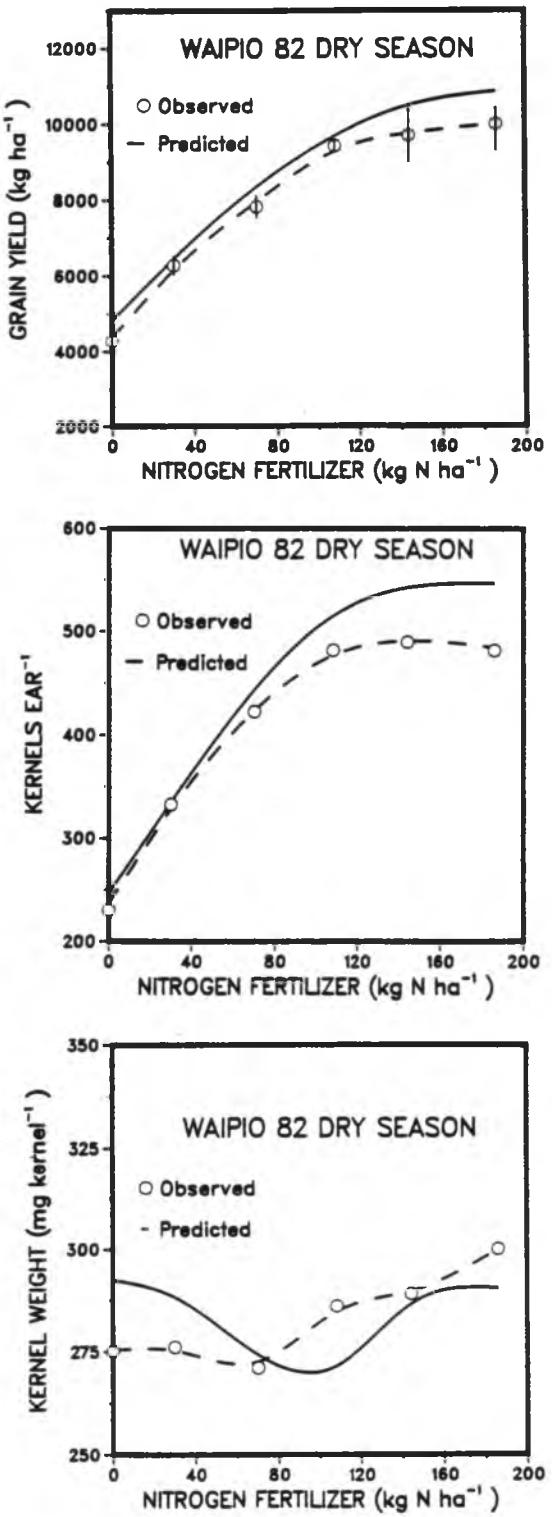


Figure 3.15 Comparison of observed and simulated grain yield, kernel numbers, and kernel weights with nitrogen fertilizer application at Waipio site (WAI-G10).

been from the original plots. The time lag between soil sampling and soil analysis may have caused mineralization of N. This would have resulted in higher mineral N in the samples than commonly encountered in the field.

The days to 75% silking were in general longer on the Hydric Dystrandent sites (Table 3.11). This, of course, is attributed to the cooler isothermic temperature regime in Hydric Dystrandept sites compared with isohyperthermic temperature regime in Tropeptic Eutrustox sites. The prolonged vegetative stage resulted in greater difference between tasseling and silking. Hence, the predicted days to silking were in general about a week after the observed days to 50% tasseling. Days to physiological maturity was available for only one experiment. The model matured the crop about 12 days earlier. Due to the limitations imposed by input data the genotype coefficients for H610 variety were not recalibrated (Table 3.4). Thus, there is a need to collect appropriate genetic data for the H610 variety.

The predicted grain yields for the Hydric Dystrandept experiments presented in Table 3.12 were in general within one standard deviation or within 10% of the observed mean yields. In Kukaiau C-11 (KUK-C11) experiment, the model tends to overpredict the grain yields. Grain yield at optimum level of nitrogen (108 kg ha^{-1}) was as high as the yield at +.85 treatment (186 kg N ha^{-1}). Thus, other factors not accounted for by the model limited yields at higher levels of N fertilization. The model also confirms that 108 kg N ha^{-1} as chosen by the Benchmark Soils Project (1979) was the optimum N level for the Hydric Dystrandept site at Kukaiau.

Table 3.11 Comparison of observed and simulated silking and physiological maturity date for H610 variety on Hydric Dystrandept sites.

Experiment/site	Planting date		Days After Planting	
			Silking*	Physiological Maturity
HAL-B21	7/13/78	Observed	71	-
		Simulated	81	162
KUK-A21	6/29/78	Observed	66	-
		Simulated	74	138
KUK-C11	2/16/78	Observed	77	150
		Simulated	79	138
KUK-C12	5/23/79	Observed	69	-
		Simulated	73	128

* Observed days are to 50% tasseling.

Table 3.12 Comparison of measured and simulated yields in four Benchmark Soils Project experiments on two Hydric Dystrandept sites.

SITE		Coded N level (P, N)				
		+.85, -.85	+.40, -.40	+.85, Opt	+.40, 40+	+.85, +.85
HAL-B21	Measured[a]	4971 ± 695	6441 ± 273	7059 + 709	7622 ± 792	8169 ± 815
	Simulated	4738*	6735	8412	8695	8695*
KUK-A21	Measured	6982 ± 954	6955 ± 1537	7113 ± 609	7107 ± 956	7852 ± 1591
	Simulated	6404*	7893*	8611	8685	8685*
KUK-C11	Measured	7358 ± 840	7257 ± 418	8629 ± 1085	8161 ± 357	8768 ± 433
	Simulated	8035*	9348	10031	10035	10035
KUK-C12	Measured	7249 ± 1529	8221 ± 691	8984 ± 724	9213 ± 281	9262 ± 509
	Simulated	7310*	8817*	8823*	8823	8823*

[a] Mean yields ± one standard deviation of observations.
* Simulated yields are within one standard deviation of observed mean yields.

In the Kukaiau C-12 experiment model predictions, though within a standard deviation, were lower than the observed yields. Analysis of grain yield components indicated that the under-predictions were attributed to lighter predicted kernel weights. The probable reason for light kernels may have been the shorter grain filling period. However, as mentioned earlier with limited data on phenological events, it was not possible to ameliorate this problem. The model consistently overpredicted grain yield for the +.40, +.40 treatments. Since the Hydric Dystandept experiments used for model calibration were residual P experiments, it is possible that P was limiting.

The relationships between measured and simulated grains per ear and grain weight are presented in Figure 3.16. Although there was much scatter, the model in general did not overestimate/underestimate the grain number per ear or the grain weight for the Hydric Dystrandept sites.

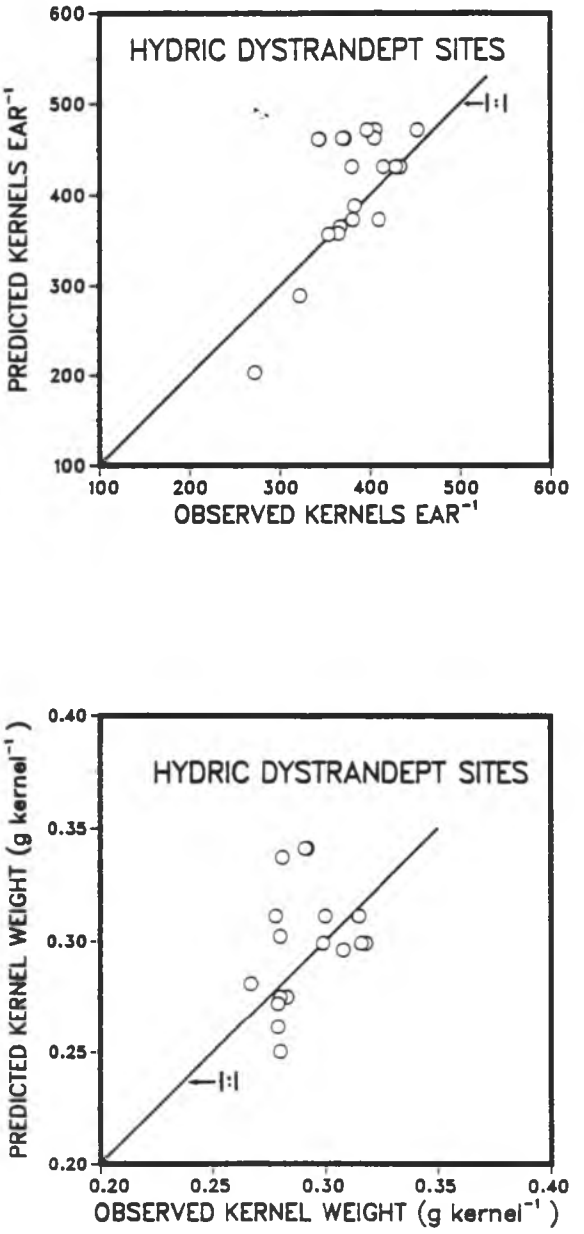


Figure 3.16 Comparison of observed and simulated kernel numbers and kernel weights on Hydric Dystrandept sites.

3.4 Conclusions

1. A field experiment was conducted to calibrate the CERES maize model for agroenvironments in the tropics. The soil and plant components were compared with the simulated values. Prior to calibration the model was verified for conditions encountered in the tropics, e.g., very low N levels and drought stress.

2. Adjustments were made for: (i) thermal time computation; (ii) maize genotype coefficients; (iii) optimum temperature for photosynthesis; (iv) the effect of minimum temperature on grain filling; (v) the effect of N deficiency and water stress on grain numbers, (vi) N mineralization constants for Tropeptic Eutrustox and Hydric Dystrandept sites; and (vii) an interactive term to accomodate the effect of other nutrients on crop growth when both water and nitrogen supply is limiting.

3. The CERES maize model was used to simulate soil water content, LAI, dry matter production, and leaf weights with time for three rates of N fertilizer and two varieties five times during the course of crop growth in the current field experiment. The predictions in general were in close agreement with the observed values. The model also accurately predicted phenological events for the two varieties, H610 and X304C.

4. The maize model was tested on other experiments from Tropeptic Eutrustox sites. The model calibration appeared reasonable as the predictions of phenological events, grain yields, grain numbers, and kernel weights were in close agreement with actual observations.

5. The model was also tested with data on Hydric Dystrandept sites. The model performance was satisfactory, i.e., the simulated results were within 20% of the observed yields or within one standard deviation of observed mean yields. Limited data on phenology prevented full evaluation of the model with respect to predictiong silking and physiological maturity dates on these sites with maize cultivar H610. Phosphorus may have been limiting in some of these experiments.

6. The overall performance of the CERES maize model in two agroenvironments was used to identify probable sources of error and potential future research. Most of the variability and overpredictions in these experiments were attributed to pests, diseases, and wind damage. Phosphorus limitation may have been a factor in some of the P-residual experiments. The model does not simulate these effects. Another factor that may explain inadequate accounting of seasonal variations in growth and development is the change in the photosynthetically active radiation (PAR)/solar radiation ratio. Preliminary investigation has indicated that there may be seasonal variation in PAR/solar radiation (D. P. Bartholomew, unpublished data). Changes in PAR/solar radiation with season and latitude have been reported (Nathan, 1982; Meek et al., 1984).

IV. VALIDATION OF THE CERES MAIZE MODEL

4.1 Introduction

The model validation process involves running the model with independent data. Therefore, none of the experiments that had been used for model building or model calibration were used for this purpose. For most models of this complexity, insufficient data are available for testing without designing a specific experiment for that purpose. Models that do not perform reasonably when executed with realistic data may be eliminated, modified, or recalibrated. Thus, before designing expensive experiments to rigorously test the model, existing data was used to validate the model.

Test of reasonableness is complicated by type and amount of data required for model validation. The input data as well as the data required for comparison purpose should be realistic. Qualitative evaluation generally involves graphical display of observed and simulated values. A "good" model would have less scatter around the 1:1 line, and the points would be evenly distributed on either side of the 1:1 line. In general tables and plots are constructed and viewed as if they were possible outputs from the real system.

Since a simulation model is built to provide results that resemble the outputs from the real system, the statistical analysis from simulation is similar to the statistical analysis of data from an actual system. No general form of statistical analysis has been recommended for simulation models. A model is built for a specific purpose, and therefore the analysis is model-specific.

In the present chapter the CERES maize model is validated on data from Benchmark Soils Project experiments in Indonesia, the Philippines, and Hawaii. Data from Waimanalo Experimental Station and Maui Soil Climate Project is also included. The model is evaluated by: (i) qualitative comparison of observed and simulated data with the help of graphs and tables;
(ii) a statistical approach employing the sum of squares criterion (Wood and Cady, 1984); and (iii) Freese's chi-squared test (Reynolds, 1984).

4.2 Materials and Methods

4.2.1 Experimental Sites

The CERES maize model was validated with data from Benchmark Soils Project sites in Indonesia, the Philippines, and Hawaii. Two other sources of field data were from the Waimanalo Experimental Station, Oahu, Hawaii (Lee 1983), and the Soil Climate Project, Maui, Hawaii (Bartholomew, unpublished data).

The Waimanalo data was for six plant densities (5, 7.5, 12.5, 15.0, and 20.0 plants m^{-2}), with bimonthly plantings for two years. However, due to missing weather data the simulation was carried out for eight plantings only (Table 4.1). These experiments received 200 kg N ha^{-1}. P and other nutrients, as well as water, were considered non-limiting. The Maui experiments also had optimum treatments with 186 kg N ha^{-1} and drip irrigation.

The remaining experiments from the Benchmark Soils Project in most cases had 6 rates of applied N: 0, 29, 70, 108, 144 and 186 kg N ha^{-1}. These rates, however, were not the same for all Benchmark sites. Henceforth, coded N values (0, -0.85, -0.40, opt, +0.40, and +0.86) will be used to denote the amount of N applied (Appendix 3.2). Maize hybrid "X304C" (Pioneer Hi-Bred International) was used in the above experiments except those on the Hydric Dystrandept sites in Hawaii (Table 4.1) in which hybrid "H610" (=Ant 2D X B14A) was planted.

Table 4.1 Experiments used for validation of the CERES maize model.

Site/Block	Location	Planting Date	Season
	Tropeptic Eutrustox		
WAI-J84	Oahu, Hawaii	6/28/84	Dry
WAI-F10		11/17/82	Wet
MOL-L10	Molokai, Hawaii	6/08/82	Dry
MOL-M10		6/24/80	Dry
MOL-N10		5/20/81	Dry
MOL-N20		12/02/82	Wet
	Typic Palendult		
NAK-L10	South Sumatra, Indonesia	12/11/80	Wet
NAK-L20		11/25/81	Wet
NAK-A30		6/01/81	Dry
NAK-D30		6/12/81	Dry
NAK-O10		12/09/82	Wet
NAK-P10		12/16/82	Wet
BPMD-A30	South Sumatra, Indonesia	6/11/81	Dry
BPMD-C20		12/13/80	Wet
BPMD-C30		11/27/81	Wet
BPMD-C40		12/18/82	Wet
BPMD-D40		12/09/82	Wet

Table 4.1 (continued) Experiments used for validation of the CERES maize model.

Site/Block	Location	Planting Date	Season
	Typic Paleudult		
BUK-A30	South Sumatra, Indonesia	6/04/81	Dry
BUK-D20		6/04/81	Dry
BUK-A40		6/02/82	Dry
BUK-F10		5/19/82	Dry
BUK-C30		11/26/81	Dry
BUK-E20		12/02/81	Wet
BUK-E10		12/12/80	Wet
BUK-H10	South Sumatra, Indonesia	12/17/80	Wet
BUK-G10		12/11/82	Wet
SOR-A20	Luzon,Philippines	2/12/81	Wet
SOR-A30		2/13/82	Wet
SOR-B10		2/12/81	Wet
SOR-B20		2/09/82	Wet
SOR-E20		6/24/82	Dry
SOR-F10		6/24/82	Dry
DAV-L10		8/29/81	Dry
	Hydric Dystrandept		
LPHS-D30	Java, Indonesia	6/21/82	Dry
LPHS-G20		12/02/82	Wet

Table 4.1 (continued) Experiments used for validation of the CERES maize model.

Site/Block	Location	Planting Date	Season
	Hydric Dystrandept		
PUC-K20	Naga City, Philippines	6/22/81	Dry
PUC-Q40		1/29/82	Wet
PUC-Q50		1/05/83	Wet
PUC-R40		6/04/82	Dry
PUC-S20		2/06/81	Wet
PUC-S30		2/08/82	Wet
PUC-T10		1/18/83	Wet
PAL-D40	Camarines Sur, Philippines	6/05/82	Dry
PAL-F20		1/16/81	Wet
PAL-F30		1/30/82	Wet
PAL-F40		1/06/83	Wet
PAL-G30		2/06/82	Wet
BUR-E20		2/04/81	Wet
BUR-E30		2/22/82	Wet
IOLE-E10*	Hawaii	6/08/78	Dry
IOLE-I10*		2/12/79	Wet
IOLE-L10*		3/18/82	Dry
KUK-D11*		1/06/78	Wet
KUK-D20*		2/02/79/	Wet

Table 4.1 (continued) Experiments used for validation of the CERES maize model.

Site/Block	Location	Planting Date	Season
	Waimanalo Experimental Station		
Waimanalo	Oahu, Hawaii	Jan. 1980-July 1981	
	Soil Climate, Maui		
Niftal (77 MSL)	Maui, Hawaii	4/24/84	Dry
Hailemaile (340 MSL)		4/24/84	Dry
Kekoa (800 MSL)		4/24/84	Dry

* Maize hybrid H610 planted on these sites, at the remaining sites X304C variety was planted.

4.2.2 Laboratory Analysis

Soil nitrate and ammonium levels were not available for subsoil samples in many of the Benchmark Soils Project experiments. Profile samples from selected sites were analyzed for NH_4^+ and NO_3^- by magnesium oxide employing steam distillation with Devarda's alloy (Keeney and Nelson, 1982).

4.2.3 Statistical Validation Analyses

Validation is a crucial phase in the modeling work, and it is a continuous procedure. The fact that one or more validation tests indicate the model is performing adequately must not be considered the end of validation. The model predictions in the present study would be evaluated using (i) sum of squares, R test (Wood and Cady, 1984) and (ii) Freese statistic (Freese, 1960; Reynolds, 1984).

R Test

In general experimental data used for model validation had been generated using Completely Randomized Design (CRD) or Randomized Complete Block Design (RCBD). However, the model does not simulate the replication effect. Thus, simulated values presented in the present study are the same for all plots receiving the same treatment. For CRD experiments R_1 statistics could be used to assess the equivalence of simulated yields with observed yields (Wood and Cady, 1984):

$$R_1 = \frac{\sum_{i=1}^{t}\sum_{j=1}^{r}(Y_{ij} - X_i)^2}{\sum_{i=1}^{t}\sum_{j=1}^{r}(Y_{ij} - \bar{Y}_i)^2} \qquad (4.1)$$

where Y_{ij} = observed yield from treatment i and replicate j (i = 1,...t and j = 1,...r)

X_i = represents simulated yields from treatment i.

The null hypothesis for the above statistics is that there is no difference between the simulated result and treatment mean. The assumptions required for the F distribution (sums of squares criterion) are:

(i) the yield of experiment must follow a normal distribution with variance ^{2} and the mean yield correctly specified by the model,

(ii) both the numerator and denominator must be multiples of chi-square random variables, and

(iii) the numerator and denominator have to be statistically independent.

Equation (4.1) is modified such that assumption (iii) is not violated:

$$R_1\text{-}1 = \frac{\sum_{r=1}^{t}\sum_{j=1}^{r}(Y_{ij}-X_i)^2 - \sum_{i=1}^{t}\sum_{j=1}^{r}(Y_{ij}-\bar{Y}_i)^2}{\sum_{i=1}^{t}\sum_{j=1}^{r}(Y_{ij}-\bar{Y}_i)^2}$$

$$= \frac{r\sum_{i=1}^{t}(\bar{Y}_i-X_i)^2}{\sum_{i=1}^{t}\sum_{j=1}^{r}(Y_{ij}-\bar{Y}_i)^2} \qquad (4.2)$$

The correct normalization for R_1-1 is (r - 1) (R_1-1) (Wood and Cady, 1984). The above statistics follow the F-distribution with t and t(r - 1) degrees of freedom.

The R_1 statistic on modification could also be used for RCB designs. However, the underlying assumptions have not been tested (F.B. Cady, personal communication). Thus, in the current study the R_1 statistic was used for CRD.

Modified Freese Statistic

In order to determine the usefulness of a model it is necessary to know in some sense how "close" a predicted value X is likely to be to an observed value Y. Freese (1960) approach to determining the accuracy requirement is to have the user specify values e and a such that if

$$P(|D| \leq e) \geq 1 - a \tag{4.3}$$

Here $D_i = Y_i - X_i$ for i = 1, 2...n. The probability statement (4.3) is with respect to the unconditional distribution, i.e., plots selected at random from the complete population of all plots of interest. If the distribution of D is normal with E(D) = 0 and $D^2/Var(D)$ has a chi-squared distribution with one degree of freedom (1) then

$$P[D^2/Var(D) \leq \chi^2_{1-a}(1)] = 1 - a \tag{4.4}$$

where $\chi^2_{1-a}(V)$ represents 1-a quantile of the chi-squared distribution with V degrees of freedom and variance of D, Var(D). Since $\chi^2_{1-a}(1) = z^2_{1-a/2}$, where $z_{1-a/2}$ is the (1-a/2) quantile of the standard normal distribution, Equation (4.4) can be written as:

$$e^2 \geq \mathrm{Var}(D) z^2_{1-a/2}$$

or as

$$\mathrm{Var}(D) \leq e^2/z^2_{1-a/2} \qquad (4.5)$$

The model will be acceptable if the variance of D is no larger than $e^2/z^2_{1-a/2}$. The translation of error requirement (Eq. 4.3) into variance bound (Eq. 4.5) assumes the model is not biased, i.e., E(D) = 0, and that distribution is normal (Reynolds, 1984).

If the model is biased then Var(D) would need to be even smaller than found in Eq 4.5 and if the bias is large enough it may not be possible to meet the error requirement no matter how small the variance.

Having determined that Var(D) must satisfy Eq. 4.5, Freese (1960) proposed to test the null hypotheses:

$$H_o: \quad E(D) = 0 \text{ and } \mathrm{Var}(D) \geq e^2/\chi^2_{1-a}(1) \qquad (4.6)$$

If the null hypothesis is not rejected all that could be concluded is that there was not enough evidence to reject the null hypothesis. From the user's point of view, a more conservative approach would be to judge the technique as adequate only if there is strong evidence that it is as good as required (Reynolds, 1984).

$$H'_o: \quad \mathrm{Var}(D) \geq e^2/\chi^2_{1-a}(1)$$

This hypothesis would be rejected at significance level a' if

$$\sum_{i=1}^{n} D_i^2 \, {}^2_{1-a}(1)/e^2 \leq \chi \, {}^2_{a'}(n) \qquad (4.7)$$

i.e., if the test statistic is the lower tail of the chi-squared distribution. The model would then be accepted only if the test rejects so that the proof is put on the model.

In some cases, the user of a model may be more interested in the percentage error than in the absolute value of the error. The percent error is 100¶D/Y¶ and if the user specifies a value p such that the percent error should not be > 100 p with probability 1-a, then the requirement is that

$$P(\P D/Y\P \leq p) \geq 1 - a \tag{4.8}$$

If the unconditional distribution of D/Y (¶D/Y¶) is normal with mean 0 then the model would be considered acceptable only if

$$\sum_{i=1}^{n} D_i^2 \, \chi^2_{1-a}(1)/Y_i^2 p^2 \leq \chi^2_{a'}(n) \tag{4.9}$$

One problem with Freese's general approach is that different users of the model may have different accuracy requirements and thus may have different values of e. This critical error, e^*, would be the smallest value of e which will lead to the rejection of null hypothesis (i.e. acceptance of the model) that $Var(D) \geq e^2/z^2_{1-a/2}$. The value of e* is given by:

$$e^* = \left[\sum_{i=1}^{n} (D_i^2 \chi^2_{1-a}(1)/\chi^2_{a'}(n) \right]^{i/2} \tag{4.10}$$

The critical error e* thus gives a more conservative picture of the capabilities of the model. The critical percentage, p*, is similarly given as:

$$p^* = \left[\sum_{i=1}^{n} (D_i^2 \chi^2_{1-a}(1)/Y_i^2 \chi^2_{a'}(n) \right]^{1/2} \qquad (4.11)$$

Therefore, if the user specifies e or p values smaller than the critical then the model would be considered inappropriate.

If there is bias in the model, i.e., $E(D) \neq 0$, a procedure presented by Freese (1960) could be used. But before this test is used it is assumed that the bias in the model could be removed. Equation (4.7) would be modified to:

$$\sum_{i=1}^{n} (Z_i \chi^2_{1-a}(1)/e^2 \leq \chi^2_{a'}(n-1) \qquad (4.12)$$

where $Z_i = D_i^2 - nB^2$

and $B = \sum_{i=1}^{n} D_i/n$

Simalarly bias corrected critical error, e** would be:

$$e^{**} = \left[\sum_{i=1}^{n} (Z_i \chi^2_{1-a}(1)/\chi^2_{a'}(n-1) \right]^{1/2} \qquad (4.13)$$

4.3 Results and Discussion

4.3.1 Validation of the CERES maize model on Tropeptic Eutrustox sites

The CERES maize model was used to simulate six experiments on two Tropeptic Eutrustox sites in Hawaii. These experiments were not used in the previous chapter for calibration. The phenological events and grain yield predictions were compared with the observed results.

The model predicted that days to silking was at the most four days more than the observed days to tasseling (Table 4.2). The model predicts days to silking (end of vegetative stage) and does not consider tasseling as a phenological event. The experimental data, on the other hand, did not have observed days to silking, hence the comparison of predicted days to silking with observed days to tasseling (Table 4.2). The model accurately predicted the days to anthesis for winter and summer plantings at both the Waipio and Molokai sites in Hawaii. The observed difference for days to tasseling at Waipio for winter and summer plantings was 14 days, the model predicted 13 days difference for days to silking. Similarly the difference was about 16 days for both observed and simulated results at Molokai site. In addition to winter and summer differences the model predicted the delay in days to anthesis at the Molokai site (Table 4.2).

Days to physiological maturity was in general under-predicted by the model. However, it may well be that the days to physiological maturity which requires destructive sampling and observance of black layer was determined late in some of these experiments. For the MOL-N20 experiment, the physiological maturity date was not available

Table 4.2 Validation of simulated days to silking and days to physiological maturity with the observed data on Tropeptic Eutrustox sites in Hawaii.

Site/Block	Planting Date		Days After Planting	
			Silking*	Physiological Maturity
WAI-J84	06/28/84	Actual	60	113
		Simulated	64	115
WAI-F10	11/17/82	Actual	74	149
		Simulated	77	146
MOL-L10	06/08/82	Actual	63	122
		Simulated	64	114
MOL-M10	06/24/80	Actual	65	131
		Simulated	69	125
MOL-N10	05/20/81	Actual	68	141
		Simulated	71	127
MOL-N20	12/02/82	Actual	81	-
		Simulated	84	126

*Observed values are days to 50% tasseling.

probably because the crop was harvested early due to lodging. Although the observed phenological dates do not have any variance term with them the standard deviation would be about two days for summer plantings and probably more for the winter plantings. Thus, the model prediction seems to be reasonable.

At the Waipio site the observed variance in the grain yield was much lower than the variance in Molokai experiments (Table 4.3). In general at Molokai site the wind activity is high enough to affect plant growth in windward-facing plots, e.g., shredded leaves. In addition wind may be high enough to cause severe lodging (MOL-N20). Disease and pest damages though not severe in any of these experiments were consistently present.

The CERES model does not simulate the effect of pests and disease damage, wind damage, and nutrient deficiency (except N). Thus, as expected the model overestimated the grain yield for MOL-N20 experiment at all levels of N (Table 4.3). The overestimation was most severe for low N treatments. The low N plants probably had weaker stalks and were severely lodged. The field notes confirmed this. The predictions for many of the experiments were close to the actual results. In most cases the predicted values were within 20% of the actual yields. The model as illustrated in Figure 4.1 showed varying degrees of nitrogen response in all experiments. There was no significant response to N application in MOL-M10 experiment probably because the leaves were wind-damaged. The model, on the other hand, showed slight response to N application because it is driven by nitrogen and weather, but does not include wind speed (Figure 4.1).

Table 4.3 Validation of simulated grain yields with observed yields on two Tropeptic Eutrostox sites in Hawaii.

SITE		Coded N level (P, N)					
		Opt, 0	+.85, −.85	+.40, −.40	+.85, Opt	+ 40, + 40	+.85, +.85
WAI-J84[a]	Measured	-	-	-	-	-	11223
	Simulated						10923
WAI-F10	Measured	-	5115 ± 364	5917 ± 445	7903 ± 160	9299 ± 436	9271 ± 904
	Simulated		4742	6926	8810	9773	9818*
MOL-L10	Measured	4995 ± 726	6581 ± 1218	7314 ± 569	7372 ± 501	420 ± 508	8907 ± 689
	Simulated	5442*	6536*	7793*	8674	8998	8998*
MOL-M10	Measured	9867 ± 720	9349 ± 466	9796 ± 509	10487 ± 314	9914 ± 301	10606 ± 310
	Simulated	10046*	10920	12035	12176	1276	12176
MOL-N10	Measured	6551 ± 1937	6857 ± 1125	7521 ± 419	8460 ± 812	8038 ± 1162	9468 ± 1626
	Simulated	6071*	7354*	8994	9730	9118*	9918*
MOL-N20[b]	Measured	1139 ± 515	2308 ± 415	4405 ± 784	5098 + 894	4562 ± 634	7495 ± 100
	Simulated	6058	7905	8176	8176	8176	8176

[a] Unreplicated experiment with 300 kg N ha^{-1}.
* Simulated yields are within one standard deviation of mean yields.
[b] Lodging.

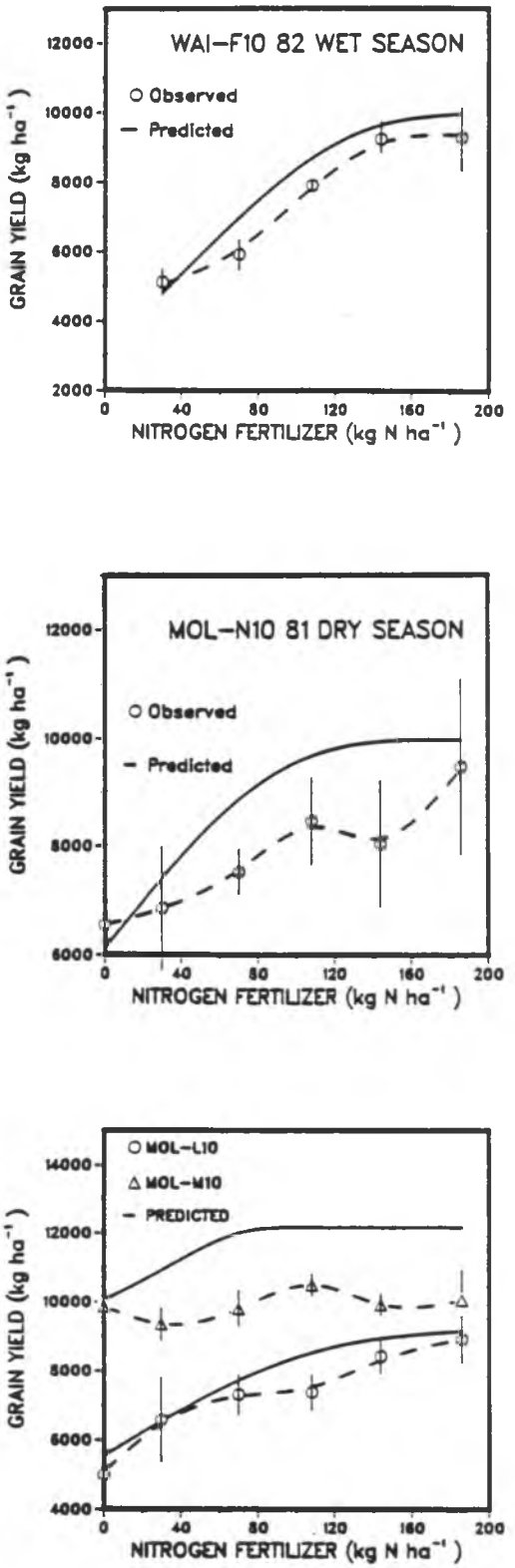


Figure 4.1 Comparison of observed (+ one standard deviation of observations) and simulated grain yield for four experiments from Tropeptic Eutrustox sites.

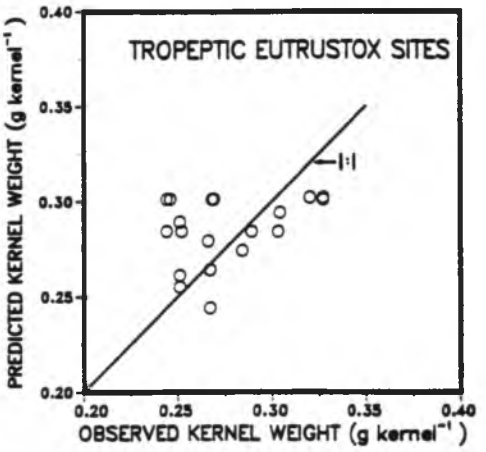
The grain weight predictions generally were not "close" to the actual predictions (Appendix 4.1). There was much scatter about the 1:1 line for grain weights (Figure 4.2a). However, the model prediction was not significantly different from the results obtained in the previous chapter (after calibrating the model to the observed data - Figure 3.14). In general the model did better with predicting kernels ear^{-1} (Appendix 4.2). However, as evident from Figure 4.2b the model overpredicted kernel numbers. The overpredictions are mainly for the high N treatments (Appendix 4.2). As explained in the previous chapter the overestimation seems justifiable.

The grain yield prediction for the experiments used for validation were similar to the prediction for calibration experiments (Figure 4.2c). Thus, the model calibration was appropriate for the Tropeptic Eutrustox sites as shown by the validation test. A better fit between observed and simulated results would have been possible if the model in the calibration stage was adjusted to fit the experimental data.

4.3.2. Validation of the CERES maize model prediction on Typic Paleudult sites

Data sets from five different sites in Indonesia and the Philippines were used to validate the CERES model. In the calibration of the CERES model none of the experiments from Typic Paleudult sites were used. Thus, the model was validated on data from

A



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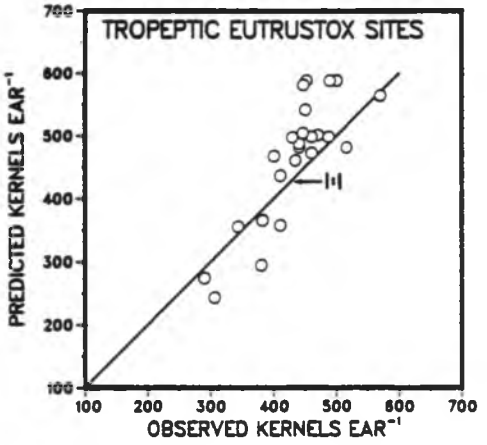

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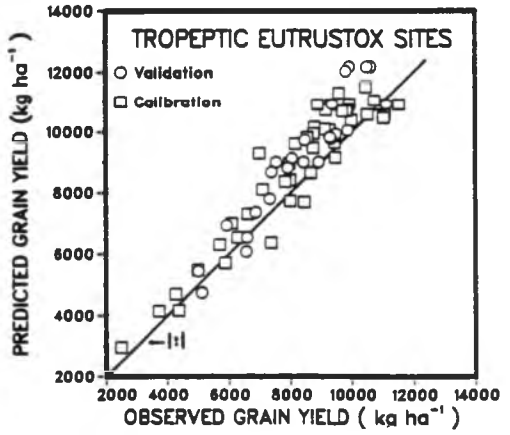


Figure 4.2 Comparison of observed and simulated (A) kernel weights, (B) kernel numbers, and (C) grain yield on Tropeptic Eutrustox sites.

The experiments were assumed to have: (i) optimal levels of all nutrients except N, (ii) complete irrigation throughout the growing season, and (iii) minimal disease, insect and pest damage. However, as evident from model predictions and confirmed by the field notes, a few of these experiments had encountered drought stress, disease and insect damage, and severe lodging.

For these sites, predicted days to silking were compared with observed days to tasseling. The model predicted that in general silking occurred about seven days after tasseling (Table 4.4). This may be longer than usually observed in the field. However, no data were available for these sites to validate the days to silking prediction. In NAK-L20 and BPMD-C20 the predicted days to silking were higher by about 15 days. The tasseling period for these experiments was spread over 12 days. Thus, the observed days to tasseling have large variance.

Physiological maturity predictions in general were close to the observed values. However, for the plants that had lodged or had faced drought stress the observed days to physiological maturity were shorter than predicted by the model (Table 4.4). It had been reported that stem rot (associated with K deficiency) leads to early maturity in corn (Aldrich et al., 1982). Likewise water stress during the grain filling stage tends to reduce the days to physiological maturity. Therefore, in BPMD-A30, BUK-A40, and BUK-F10 experiments which had encountered drought stress the physiological maturity was earlier by four to twelve days with respect to the predicted date. The reduction in supply of assimilates to these plants may have enhanced early maturity. Also, a

Table 4.4 Validation of simulated days to silking and days to physiological maturity with the observed data on Typic Paleudult sites in Indonesia and the Philippines.

Site/Block	Planting Date		Days After Planting	
			Silking*	Physiological Maturity
NAK-L10	12/11/80	Observed	53	111
		Simulated	59	104
NAK-L20	11/25/81	Observed	54	110
		Simulated	67	119
NAK-A30	06/01/81	Observed	57	103
		Simulated	61	106
NAK-D30	06/12/81	Observed	52	102
		Simulated	63	108
NAK-010	12/09/82	Observed	52	100
		Simulated	57	99
NAK-P10	12/16/82	Observed	47	97
		Simulated	55	97
BPMD-A30[a]	06/11/81	Observed	53	95
		Simulated	63	110
BPMD-C20	12/13/80	Observed	55	104
		Simulated	72	121
BPMD-C30	11/27/81	Observed	52	107
		Simulated	62	106
BPMD-C40	12/18/82	Observed	54	100
		Simulated	60	107

Table 4.4 (continued) Validation of simulated days to silking and days to physiological maturity with the observed data on Typic Paleudult sites in Indonesia and the Philippines.

Site/Block	Planting Date		Days After Planting	
			Silking*	Physiological Maturity
BPMD-D40	12/09/82	Observed	50	98
		Simulated	61	107
BUK-A30	06/04/81	Observed	57	109
		Simulated	59	104
BUK-D20	06/04/81	Observed	57	105
		Simulated	59	104
BUK-A40[a]	06/02/82	Observed	61	110
		Simulated	65	114
BUK-F10[a]	05/19/82	Observed	59	104
		Simulated	64	116
BUK-C30	11/26/81	Observed	58	110
		Simulated	68	122
BUK-E20	12/02/81	Observed	61	116
		Simulated	69	122
BUK-E10	12/12/80	Observed	55	106
		Simulated	62	108
BUK-H10	12/17/80	Observed	59	114
		Simulated	69	116
BUK-G10	12/11/82	Observed	56	107
		Simulated	65	112

Table 4.4 (continued) Validation of simulated days to silking and days to physiological maturity with the observed data on Typic Paleudult sites in Indonesia and the Philippines.

Site/Block	Planting Date		Days After Planting	
			Silking*	Physiological Maturity
SOR-A20	02/12/81	Observed	58	103
		Simulated	62	105
SOR-A30[b,c]	02/13/82	Observed	64	112
		Simulated	73	122
SOR-B10	02/12/81	Observed	60	103
		Simulated	62	105
SOR-B10[b,c]	02/09/82	Observed	65	113
		Simulated	73	123
SOR-E20[b]	06/24/82	Observed	59	108
		Simulated	66	117
SOR-F10[b]	06/24/82	Observed	58	105
		Simulated	66	117
DAV-L10	08/29/81	Observed	50	107
		Simulated	58	106

[a] Water stress.

[b] Moderate to severe lodging.

[c] Stem rot.

good management practice is to harvest the lodged crop as soon as possible to avoid rotting of grain. Thus, lodged experiments may have been harvested before the physiological maturity date.

As illustrated in a later section (4.3.6) the phenological development is highly sensitive to temperature. Errors in temperature recording therefore, would lead to erroneous prediction of phenological dates.

The grain yield predictions for the normal experiments were good. The model was able to predict yields ranging from 2500 to 10,000 kg ha^{-1}. The predictions were either within a standard deviation or within 10 to 15 percent of the mean yields (Table 4.5). However, for the experiments which had lodging, water stress, severe disease or stalk rot problems the predicted grain yields were too high (Table 4.5). After eliminating the drought-affected and lodged experiments the model still predicted higher yields (Figure 4.3). The model had been calibrated to predict yields higher than observed. This bias was due to the fact that the CERES model did not simulate disease and insect damage and competition with weeds. Thus, if the 1:1 line had an intercept of 500 kg ha^{-1}, the fit between the observed and simulated results would have been better.

The CERES maize model was able to simulate N response at all the Typic Paleudult sites. At the Nakau site in Sumatra, Indonesia, the model predicted yields ranging from 2500 kg ha^{-1} to 10,000 kg ha^{-1} with reasonable accuracy. The model was also able to simulate consistently higher yields for the wet season-plantings (Table 4.5 and Figure 4.4). Temperature and solar radiation were more favorable for

Table 4.5 Validation of simulated grain yields with observed yields on Typic Paleudult sites in Indonesia and Philippines.

SITE		Coded N level (P, N)					
		Opt, 0	+.85, -.85	+.40, -.40	+.85, Opt	+.40, +.40	+.85, +.85
NAK-L10[a]	Measured[b]						10661 ± 670
	Simulated						10387*
NAK-L20	Measured	5710 ± 793	6343 ± 1002	7341 ± 362	7880 ± 203	8228 ± 207	8338 ± 1118
	Simulated	6085*	7209*	8318	8931	8934	8934*
NAK-A30	Measured	3705 ± 700	4620 ± 32	4977 ± 263	5009 ± 381	5191 ± 323	6223 ± 1597
	Simulated	3456*	4975	6675	7520	7768	7768*
NAK-D30	Measured	2473 ± 204	4322 ± 486	5926 ± 566	6169 ± 887	5958 ± 225	6346 ± 346
	Simulated	3283	4695*	6285*	7341	7785	7797
NAK-010	Measured	5871 ± 833	8028 ± 671	7129 ± 1208	8240 ± 390	8191 ± 479	9834 ± 383
	Simulated	7533	8333*	9132	9522	9614	9614*
BPMD-A30[c]	Measured	3427 ± 480	3723 ± 600	3864 ± 112	3583 ± 276	4524 ± 188	4446 ± 189
	Simulated	6143	6927	7727	7982	7982	7982
BPMD-C20	Measured	5671 ± 647	7058 ± 842	7457 ± 715	8728 ± 250	8082 ± 637	8737 ± 984
	Simulated	5561*	6463*	7647*	8396	8753	8938*
BUK-E10[a]	Measured						8856 ± 603
	Simulated						8871*
BUK-H10[a]	Measured						9238 ± 480
	Simulated						8991*
BUK-G10[a]	Measured						9283 ± 456
	Simulated						8225

Table 4.5 (continued) Validation of simulated grain yields with observed yields on Typic Paleudult sites in Indonesia and Philippines.

SITE		Coded N level (P, N)					
		Opt, 0	+.85, -.85	+.40, -.40	+.85, Opt	+.40, +.40	+.85, +.85
SOR-A20	Measured	3693 ± 1119	5144 ± 1746	6216 ± 681	6766 ± 826	6609 ± 455	7798 ± 1104
	Simulated	3958*	5375*	6890*	8031	8295	8295*
SOR-A30[d,e]	Measured	2475 ± 1911	5079 ± 1236	5400 ± 186	6146 ± 706	6763 ± 148	6715 ± 816
	Simulated	3365*	4916*	6546	7713	8713	9451
SOR-B10	Measured	3297 ± 1175	3518 ± 335	5254 ± 447	6532 ± 552	6479 ± 158	77245 ± 759
	Simulated	3472*	4972	6607	7757	8295	8295*
SOR-B20[d,e]	Measured	3900 ± 756	4949 ± 582	5738 ± 318	7101 ± 526	6697 ± 5990	7651 ± 816
	Simulated	4025*	5392*	7051	8254	9144	9650
SOR-E20[d]	Measured	2411 ± 372	3753 ± 381	3756 ± 208	4989 ± 662	40735 ± 272	5000 ± 249
	Simulated	3322	4658	6059	6145	6145	6145
SOR-F10[d]	Measured	2527 ± 143	4435 ± 658	4786 ± 910	5299 ± 571	5304 ± 292	6415 ± 499
	Simulated	3322	4658*	6059	6145	6145	6145*
BPMD-C30	Measured	2181 ± 867	3830 ± 813	5320 ± 624	6314 +283	7147 ± 631	7402 ± 837
	Simulated	3176	4824	6592	7836	8002	8008*
BPMD-C40	Measured	5392 ± 535	5936 ± 167	6631 ± 820	7889 ± 664	7756 ± 1050	7867 ± 1040
	Simulated	4743*	5907*	7284*	8033*	8219	8219*
BPMD-D40	Measured	5785 ± 698	6212 ± 556	8317 ± 1998	8502 ± 514	8399 ± 407	8599 ± 1279
	Simulated	5686*	6693*	7750*	8160*	8162*	8162*
BUK-A30[a]	Measured						6114 ± 281
	Simulated						7476

Table 4.5 (continued) Validation of simulated grain yields with observed yields on Typic Paleudult sites in Indonesia and Philippines.

SITE		Coded N level (P, N)					
		Opt, 0	+.85, -.85	+.40, -.40	+.85, Opt	+.40, +.40	+.85, +.85
BUK-A40[c]	Measured						5938 ± 339
	Simulated						7476
BUK-F10[c]	Measured						2415 ± 230
	Simulated						8407
BUK-C30[a]	Measured						8519 ± 456
	Simulated						8249*
BUK-E20[a]	Measured						8089 ± 848
	Simulated						8500*
DAV-L10	Measured		6055 ± 249	7676 ± 418	8226 ± 559	8235 ± 274	8454 ± 310
	Simulated		6351	7680*	8510*	8844	8965

[a] Initial soil nitrogen level not known.
[b] Mean yields ± one standard deviation of observations.
* Simulated yields are within one standard deviation of observed mean yields.
[c] Plants came under water stress.
[d] Moderate to severe lodging.
[e] Stem rot.

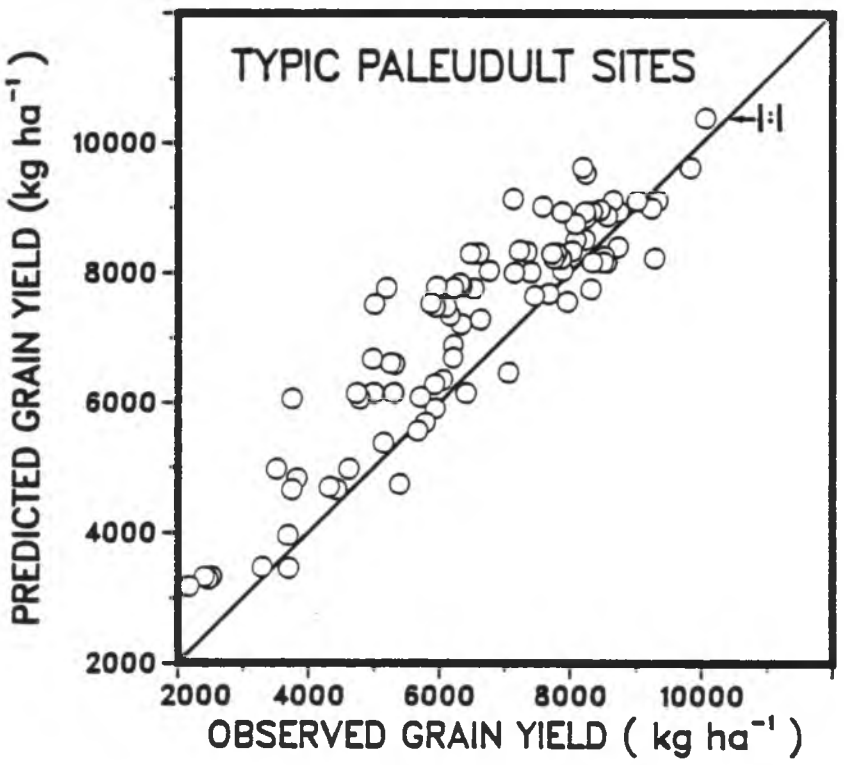


Figure 4.3 Comparison of observed and simulated grain yields on Typic Paleudult sites in Indonesia and Philippines.

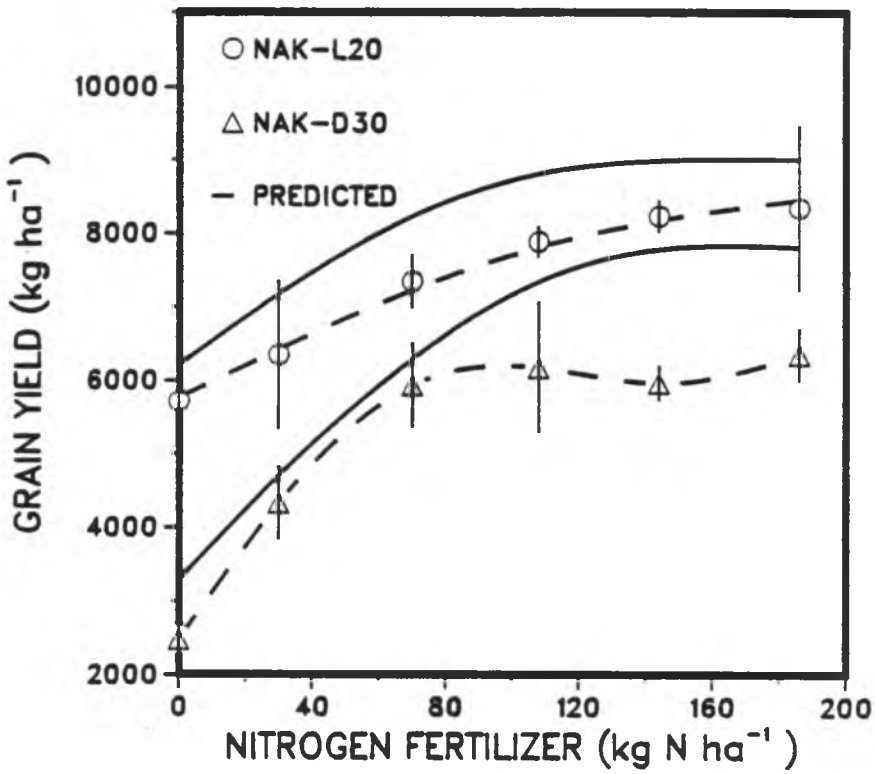


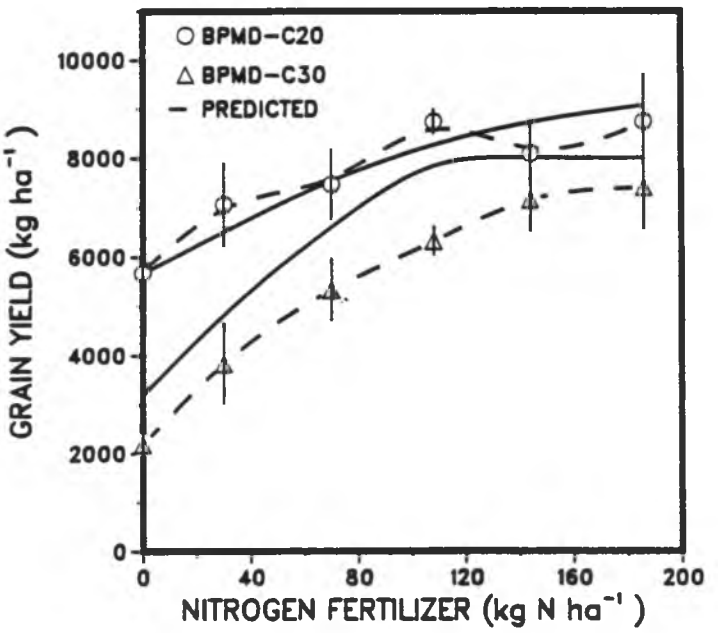
Figure 4.4 Comparison of observed (± one standard deviation of observations) and simulated grain yield at Nakau site (Indonesia) with N application.

the November-December planting. In NAK-L20 and NAK-D30 experiments the simulated yields in general were higher than the observed yields (Figure 4.4). Part of the overprediction is attributed to infection by downy mildew (Scherospora sorghi). The lower yields in NAK-D30 at zero nitrogen application may be due to N-induced deficiency of some other nutrients, e.g., P. This effect may not have occurred in the NAK-L20 experiment because the initial soil nitrogen level was higher.

The N response to three experiments on BPMD site, Sumatra, Indonesia is shown in Figure 4.5. On BPMD-A30 experiment the model predictions were twice as high. The difference is due to drought stress. On the other hand, the model assumed complete irrigation. This example shows the need to validate the model with sound data.

The model predictions on two experiments SOR-A20, Luzon and DAV-L10, Mindano, the Philippines are shown in Figure 4.6. The model correctly simulated the effect of leaching due to heavy rain in these experiments. Thus, simulated results were close to the actual yields in both experiments (Figure 4.6).

Analysis of grain yield components showed that kernel weights were not accurately predicted by the model (Appendix 4.3). Although there is much scatter as expected from the small range of kernel weights, in general the model did not over- or underestimate the kernel weights (Figure 4.7a). The simulated kernel numbers were in good agreement with the actual values (Figure 4.7b). However, the simulated values tend to be higher than the observed (Figure 4.7b and Appendix 4.4). The model simulated a wide range of (100 to 600) kernels ear^{-1} with reasonable closeness to the actual values.



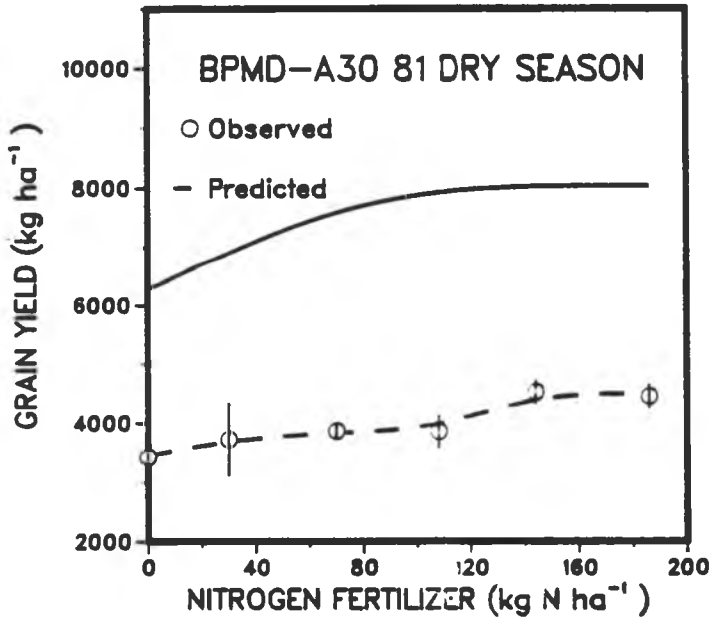


Figure 4.5 Comparison of observed (± one standard deviation of observations) and simulated grain yield with N application at BPMD, Indonesia.

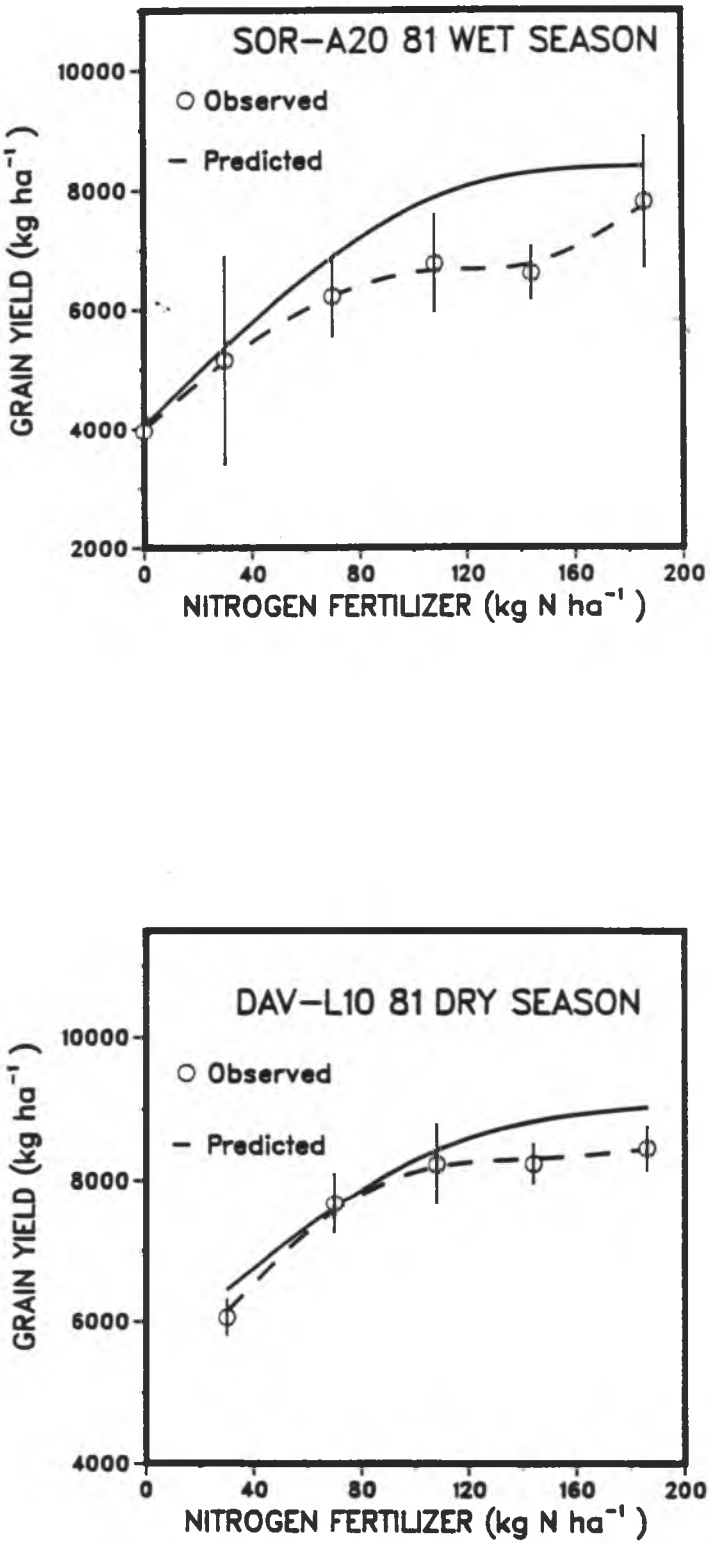
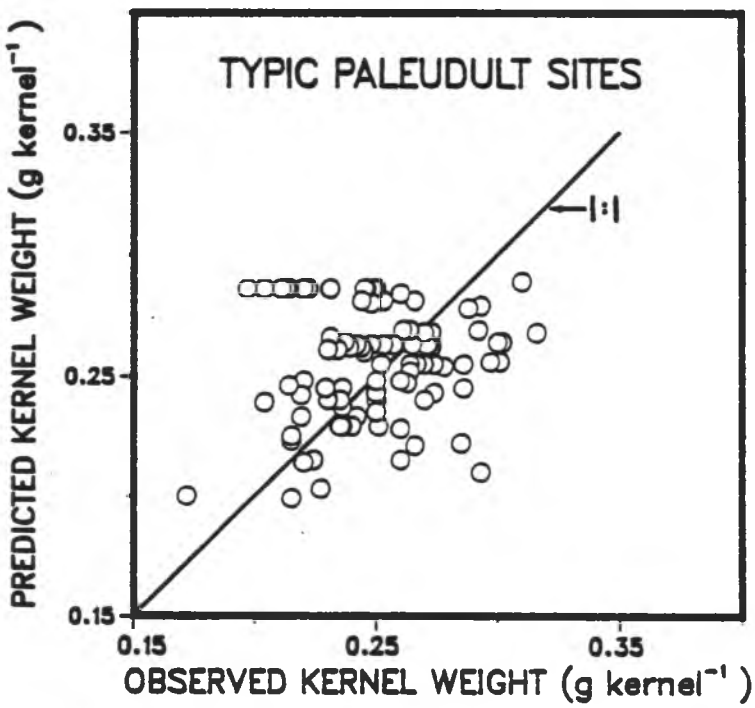


Figure 4.6 Comparison of observed (± one standard deviation of observations) and simulated grain yield with N application at two sites in the Philippines.

A



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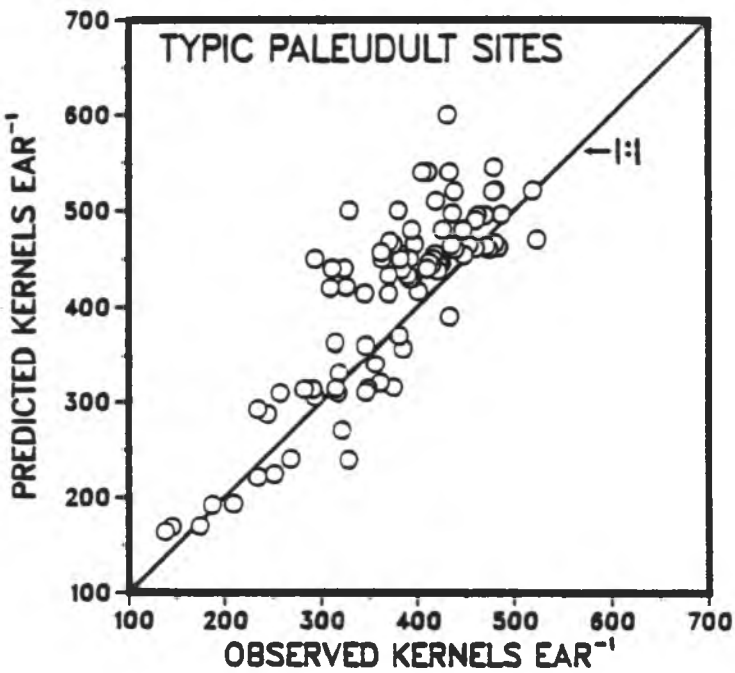


Figure 4.7 Comparison of observed and simulated (A) kernel weights and (B) kernel numbers on Typic Paleudult sites.

4.3.3 Validation of the CERES maize model prediction on Hydric Dystrandept sites

The validation on Hydric Dystrandept sites involved experiments from Indonesia, the Philippines, and Hawaii. These experiments were from one site in Indonesia, three in the Philippines, and two in Hawaii (Table 4.1).

The simulated days to silking as well as to physiological maturity were in close agreement with actual days for most of the experiments. The largest deviations occurred in experiments which were affected by water stress, lodging or stalk rot (Table 4.6). On the average, simulated days to silking occurred four days after the observed tasseling date. The predicted days to anthesis therefore, seems reasonable.

The seasonal variation in days to tasseling due to latitudinal difference ranged from 5 days in Indonesia, 10-12 days in the Philippines and as high as 19 days in Hawaii. Likewise the model predictions for difference in days to anthesis were 5 days in Indonesia, up to 12 days in the Philippines, and as high as 19 days for the Hawaiian experiments. Thus, the model accurately simulated the effect of seasons on phenological development of the maize plant. Maize hybrid, X304C was planted in Indonesia and the Philippines while the hybrid H610 was grown in Hawaii. The model also simulated the genetic differences between the two cultivars accurately.

Physiological maturity occurred earlier in experiments which were affected by water stress or had lodging of plants. Otherwise model predictions were close to the observed results.

Table 4.6 Validation of simulated days to silking and days to physiological maturity with the observed data on Hydric Dystrandept sites in Indonesia, the Philippines and Hawaii.

Site/Block	Planting Date		Days After Planting	
			Silking*	Physiological Maturity
LPHS-D30[a]	06/21/82	Observed	80	147
		Simulated	86	158
LPHS-G20	12/02/82	Observed	75	139
		Simulated	81	143
PUC-K20[b]	06/22/81	Observed	64	115
		Simulated	76	125
PUC-Q40	01/29/82	Observed	68	117
		Simulated	72	122
PUC-Q50[c]	01/05/83	Observed	66	125
		Simulated	66	122
PUC-R40[b]	06/04/82	Observed	62	105
		Simulated	66	120
PUC-S20	02/06/81	Observed	68	115
		Simulated	70	122
PUC-S30	02/08/82	Observed	70	120
		Simulated	73	126
PUC-T10	01/18/83	Observed	73	132
		Simulated	68	122
PAL-D40[b]	06/05/82	Observed	60	112
		Simulated	64	119

Table 4.6 (continued) Validation of simulated days to silking and days to physiological maturity with the observed data on Hydric Dystrandept sites in Indonesia, the Philippines and Hawaii.

Site/Block	Planting Date		Days After Planting	
			Silking*	Physiological Maturity
PAL-F20[b]	01/16/81	Observed	69	120
		Simulated	72	122
PAL-F30	01/30/82	Observed	68	123
		Simulated	68	118
PAL-F40	01/06/83	Observed	65	118
		Simulated	68	118
PAL-G30	02/06/82	Observed	69	125
		Simulated	69	118
BUR-E20[b]	02/04/81	Observed	71	124
		Simulated	72	122
BUR-E30[b,d]	02/22/82	Observed	70	123
		Simulated	71	121
IOLE-E10	06/08/78	Observed	72	-
		Simulated	78	140

Table 4.6 (continued) Validation of simulated days to silking and days to physiological maturity with the observed data on Hydric Dystrandept sites in Indonesia, Philippines and Hawaii.

Site/Block	Planting Date		Days After Planting	
			Silking*	Physiological Maturity
IOLE-I10	02/12/79	Observed	91	-
		Simulated	96	160
IOLE-L10	05/18/82	Observed	72	121
		Simulated	77	132
KUK-D11	01/06/78	Observed	83	160
		Simulated	85	150
KUK-D20	02/02/79	Observed	84	-
		Simulated	80	145

[a] Volcanic ash fall.

[b] Lodging.

[c] Water stress.

[d] Stalk rot.

The predicted grain yields on Hydric Dystrandept sites were higher than the observed yields (Figure 4.8). In LPHS-D30 experiment the simulated results showed marked response to applied nitrogen (Figure 4.9). However, the observed results were quite contrary. Although this experiment had some weeds and disease incidence, the main problem was low solar radiation. The plants were receiving less light than recorded by the weather station, firstly, because some of the plots were shaded by nearby bamboo trees (J. A. Silva, personal communication) and secondly, four weeks after emergence the leaves were covered with volcanic ash. The ash fall continued until the tasseling stage. In the LPHS-G20 experiment there was no insect, disease, or lodging damage. However, at higher rates of N application, viz., 144 and 186 kg N ha^{-1}, the observed yields seemed affected by nutrient deficiency or some other external factor (Table 4.7). At these rates predicted values were higher by about 30%.

At the PUC site, in the Philippines the observed yields ranged from 2760 kg ha^{-1} to 10365 kg ha^{-1}. The lower yields were attributed to typhoon damage and water stress. The model correctly simulated the high yielding as well as the low yielding experiments (Figure 4.10). The results indicated that in some locations, year to year variation in yield may be as large as the seasonal variation for the same month planting (Figure 4.10). Both these experiments were planted in January but in different years.

In general the simulated yields for zero nitrogen or -0.85 treatments were higher than the observed yields (Table 4.7). In the Andisols (e.g. Hydric Dystrandept) the time lag between soil sampling

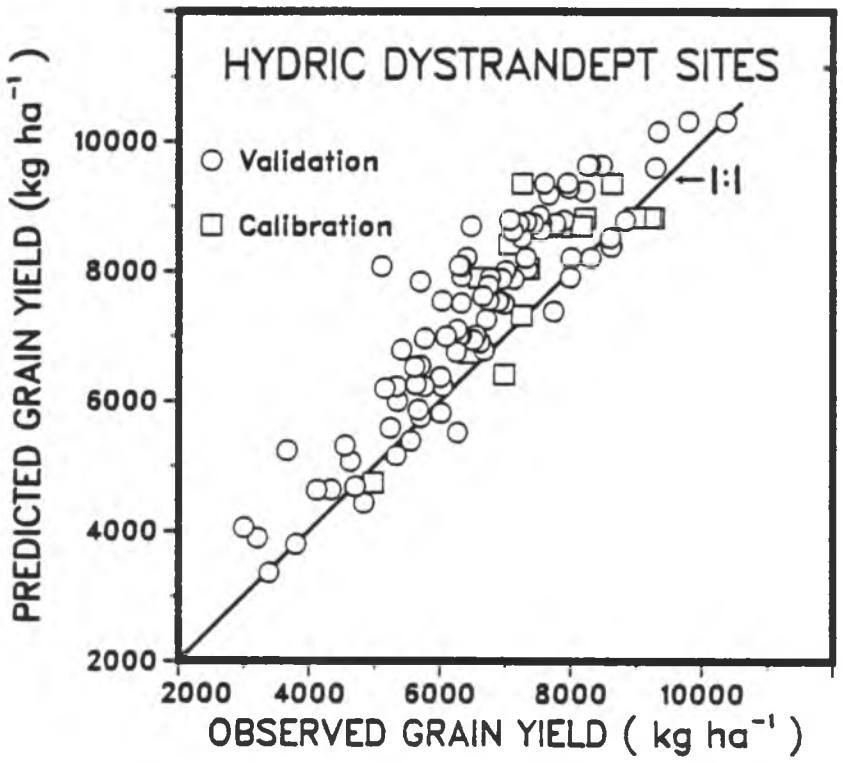


Figure 4.8 Comparison of observed and simulated grain yields as obtained from calibration and validation of the CERES maize model on Hydric Dystrandepts.

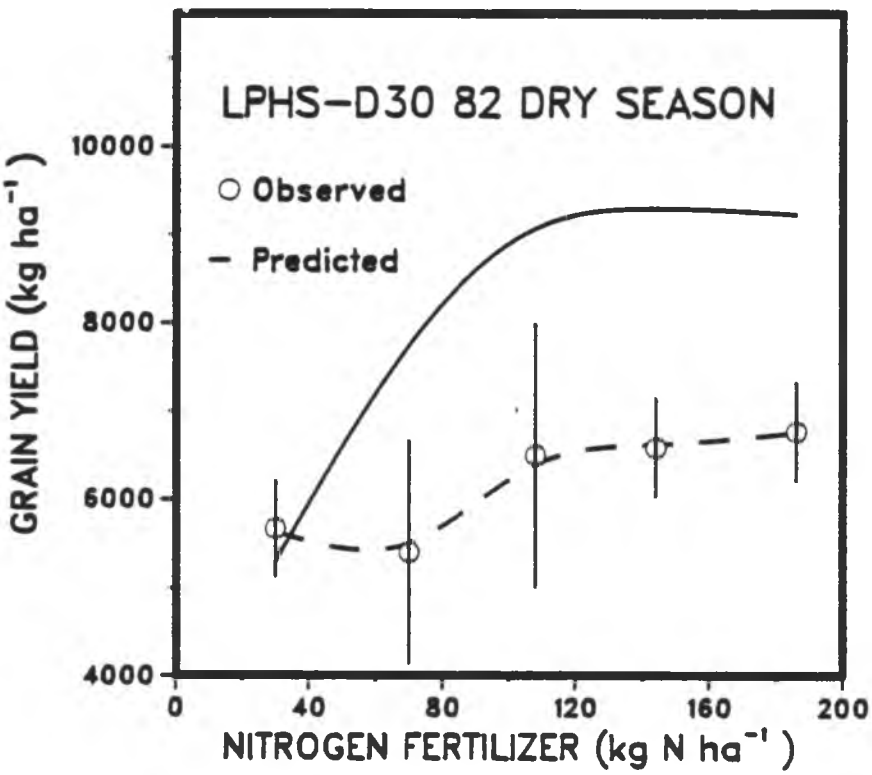


Figure 4.9 Comparison of observed and simulated grain yield where the observed yield was influenced by shading and volcanic ash fall.

Table 4.7 Validation of simulated grain yields with observed yields on Hydric Dystrandept sites in Indonesia, Philippines and Hawaii.

SITE		Coded N level (P, N)					
		Opt, 0	+.85,-.85	+.40,-.40	+.85, Opt	+.40,+.40	+.85,+.85
LPHS-D30[b]	Measured[a]		5663 ± 542	5397 ± 1262	6491 ± 1489	6575 ± 558	6758 ± 562
	Simulated		5215*	7789	9164	9210	9210
LPHS-G20	Measured	3384 ± 783	4331 ± 906	5630 ± 1235	5694 ± 1596	5102 ± 469	6323 ± 686
	Simulated	3354*	4630*	6249*	7834*	8069	8072
PUC-K20	Measured		5233 ± 480	5698 ± 183	6322 ± 601	6327 ± 393	6289 ± 545
	Simulated		5580*	6537	7501	7914	8081
PUC-Q40	Measured	3206 ± 1042	5325 ± 713	6247 ± 607	6767 ± 64	7544 ± 476	7517 ± 444
	Simulated	3886*	5156*	6750*	7890	8625	8856
PUC-Q50[c]	Measured	2952 ± 1011	5685 ± 1100	5134 ± 797	5980 ± 272	6674 ± 572	6960 ± 765
	Simulated	4003	5755*	7672	8812	9648	9648
PUC-R40[d]	Measured	2768 ± 327	4118 ± 785	4982 ± 43	5671 ± 748	5645 ± 556	5742 ± 389
	Simulated	3513	4779*	6050	6877	7293	7413
PUC-S20	Measured	3798 ± 2079	3660 ± 557	6677 ± 311	7991 ± 454	7274 ± 410	8601 ± 68
	Simulated	3792*	5234	6776*	7902*	8512	8512
PUK-S30	Measured	2994 ± 371	4545 ± 307	6510 ± 486	7328 ± 743	7064 ± 569	7973 ± 219
	Simulated	4048	5310	6930*	8030*	8788	9280
PUC-T10	Measured	7738 ± 1078	8619 ± 160	9286 ± 288	9329 ± 160	9790 ± 564	10365 ± 229
	Simulated	7372*	8376	9596*	10154*	10312*	10312*

Table 4.7 (continued) Validation of simulated grain yields with observed yields on Hydric Dystrandept sites in Indonesia, Philippines and Hawaii.

SITE		Coded N level (P, N)					
		Opt, 0	+.85,-.85	+.40,-.40	+.85, Opt	+.40,+.40	+.85,+.85
PAL-D40[d]	Measured	4628 ± 166	5664 ± 186	5609 ± 464	6613 ± 346	6324 ± 867	6459 ± 333
	Simulated	5067	1861*	65222	6897	7001	7001
PAL-F20[d]	Measured	6002 + 115	6701 ± 376	6409 ± 364	7426 ± 362	7205 ± 362	7540 ± 72
	Simulated	6364	7250	8204	8732	8732	8732
PAL-F30	Measured	4701 ± 399	6009 ± 139	5763 ± 791	6745 ± 317	6025 ± 619	6902 ± 451
	Simulated	4679*	5811	6956	7536	7536	7536
PAL-F40	Measured	5346 ± 522	6259 ± 543	7000 ± 96	8002 ± 368	7309 ± 65	8302 ± 648
	Simulated	5990	7093	8000	8201*	8201	8201*
PAL-G30	Measured	4114 ± 517	5701 ± 625	6088 ± 292	6652 ± 365	7129 ± 783	6941 ± 6
	Simulated	4625*	5745*	6989	7612	7876*	7876
BUR-E20[d]	Measured	5409 ± 393	6739 ± 941	7319 ± 929	8205 ± 291	7594 ± 459	7950 ± 533
	Simulated	6782	7772	8755	9229	9350	9357
BUR-E30[d,e]	Measured	2074 ± 494	5128 ± 462	4211 ± 598	4889 ± 547	3831 ± 906	4130 ± 781
	Simulated	5407	6378	7548	8170	8296	8296
IOLE-E10	Measured		6263	6980	7113	6478	7768
	Simulated		5510	7490	8618	8691	8691

Table 4.7 (continued) Validation of simulated grain yields with observed yields on Hydric Dystrandept sites in Indonesia, Philippines and Hawaii.

SITE		Coded N level (P, N)					
		Opt, 0	+.85, -.85	+.40, -.40	+.85, Opt	+.40, +.40	+.85, +.85
IOLE-L10	Measured		4833 ± 335	5151 ± 293	5755 ± 178	5325 ± 364	6037 ± 271
	Simulated		4427	6189	6221	6221	6221*
KUK-D11	Measured		6293 ± 1637	7663 ± 718	8254 ± 522	8291 ± 245	8471 ± 354
	Simulated		6988*	9178	9633	9633	9633
KUK-D20	Measured		5546 ± 807	6889 ± 1049	7766 ± 1079	7892 ± 636	8828 ± 365
	Simulated		5381*	7524*	8735*	8783	8783*

[a] Mean yields ± one standard deviation of observations.
* Simulated yields are within one standard deviation of observed mean yields.
[b] Volcanic ash fall.
[c] Water stress.
[d] Lodging.
[e] Pest damage.

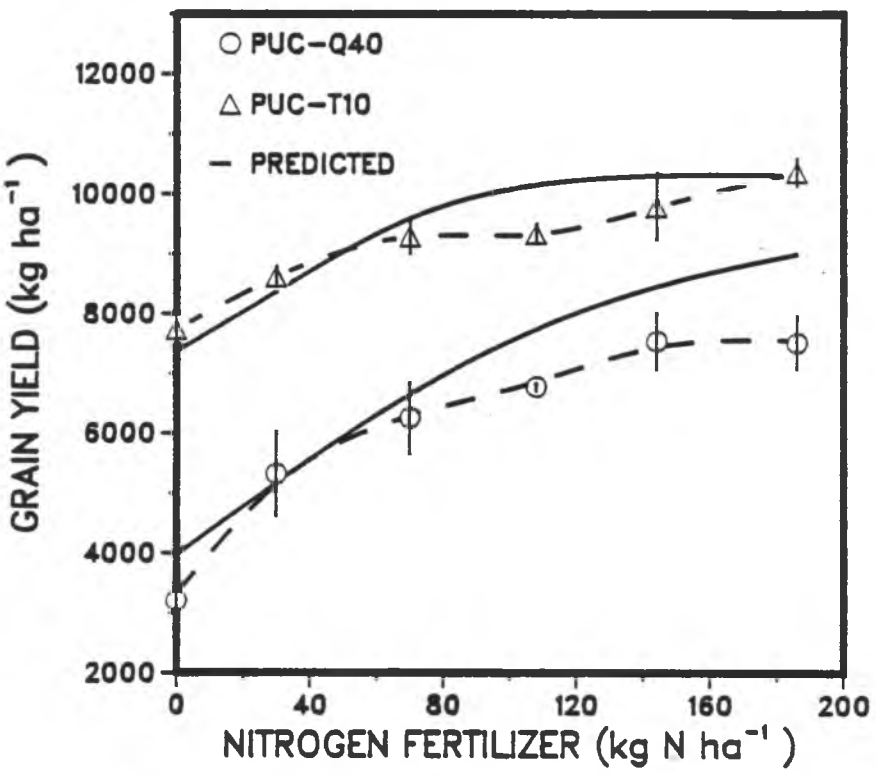


Figure 4.10 Comparison of observed (± one standard deviation of observations) and simulated grain yield with N application at PUC site, Philippines.

laboratory analyses for NO_3^- and NH_4^+ may have resulted in mineralization of large amounts of organic N. The laboratory-determined soil NO_3^- and $NH4^+$ levels therefore, would be considerably higher than the field levels. This error in initial soil N determination therefore, explains some of the anamolies in simulated results (Figure 4.11)

For BUR-E30 experiment the predicted results were twice as high as the observed (Table 4.7). This experiment was partially damaged by a typhoon and there was a significant amount of grain loss due to pests (rats and birds).

The CERES model predictions for grain yield were not close to the observed yield for the H610 cultivar (Figures 4.12 and 4.13). For the KUK-D11 experiment the model predictions were higher than the observed (Figure 4.12a). On the KUK-D20 experiment the model predictions were much better (Figure 4.12b). The KUK-D11 is a residual phosphorus experiment and this nutrient may have been deficient. The yields in the IOLE-L10 experiment were lower than the simulated yields because there was a severe infestation of Northern leaf blight (Helminthosporium turcicum) during the grain filling stage (Figure 4.13).

As with the previous soil families, the grain weight predictions for the Hydric Dystrandept sites were not good (Appendix 4.5). There was much scatter around the 1:1 line (Figure 4.14a). This is more apparent because of the short range in observed and simulated kernel weights. On the other hand the model did better with kernel number

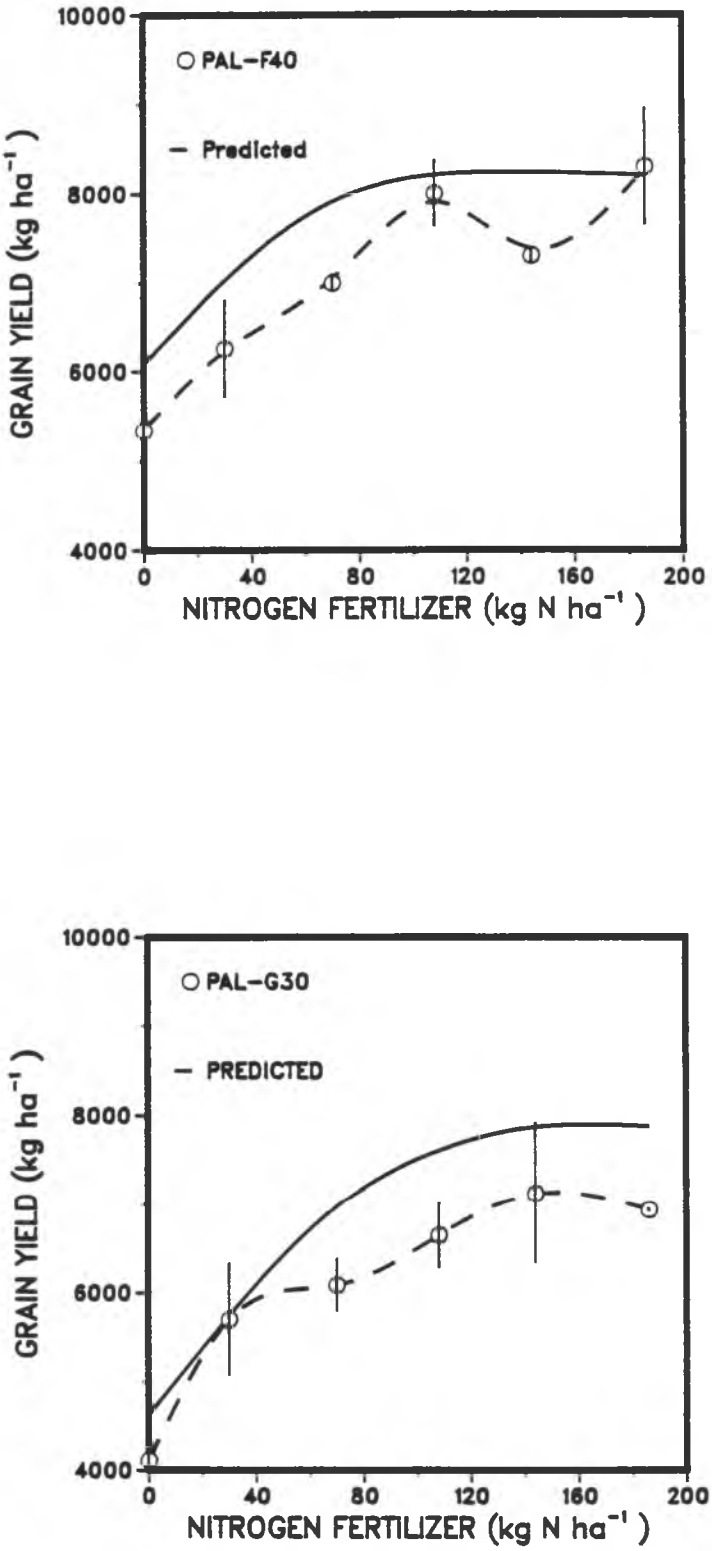


Figure 4.11 Comparison of observed (± one standard deviation of observations) and simulated grain yield with N application at Palestina site, Philippines.

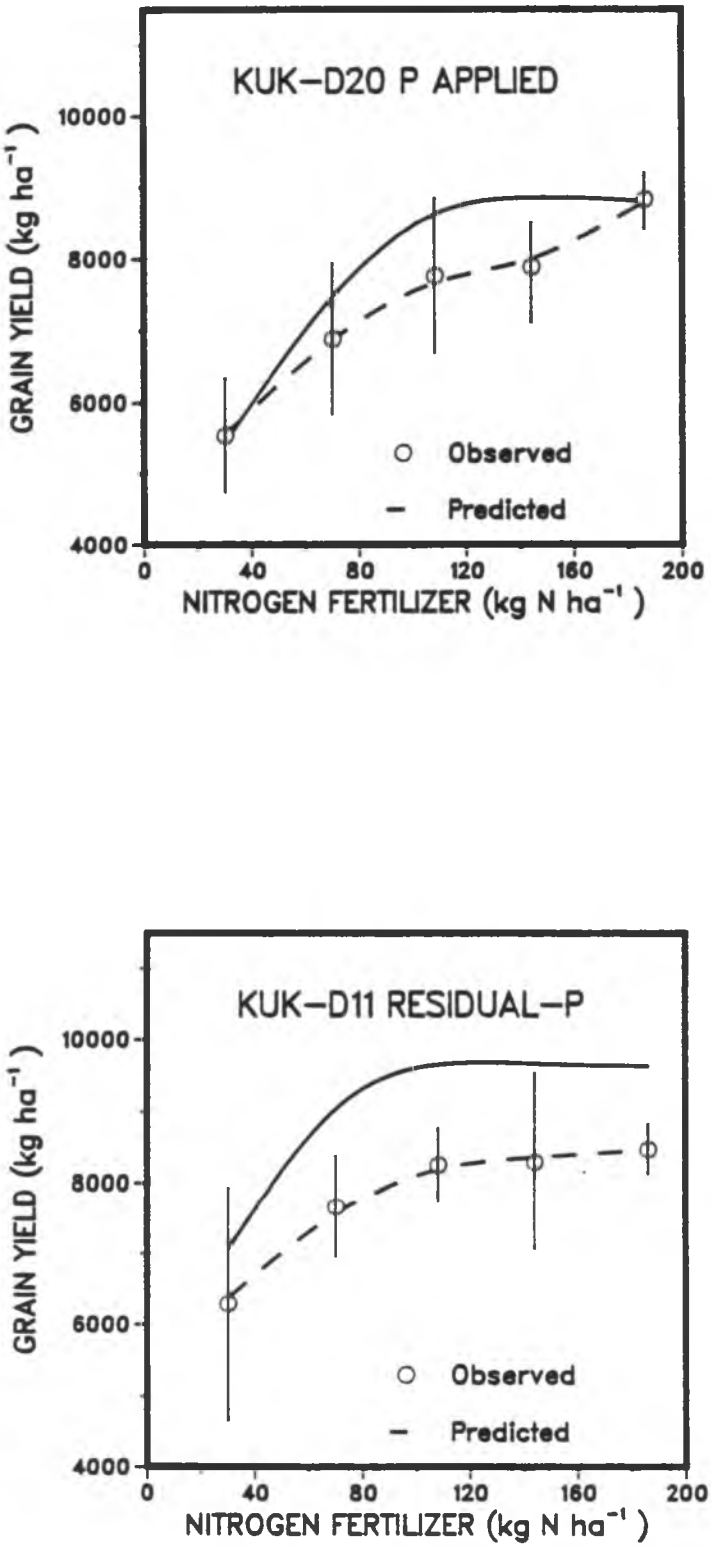


Figure 4.12 Comparison of observed (± one standard deviation of observations) and simulated grain yield with N application for (A) residual P experiment and (B) optimum applied P experiment.

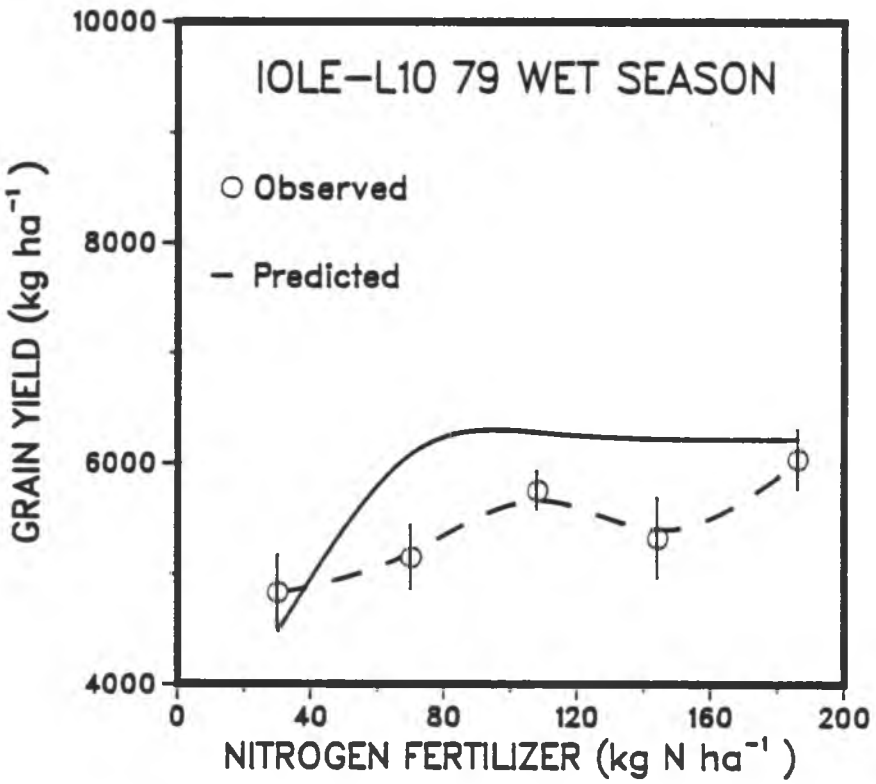
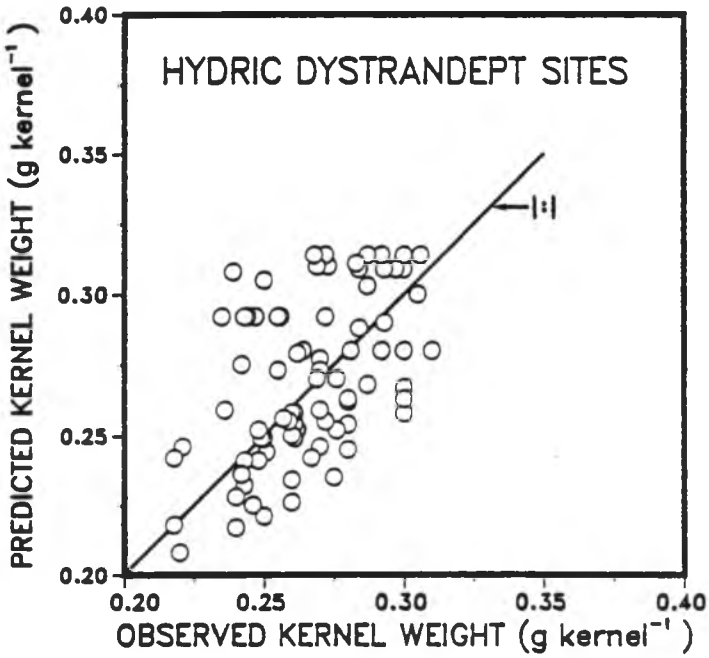


Figure 4.13 Comparison of observed (± one standard deviation of observations) and simulated grain yield with N application on Iole site, Hawaii.

A



B

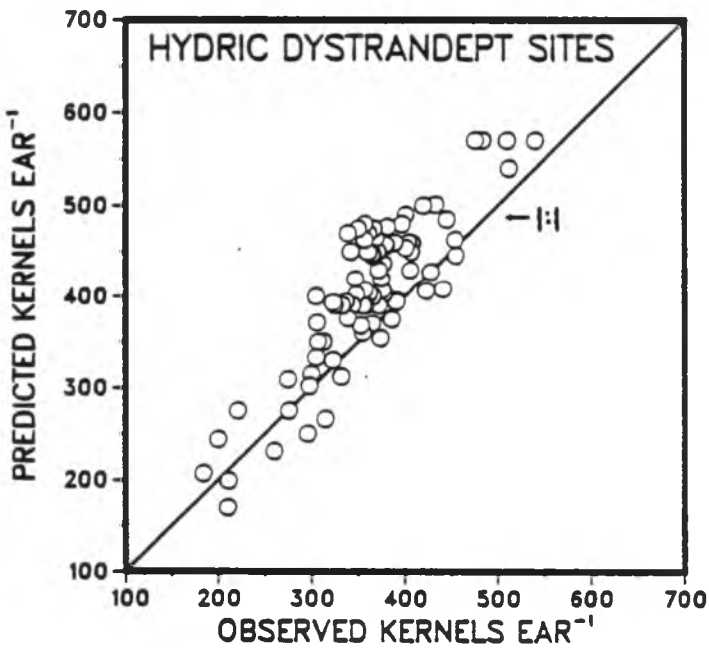


Figure 4.14 Comparison of observed and simulated (A) kernel weights and (B) kernel numbers on Hydric Dystrandept sites.

predictions (Appendix 4.6). In general the simulated values were higher than the observed (Figure 4.14b). The model also correctly simulated the effect of N fertilization on number of kernels ear^{-1} (Figure 4.15).

4.3.4 Validation of the CERES maize model on the slopes of Mount Haleakala, Maui

The CERES maize model was tested on three agroenvironments along the slopes of Mt. Haleakala, Maui, Hawaii. The three sites were at 77, 340 and 800 m above sea level. The soils on these sites consisted of a mollisol, ultisol, and andisol, respectively.

Despite the difference in the agroenvironments the model accurately predicted emergence, end of juvenile stage, anthesis and physiological maturity. The simulated days to emergence was generally two days earlier than the actual (Table 4.8). The model was able to simulate the two-three days delay in emergence at the highest elevation compared to the lower elevations. The model was also able to simulate the delay in days to the end of the juvenile stage with increasing elevation or decreasing temperature gradient. The observed difference in days to anthesis between the lowest and the highest elevation was 42 days. The simulated difference was 30 days (Table 4.8). This twelve day difference arises because the model delayed silking by 5 days at the lowest elevation and enhanced silking by 7 days at the highest elevation.

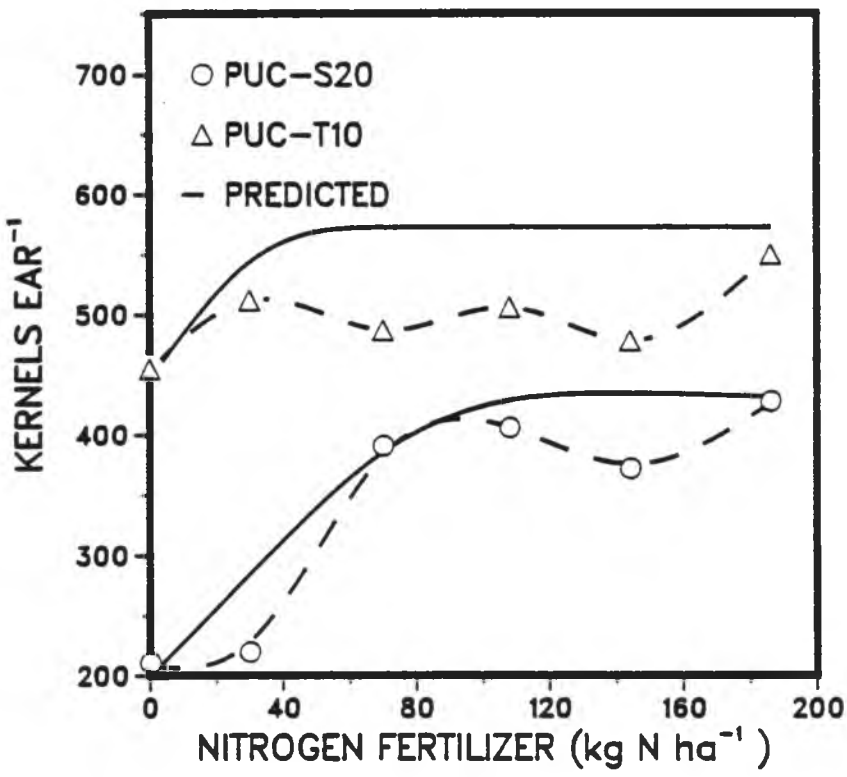


Figure 4.15 Effect of N application on observed and simulated grain numbers.

Table 4.8 Comparison of observed and simulated phenological events for X304C variety on the slopes of Haleakala, Maui, Hawaii.

Elevation (m)		Days After Planting[a]			
		Emergence	End of juvenile Stage	Silking	Physiological Maturity
77	Observed[b]	6	23	62	120
	Simulated	5	25	67	119
340	Observed	7	28	73	138
	Simulated	5	28	73	132
800	Observed	9	42	104	176
	Simulated	7	38	97	174

[a] Planted on April 24, 1984.

[b] Bartholomew (unpublished data).

The model accurately simulated the fifty-six day delay in physiological maturity at the highest elevation. Thus, from the results of these and other sites, it seems reasonable to conclude that the CERES maize model is capable of simulating phenological development for maize variety X304C in a wide range of agroenvironments with reasonable accuracy.

The simulated grain yields for the Maui sites were within one standard deviation of the actual mean yield (Table 4.9). The model predicted lower yield for the highest elevation-site as it received only 80% of the radiation of the two lower sites. Simulated total above ground biomass in two of the experiments was within a standard deviation of the observed mean. However, at the intermediate elevation the simulated value was higher than the actual.

Overall the model performance was acceptable over a wide range of agroenvironments.

4.3.5 Validation of the CERES maize model for different plant densities

The CERES maize model thus far had been calibrated with population density of approximately 50,000 to 60,000 plants ha^{-1} and then validated with similar population densities. When tested at six different planting densities for nine bimonthly plantings at the Waimanalo Experimental Station (Lee, 1983), the model simulated grain yields with reasonable accuracy for many of the experiments (Appendix 4.7). However, the model produced less grain yield for March plantings at population densities >12,500 plants ha^{-1}.

Table 4.9 Comparison of observed and simulated yields for X304C variety on the slopes of Mt. Haleakala, Maui, Hawaii.

Elevation (m)		Grain yield kg ha^{-1}	Total Dry Matter kg ha^{-1}
77	Observed[a]	11533 ± 860	25025 ± 2145
	Simulated	12339*	23699*
340	Observed	11600 ± 994	21033 ± 1898
	Simulated	12234*	25182
800	Observed	9178 ± 1654	18731 ± 4659
	Simulated	9009*	22584*

[a] Bartholomew (unpublished data).

* Simulated result is within a standard deviation of the observed mean.

In Fall and Winter plantings the CERES maize model simulated the effect of population density with reasonable accuracy (Appendix 4.7 and Figure 4.16). At higher population densities the model realistically simulated lower grain yields. The model accounts for barrenness (no kernels) due to high population density.

The September to January plantings had severe lodgings, weed problems, insect damage and diseases. These problems are associated with the wet season and strong wind (Aldrich et. al., 1978). Hence, the simulated values were higher than the observed (Appendix 4.7).

For May to July plantings the simulated grain yields increased with increasing population density. However, the measured grain yields declined at 150,000 plants ha^{-1}. This may indicate that at high population densities nutrient deficiency, lodging, and/or water stress may come into play. The model tends to show that light was not limiting even at the highest population density for March to July plantings. With some caution, simulated results can be used to obtain deeper insight into results of field experiments.

The CERES model showed that the the highest grain yield (for planting density = 75,000 plants ha^{-1}) was obtained during March to July plantings and the lowest during September to November plantings (Figure 4.17). This trend was also followed by the observed yield. However, as mentioned earlier the grain yields during September to January plantings were lower because of weeds, lodging, insect damage and disease incidence. Overall the simulated yields increased with increasing solar radiation. This effect had been reported on the observed yields as well (Lee, 1983).

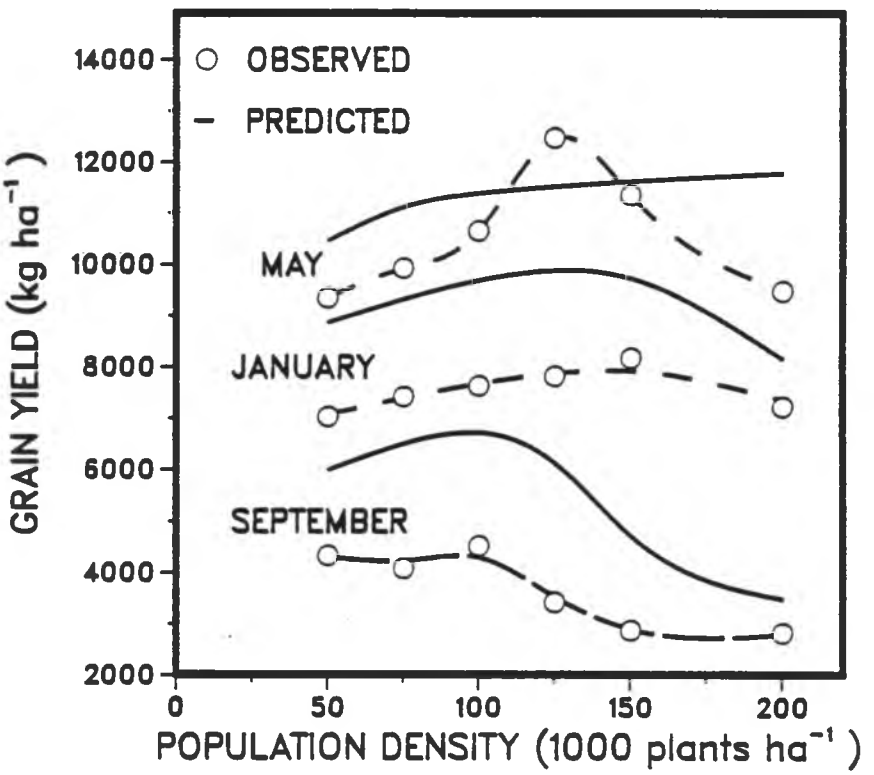


Figure 4.16 Effect of population density on 3 plantings: January, May and September.

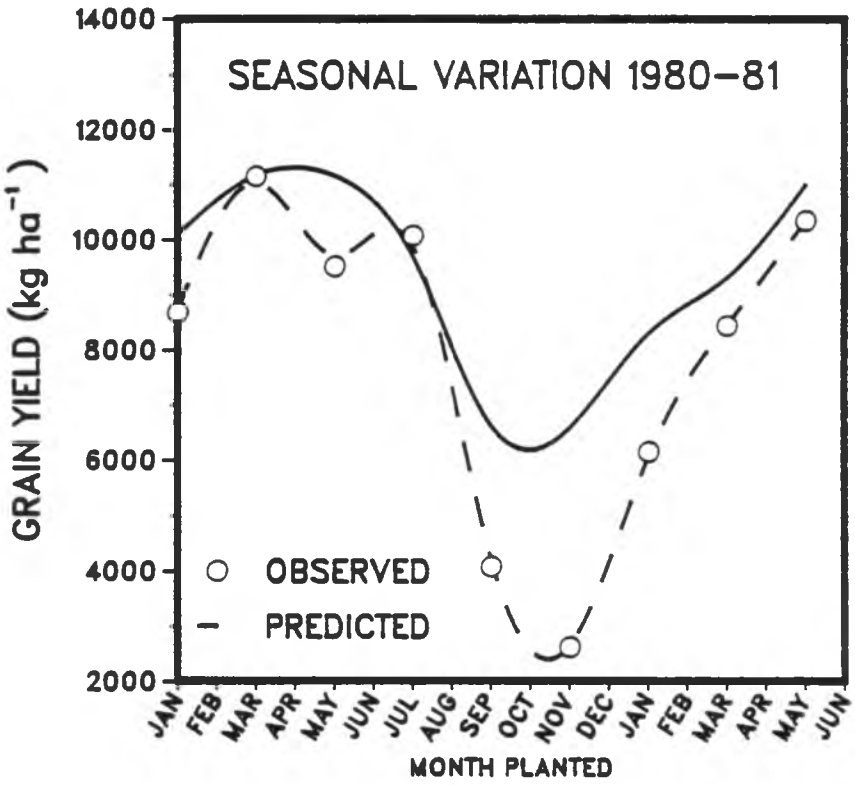


Figure 4.17 Simulating seasonal variation in yield.

4.3.6 Sensitivity Analysis

The sensitivity of the CERES maize model to solar radiation, and maximum and minimum air temperatures is evident from Table 4.10. The model was run first with extra 100 langleys day^{-1} solar radiation (15-20% increase over the average solar radiation) and then with daily maximum and minimum temperatures both lowered by 2°C for the entire growing season. For both of the above situations other conditions were identical to the field experiment except the amount of N applied was increased. Therefore, in none of the above simulations nitrogen was limiting.

The increased solar radiation resulted in increased grain yield and total dry matter production. The increase in non-grain components was larger than the grain yield (Table 4.10). The increased solar radiation as expected did not affect the phenological development. Since the initial solar radiation was high, the response was not marked (increase of less than 400 kg ha^{-1}). A reduction in solar radiation by 100 langleys day^{-1} however, resulted in grain yield of 10,900 kg ha^{-1} - a reduction of about 1400 kg ha^{-1} (Table 4.10). This indicates that the model was sensitive to effects of light saturation.

Subtraction of 2°C from both the minimum and maximum air temperatures resulted in 6-day delay in silking and 12-day delay in physiological maturity (Table 4.10). The delay resulted in 700 kg ha^{-1} and 3200 kg ha^{-1} increase in grain yield and total above-ground biomass produced, respectively (Table 4.10). The lowered temperature combined with high solar radiation (naturally occurring at the Niftal site, Maui) resulted in yields typical of mid-western U.S.A.

Table 4.10 Sensitivity Analysis to solar radiation and temperature at Niftal site (77 MSL), Maui.

		Niftal Site	Solar radiation + 100 cal cm^{-2} day^{-1}	Max. and min. temp. -2°C
Silking (DAP)	Observed	62	-	-
	Simulated	67	67	73
Physiological Maturity (DAP)	Observed	120	-	-
	Simulated	119	119	131
Grain Yield (kg ha^{-1})	Observed	11533	-	-
	Simulated	12339	12765 (10900*)	13039
Total Dry Matter (kg ha^{-1})	Observed	25025	-	-
	Simulated	23699	25807	26961

* Solar radiation - 100 cal cm^{-2} day^{-1}

The sensitivity analysis also emphasizes the need for reliable weather data. Thus, if the radiometer is incorrectly calibrated the model prediction would be in error. In general there is atleast 10% error in measured solar radiation values (F. Brock, personal communication). Similarly errors in temperature recordings could affect simulated phenological development as well as final yields. The necessity of having standard weather station at all sites where modeling experiments are carried out is also illustrated. For example, a non-standard weather station may be recording temperatures which may be in error by just 2°C. However, a 2°C difference as shown in Table 4.10 made a significant difference in simulated phenological development and grain production.

4.3.7 Statistical Validation

The model prediction was nonsite-specific. In most cases the predictions were close to the measured yields and observed phenological dates. The model was evaluated statistically using the R test (Wood and Cady, 1984) and the modified Freese statistic (Reynolds, 1984).

R test

The R statistic was carried out on four experiments from Tropeptic Eutrustox sites in Hawaii and five experiments from the Typic Paleudult site, in Nakau, Indonesia (Table 4.11). The test did not include the MOL-N20 experiment on Tropeptic Eutrustox because the plants were severely affected by wind damage.

Table 4.11 Statistical validation of simulated results from two Tropeptic Eutrustox sites and a Typic Peleudult site using R statistic

Site	[A]	[B]	Normalized[a] R_1-1	Tabulated F*
WAI-F10	2503744	2727924	5.52	3.33
MOL-L10	2468844	6631189	2.23	3.00
MOL-M10	17947468	2565763	41.97	3.00
MOL-N10	5628938	19693354	1.71	3.00
NAK-L20	3803363	6193029	3.69	3.00
NAK-A30	18404305	6721695	16.44	3.00
NAK-D30	7741024	3137472	14.79	3.00
NAK-010	10584131	7096951	8.94	3.00
NAK-P10	4733048	7632881	1.86	3.00

* At 95% Significance level

a If Normalized R_1-1 $\leq$ F then model prediction is not significantly different from observed yields.

R_1-1= r[A]/[B] where:

$$[A] = \sum_{i=1}^{t} (\bar{Y}_i - X_i)^2$$

$$[B] = \sum_{i=1}^{t} \sum_{j=1}^{r} (Y_{ij} - \bar{Y}_i)^2$$

Equation 4.2 was utilized to compute R_1-1 values for each of the experiments. The numerator, denominator, and R_1-1 values are presented in Table 4.11. In all except three experiments model prediction was significantly different from the actual yields at the 95% confidence level.

Since the null hypothesis for the test states that the simulated values are no different from the observed values, acceptance of the null hypothesis does not indicate how "good" the model predictions were in those cases. The null hypothesis may not be rejected because the experiment had a large coefficient of variation. Therefore, a model may be accepted because of a "bad" field experiment. This problem associated with R statistic is evident from Figure 4.1 in which the test rejected a subjectively "good" model prediction on WAI-F10 while accepting a "poor" one (MOL-N10).

Modified Freese Test

The Freese statistic was applied to the same data set mentioned above. However, the evaluation was done on a per site basis. This would evaluate the model performance on a broader scale. Also, the chi-square test is not very sensitive with lower degrees of freedom.

The modified Freese test (Equation 4-7) as suggested by Reynold's was used. The rejection of the null hypothesis therefore, would give strong evidence that the model is as good as required. Before carrying out statistical validation, correction for bias was made (Equation 4.12). The correction for bias (a constant) is justified because the model was calibrated such that it predicted higher yields. The model

assumed: (i) complete irrigation; (ii) all nutrients at optimal levels except nitrogen, (iii) no pests, weeds, and diseases, and (iv) no wind damage. In the field, one or more of the assumptions were not met in almost every case. The model has been designed to minimize the need for future model calibration when the unaccounted factors are later incorporated into the model.

The test utilized the critical error, e^{**}, concept (Equation 4.13). The critical error would indicate whether the model is adequate for the intended purpose. The critical error values for simulated grain yields on Tropeptic Eutrustox sites, Hawaii and the Typic Paleudult site, Nakau, Indonesia were 1215 kg ha^{-1} and 1268 kg ha^{-1}, respectively at the 95% confidence level. Grain yield of 1215 kg ha^{-1} would be the smallest value of e which would lead to the rejection of the null hypothesis (i.e., acceptance of the model) on Tropeptic Eutrustox sites. If a user required higher accuracy ($e<e^{**}$) then the model would not be suitable. For global predictions the critical error values obtained seem reasonable. However, for a site-specific predictions a user may require higher accuracy.

The Freese test also showed that the model had similar accuracy for different soil families, i.e., the model was nonsite-specific. The overall performance of the model suggests that it can now be used to predict maize growth and yield in a wide range of tropical environments without benefit of calibration at each site.

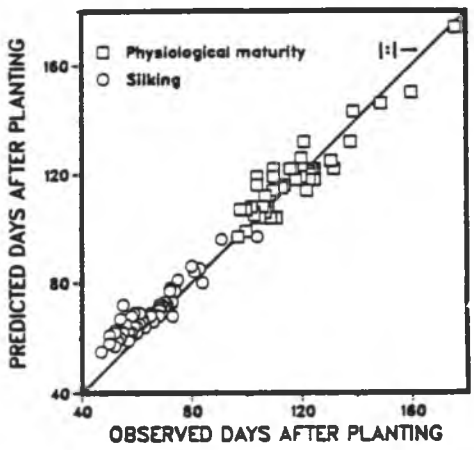
Statistical tests evaluate predicted values with the observed data. However, the input data should also be evaluated, as errors in them would lead to erroneous predictions.

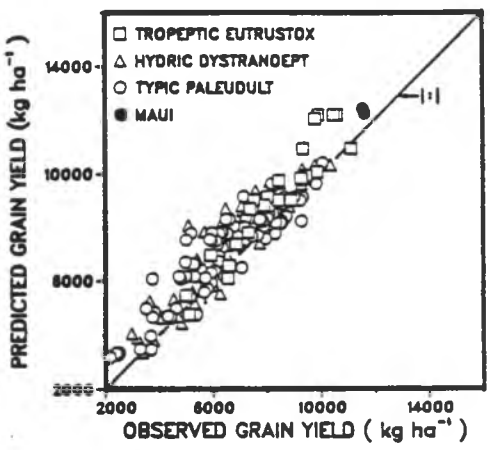
4.4 Conclusions

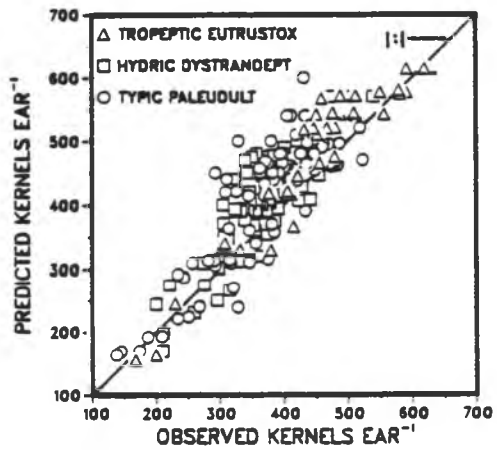
1. CERES model predictions for phenological development, kernel weights, kernels ear^{-1}, and grain yield were non-site specific (Figure 4.18). The predictions were not biased on a per site basis. Therefore, the CERES maize model was able to perform equally well on a wide range of agroenvironments. The range of soils included oxisol, ultisol, andisol, and mollisol. The sites ranged from 5° S latitude to 21°N latitude and 77 to 800 meters above sea level. The observed grain yields on these sites ranged from 2000 to 11500 kg ha^{-1} and days to anthesis ranged from 48 to 100 days after planting (DAP) and physiological maturity varied from 97 to 176 DAP.

2. The model simulated the effect of planting density and seasonal variation. The effects of unknown conditions were in general more pronounced in the population density experiments. During winter plantings, when population density was high, sunlight was the limiting factor. However, for summer plantings the simulated yields did not decline at high population densities implying that water or some other nutrient was limiting in the field.

3. The CERES model was able to mimic the high sensitivity of maize to temperature. This was illustrated by differences in phenological development at three sites on the Island of Maui. Sensitivity analysis also showed that lowering both maximum and minimum temperature by 2°C resulted in a six day-delay in anthesis and a 12 day-delay in physiological maturity.







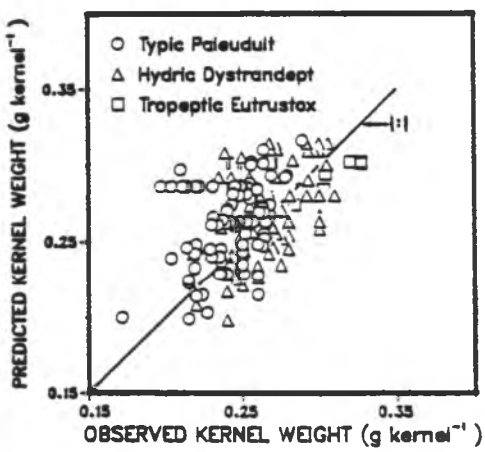


Figure 4.18 Comparison of observed and simulated yield components and phenological events.

4. The CERES model is also sensitive to light saturation. Increase in solar radiation at peak light levels resulted in only 400 kg ha^{-1} increase in grain yield whereas a similar reduction in solar radiation led to 1400 kg ha^{-1} decline.

5. Unmeasured environmental and management variables caused considerable difference between the simulated and observed values. These variables affected not only yield predictions but also the phenological development. Physiological maturity was earlier in experiments which came under water stress during grain filling. Similarly, lodging of plants during grain filling led to early maturity. This may have resulted from restricted supply of assimilates due to split stalks and/or lower light interception. In some cases lodged crops were harvested before physiological maturity.

6. Water stressed crops resulted in half the simulated amount of grain yield. Similarly, crops which had weeds, leaves damaged by strong winds, or covered by ash fall (LPHS-D30) produced lower yields than simulated. Also, at optimal levels of N expected increase in yield was not obtained because other nutrient(s) probably became limiting.

7. The preliminary testing with R statistic of some nine experiments indicated that, in only a few cases, model predictions were not different from the actual observation. The R test accepted model predictions which were subjectively poor because the field experiment had a large coefficient of variation. The Freese statistic, on the other hand, showed that the CERES maize model was capable of simulating

grain yields from 2500 kg ha^{-1} to 11,200 kg ha^{-1} with a critical error of approximately 1200 kg ha^{-1} when a model bias to overestimate in yield was taken into account. The higher predicted yield was attributed to yield reduction from weeds, insects, and pathogens; wind damage; and nutrient deficiencies not accounted for in the model.

V. ASSESSMENT OF PHOSPHORUS AVAILABILITY ON A WIDE RANGE OF SOILS

5.1 Introduction

The availability of P to plants depend on the amount of different P forms present in soils. The factors affecting phosphorus content and availability in soil include: organic carbon, carbonates, pH, and clay content, iron oxides, exchangeable Ca, and active Al component, soil age, parent material, climate, management history at the site, and probably other factors. The soil fraction P considered most important for determining plant available P are (i) the soil solution P and (ii) the labile P or the quantity of soil P in rapid equilibrium with solution P.

Labile P has traditionally been determined using isotopic dilution techniques (Russel et al., 1954; Mekhael et al., 1965). Alternative approach has been the use of anion exchange resin to extract soil P (Amer et al., 1955; Sibbesen, 1978). Soil solution P may be determined by measuring water solution P or from adsorption/desorption isotherms at zero P adsorption (Kunishi and Taylor, 1977).

The most frequently available measurement of soil P is soil test P determined with $NaHCO_3$ (Olsen et al., 1954), NH_4F + HCl (Bray and Kurtz, 1945), HCl + H_2SO_4 (double acid P), or 0.02 N H_2SO_4 (modified Truog P). These tests could be used to estimate labile P and generate other inputs for P models. However, the success of soil test P methods depends on the correlation and calibration between plant uptake of P or labile P and P extracted by these tests.

Several workers have observed a linear relationship between extractable or soil solution P and the amount of P added in laboratory incubations (Barrow, 1974a; Barrow and Shaw, 1975) and field studies (Barber, 1979). However, the relationship is not known for a wide range of soils, particularly from the tropics. The P fertilizer required to establish a particular soil P level has also been assessed by determining the P sorption curve for the soil (Fox and Kamprath, 1970; Peaslee and Fox, 1978; Beckwith, 1965). The availability index or external P requirement of the plant as determined by the P sorption curve method is less time consuming than incubation studies or field experiments. In general, the above sorption/desorption methods are not used by many soil testing laboratories. Therefore, correlation between soil test P methods, soil physical and chemical properties, and availability index of P would be useful towards developing a P model.

The primary objective of this research as evident from previous chapters is to develop a plant growth simulation model for the tropics by: modifying, calibrating, and validating the model for a wide range of tropical sites (agroenvironments). The objective of the present chapter is to develop regression equations as a means of generating accurate and readily available input data for a P model (Jones et al., 1984a). Thus, in the present chapter (i) labile P of a wide range of tropical soils is determined using radio-isotope ^{33}P and anion exchange resin; (ii) the labile P estimates are related to other chemical extraction methods; and (iii) regression equations relating labile P, organic P, external P requirement, buffering cpacity, etc. to readily available soil physical and chemical properties, and soil test P are developed.

5.2 Material and Methods

5.2.1 Soils

Two hundred and thirty-three top- and sub-soil samples were obtained from USDA, Soil Conservation Service; Ministry of Agriculture, Fiji; and Mauinet Project, Hawaii. These soils as presented in Table 5.1 are representative of soils found in the tropics. Most of the soils had been fully characterized and include the following chemical and physical analyses: texture, organic carbon, total nitrogen, pH, cation exchange capacity (CEC), base saturation, carbonates, KCl-extractable Al, and dithionite-citrate extractable Fe and Al.

5.2.2 Laboratory Analysis

A. Radiosotope ^{33}P technique

Labile P was determined by isotope dilution technique and by anion exchange resin technique. The isotope technique provides a means of determining labile P with minimal alteration to the soil system. Also the factors affecting the behavior of added isotopic P should be similar to those affecting added fertilizer P. Labile phosphate is often determined by the direct method of equilibrating soil with a solution of ^{32}P- (or ^{33}P-) labelled phosphate. Three commonly used isotopic dilution techniques are (i) carrier-free (McAuliffe et al., 1947); (ii) carrier P (Russel et al., 1954); and (iii) inverse-dilution (Mekhael et al., 1965). However, as discussed previously (section 2.3.3) the radiosotope method has its drawbacks and gives erroneous values for labile P in high phosphate fixing soils.

Table 5.1 Number of samples analyzed from different soil orders.

	ORDER										
Layer	Alfisol	Andisol	Aridisol	Entisol	Histosol	Inceptisol	Mollisol	Oxisol	Ultisol	Vertisol	Total
Topsoil	8	16	3	1	2	11	12	25	11	2	91
Subsoil	27	5	10	1	0	14	11	46	17	11	142
Total	35	21	13	2	2	25	23	71	28	13	233

Preliminary work was done using carrier-P isotopic dilution technique and inverse dilution technique. The carrier-free isotopic dilution method was not attempted because it overestimates labile P values in high phosphate-fixing soils (Amer, et al., 1969; Dalal and Hallsworth, 1977).

^{33}P of high specific activity (1000 mCi/mmol) was obtained from the New England Nuclear, Massachusetts as monopotassium phosphate with greater than 99% radionuclide and radiochemical purity. ^{33}P isotope was used instead of ^{32}P because the former has longer half-life, is safer, has lower energy (soft beta energy), and also gives better resolution (Robinson, 1969).

Carrier-method

The method has been adapted from Amer et al. (1969) and Dalal and Hallsworth (1977). Three gram samples of soil, oven dried basis (in duplicate), were added into a series of 50 ml polyproplene centrifuge tubes. To each of the samples 10ml of 0.03 M $CaCl_2$, 3 ml of 50 ppm $Ca(H_2PO_4)_2$ and 10 uCi ^{33}P was added. The solution was then made up to 30 ml by adding distilled water. The soil samples were then equilibrated with the 0.01 M $CaCl_2$ solution containing ^{33}P (10 uCi) and 50 mg P/kg soil for an hour. The samples were then centrifuged for 15 minutes at 12,000 r.p.m., filtered and a 0.5 ml aliquot was used for determining ^{33}P activity. The aliquot was first thoroughly dissolved in 5 ml Aquasol (universal scintillation cocktail) in a scintillation vial.

The ^{33}P activity was determined from the scintillation counts obtained using a Packard Tri-Carb liquid scintillation spectrometer

with the following setting :gain 7.5% and window opening 50-10,000. Fertilizer P content was determined by the ascorbic acid method (Olsen and Sommer, 1982). Labile P value was obtained from Equation (2.9):

$$E = x(S_i/S_t - 1) \qquad (2.9)$$

$$= x[(S_i/S_t) - 1]$$

where E = labile phosphate in mg P/kg soil,

x = amount of carrier P added with the ^{33}P in mg P/kg soil,

S_i = specific activity of the added phosphate in cpm/mg P and,

S_t = specific activity of the equilibrium solution at time t.

A sample calculation for the carrier-method as well as the inverse dilution method is presented in Appendix 5.1.

Inverse dilution method

The method was adapted from Mekhael et al. (1965) and Dalal and Hallsworth (1977). To four sets of 3 g soil samples in a 50 ml polypropelene tube, 10 ml of 0.03 M $CaCl_2$ and 1 ml aliquot of ^{33}P solution (10 uCi) was added. Two drops of toluene was added to inhibit microbial activity. The solution was then made up to 30 ml. The samples were then shaken longitudinally for two half-hour period each day for 6 days. On the sixth day two of the samples were centerifuged at 12,000 r.p.m. for 15 minutes, then filtered and analyzed for P and ^{33}P activity as in the carrier-method. To the remaining tubes 1 ml of 150 ppm phosphate solution was added. These samples were shaken for another 24 hours. The suspensions were then centrifuged, filtered, and analyzed for P and ^{33}P activity. Labile P level was determined from Equation (2.12):

$$E = x[S_t/(S - S_t)] \qquad (2.12)$$

where E = labile phosphate (mg P/kg soil),

x = amount of carrier P added (mg P/kg soil),

S = specific activity before the addition of inactive carrier (cpm/mg P), and

S_t = final specific activity (cpm/mg P).

Refer to Appendix 5.1 for a sample calculation using inverse dilution method.

B. Anion exchange resin-extractable P

The anion exchange resin method does not directly measure such soil-P factors as intensity-, quantity-, capacity-, and rate factors, but the P extracted by a resin, shaken in a soil-water suspension is the result of them. The resin functions as a plant root with a very high capability of P-uptake. Results obtained with the resin method have often been found to correlate well with plant P uptake (Amer et al., 1955; Cooke and Hislop, 1963; Zurino et al., 1972). However, the method is not in widespread routine use, probably because the analytical procedures are both time consuming and difficult to carry out on a large scale (Amer et al., 1955; Hislop and Cooke, 1968; Sibbesen, 1972). In the present study three different anionic forms of the resins were used.

Anion exchange resin chloride form

The procedure was adapted from Olsen and Sommers (1982). One gram of chloride-saturated resin (Dowex 2-X8 20-50 mesh) and 1 g of 50 mesh soil (oven dried basis) was mixed with 10 ml of distilled water in a 40 ml tube. The contents were shaken for 16 hours.

The resins were separated from the soil by washing through a 50 mesh screen tube. The resin was seived prior to the experiment so that all of it was retained on the 50 mesh sieve. The resin was then transferred into a 50 ml beaker, 25 ml of 10% NaCl was added and the contents heated over a water bath for 45 minutes. The mixture was then cooled and the extract poured into 50 ml volumetric flask. Resins were transferred back into a 50 mesh screen tube and leached with 10% NaCl until 50 ml of filtrate was obtained.

Suitable (5, 3, or 1 ml) aliquot was transferred to a spectrophotometer tube and the P concentration determined by the ascorbic acid method with the wavelength set at 850 nm.

Anion exchange resin biocarbonate form

The bicarbonate form of resin was generated by leaching the chloride form of the resin with 10% $NaHCO_3$ solution. The leaching was continued until the leachate was chloride-free. The excess bicarbonate ions were then removed with water, and the resins were air dried. The extraction procedure was identical to that used with the chloride form of the resin.

Anion exchange resin chloride-sulfate form

The procedure for the chloride-sulfate form of the resin (Anion Exchange Resin A-1P 16-50 mesh) was similar to that used for the chloride form of the resin, however, the 10% NaCl solution was replaced by a mixture of 10% NaCl- Na_2SO_4 solution.

C. Chemical extraction methods

Bray-1 P was determined by the method of Bray and Kurtz (1945), where 2 g soil was shaken in 20 ml of 0.03 M NH_4F and 0.025 M HCl for 1 minute. Double acid P was determined by the method of Sabbe and

ratio and delta pH were natural log transformed to obtain a normal distribution. The means and variances of these data were re-expressed in terms of the original data following the procedure of Haan (1977). The re-expressed means (M_x) and variances (V_x) were calculated using the equations:

$$M_x = \exp(X_y - s_y^2/2) \quad (5.4)$$

$$V_x = X_x[\exp(s_y^2) - 1] \quad (5.5)$$

where X_y= mean of log transformed data values, S^2y= variance of the log transformed data values, and X_x= mean of the original data values.

Means and variances of each property and correlation coefficients among properties at each depth were computed using the Statistical Analysis System (SAS) (Barr et al., 1979). Regression analyses were conducted with the SAS STEPWISE, BACKWARD ELIMINATION, REG and GLM procedures (Barr et al., 1979).

Breland (1974), where 5 g soil was shaken with 20 ml of 0.05 M HCl and 0.0125 M H_2SO_4 for 5 minutes. The Olsen P method as described by Olsen and Sommer (1982) was followed, where 5g soil was shaken with 100 ml 0.5 M $NaHCO_3$ (pH= 8.5) for 30 minutes. Hydroxide P was determined by the method of Dalal (1973) where 1 g soil was extracted with 100 ml of extracting solution comprising of 0.25 M NaOH and 0.1 M Na_2CO_3. After 16 hours shaking, the sample was filtered through Whatman's No. 42 filter paper. The P determination was carried out as with Olsen P, i.e., by ascorbic acid method after acidifying the aliquot to pH 5.

Modified Truog P was determined by the method adapted from Ayres and Hagihara (1952), where 1 g of soil was equilabrated with 20 ml of H_2O for 24 hours. Then extracted with 100 ml of 0.02 N H_2SO_4 containing 3 g of $(NH_4)_2SO_4$. The P determination was done using the ascorbic acid method (Olsen and Sommers, 1982). Solution (water) P method was adapted from Olsen and Sommers (1982). 2.5 g soil (oven dried basis) was shaken with 25 ml of distilled water for 1 hour, centrifuged at 10,000 r.p.m. for twenty minutes and then filtered with Whatman's No. 42 filter paper. P concentration was determined colorimetrically by the ascrobic acid method.

D. Organic P determination

The organic P content of the soils was estimated by the difference between acid extraction (0.5 N H_2SO_4) of ignited and non-ignited samples (Walker and Adams, 1958). On selected soils organic P determination was carried out by the extraction method of Mehta et al. (1954). The organic P methods followed in this study have been described by Olsen and Sommers (1982).

E. Phosphate sorption curves

P soption curves were determined by the procedure of Fox and Kamprath (1970), where duplicate samples of 3 g soil (oven dried basis) were equilibrated for 6 days in 30 ml of 0.01 M $CaCl_2$ containing amounts of $Ca(H_2PO_4)_2$ varying from 0 to 2000 ppm. During the six-day incubation period, the samples were shaken longitudinally for a 30-minute period twice daily. P was determined colorimetrically by the ascorbic acid method after filtering the solution with Whatman's No. 42 filter paper. The P in solution at zero fertilizer rates were also correlated with resin extractable P.

F. Soil physical and chemical properties

Such soil physical and chemical properties as sand, silt, and clay content, pH in water and in 1 N KCl, organic carbon, total nitrogen, cation exchange capacity, exchangeable bases, KCl extractable-Al, and dithionite-citrate extractable Al and Fe were determined by the National Soil Survey Laboratory, SCS, Lincoln, Nebraska and Ministry of Agriculture, Fiji as outlined in USDA (1972). For some of the soils, particularly Andisols P-retention and acid-oxalate extractable Fe were also determined (Searle and Daly, 1977). The above analyses were done on air dried soil samples even in the case of Andisols. On the otherhand all the P determinations were done on field moist Andisol samples.

Total bases were obtained by summing exchangeable Ca, Mg, K, and Na. Effective cation exchange capacity (ECEC) was calculated as sum of exchangeable cations plus KCl-extractable Al. Al saturation was calculated as:

$$\text{Al saturation} = (\text{KCl-extr Al}/\text{ECEC})*100 \quad (5.1)$$

Lime requirement was calculated based on neutralization of Al (Kamprath, 1970):

$$CaCO_3 \text{ cmol/kg} = 1.5*(\text{KCl-extr Al}) \text{ cmol/kg} \quad (5.2)$$

Lime requirement values in tonnes lime/ha were obtained assuming a bulk density of 1.00g/cm^3 (0.80 g/cm^3 in Andisols) and incorporation to a depth of 15 cm. The lime requirement of these soils were determined because phosphorus-lime interaction had been reported on a wide range of soils (Sanchez and Uehara, 1980). Therefore, it was deemed appropriate to study the lime requirements of these soils as well. CEC (cmol(+)/kg clay) was calculated from:

$$\text{CEC cmol/kg clay} = (\text{CEC cmol/kg soil}/\%\text{clay})*100 \quad (5.3)$$

5.2.3 Data compilation and statistical analysis

A crop growth simulation model should be able to predict performance of the crop on a long term basis. Therefore, the model should be able to simulate the effect of soil erosion on crop productivity. With this in mind the data were compiled into two categories: top soil and subsoil. The topsoil comprised of the uppermost layer in a pedon and this was not necessarily the plow layer. The remaining soils from the pedon were called the subsoil.

All the data were tested for normal probability distribution using probability plots and the Kolmogorov-Smirnoff D statistic for sample size greater than 50 and the Shapiro Wilk W test for sample size less than 50 (Shapiro and Wilk, 1965). Clay content, carbon to nitrogen

5.3 Results and Discussion

5.3.1 Comparison of chemical extraction P methods with isotope P and anion exchange resin P method

Labile P

After preliminary investigation with selected soils the carrier P method was chosen as the radioisotope ^{33}P method to determine labile P. The alternative choice, inverse dilution isotope method was not used because in many of these soils labile P value could not be calculated using this technique. The S_t (final specific activity) value as used in Equation (2.12) was greater than S which indicates some violation of experimental assumptions.

$$E = x[S_t/(S - S_t)] \qquad (2.12)$$

The factors that may have contributed to higher S_t values are in general associated with the high P-fixing nature of the soils used. After the addition of inactive carrier P the count of radiosotope ^{33}P is expected to increase because of the exchange of ^{33}P with ^{31}P, however, the increased activity of P in solution would lower the S_t value. (Refer to Appendix 5.1 for sample calculation of S and S_t values). Generally, the ^{33}P counts did increase on addition of inactive fertilizer P but the increase in solution P in the highly weathered soils was not as high or in several of these soils it remained unchanged despite the application of 150 mg P/kg soil. Thus, in highly P deficient soils almost all of the added P was adsorbed and very little was available as 'exchangeable' or labile P. Further, the addition of inactive carrier P in some of the soils resulted in lower

scintillation counts because the added P apparently caused 'precipitation' or nucleation of the isotopic P. The carrier P method on the other hand was more successful in determining the P status of a wide range of soils.

Among the different anionic forms of the resin, the chloride-sulfate saturated resin was used to estimate plant available P. As the preliminary work on some of the selected soils indicated (Table 5.2), chloride saturated anion exchange resin was not effective in extracting available P from highly weathered soils, particularly the weathered volcanic ash soils. At all pH values, the divalent SO_4^{2-} ion is adsorbed to a greater extent by the soil colloids than the monovalent Cl^- or HCO_3^- ion, as would be expected on the basis of electrostatic attraction forces alone (Bohn et al. 1979). Phosphate ions are more easily replaced by anions with higher charge density than otherwise. Phosphate and sulfate also behave similarly with respect to cation retention, both cause an increase in cation retention (Uehara and Gillman, 1981). Therefore, the rhizosphere (with univalent and multivalent ions) and chloride-sulfate resin would extract or replace more P from the soil colloids than a univalent anion exchange resin (Cl^- or HCO_3^-).

Even though the bicarbonate form of the resin was almost as effective as the chloride-sulfate resin (AEC of 5.4 cmol kg^{-1} compared to 6.0 cmol kg^{-1} Table 5.2) in extracting P from the soils, the latter was chosen because of the ease of the laboratory methodology plus the reasons cited in the preceding paragraph. The chloride-

Table 5.2 Comparison of labile P (mg P kg/soil) as obtained from anion exchange resin and isotope P methods.

Soil name	Chloride-sulfate resin [a]	Chloride resin	Bicarbonate resin	Isotope carrier-P
Torroxic Haplustoll	255.57	170.76	240.79	324.90
Torroxic Haplustoll	74.09	70.16	72.34	34.36
Torroxic Haplustoll	66.50	63.71	64.19	22.73
Ustoxic Humitropept	12.14	4.64	7.48	6.98
Oxic Dystrandept	14.78	12.50	15.90	16.74
Typic Dystrandept	2.73	0.29	1.02	3.07
Entic Dystrandept	6.58	2.22	4.59	1.80
Typic Eutrandept	9.21	5.04	9.42	11.37
Torroxic Haplustoll	102.22	73.39	82.30	75.1
Typic Paleudult	1.32	ND	0.54	2.05
Typic Paleudult	3.64	0.81	2.98	1.08
Tropeptic Eutrustox	30.06	14.92	33.41	11.48
Typic Torrox	67.20	55.24	69.00	28.10
Typic Eutrandept	4.66	5.04	5.01	9.80
Typic Hydrandept	0.30	ND	0.18	4.06
Hydric Dystrandept	0.10	ND	ND	19.78
Hydric Dystrandept	0.40	ND	0.22	4.50
Hydric Dystrandept	0.61	ND	0.50	11.34
Tropeptic Haplorthox	6.78	0.40	6.90	3.05
Typic Eutrandept	11.94	15.32	10.49	12.31
Typic Eutrandept	74.39	61.09	-	38.72

Table 5.2 (continued) Comparison of labile P (mg P kg soil^{-1}) as obtained from anion exchange resin and isotope P methods.

Soil name	Chloride-sulfate resin [a]	Chloride resin	Bicarbonate resin	Isotope carrier-P
Typic Tropofolist	66.88	50.00	-	72.41
Typic Tropofolist	29.35	33.47	-	34.28
Ardic Haplustoll	78.54	73.59	-	38.49
Ardic Haplustoll	38.76	35.68	-	24.24
Typic Vitrandept	21.15	13.91	-	16.84
Humoxic Tropohumult	0.81	ND	0.42	$S_f > S_i$
Cumulic Haplustoll	29.15	32.66	-	30.12
Typic Torrox	45.54	41.13	-	24.06
Typic Gibbsihumox	2.53	ND	-	4.03
Typic Pellustert	1.11	ND	-	$S_f > S_i$

[a] AEC for chloride-sulfate, chloride, and biocarbonate resins were 6.0, 4.0, and 5.4 cmol kg^{-1} resin respectively.

ND Not detectable.

sulfate form of the resin is commercially available, batch to batch variability in resin samples were negligible, and it is easier to use. These factors though minor may become important if the method is used as a routine laboratory procedure for soil P extraction.

From Table 5.2, the isotope carrier P method appeared as effective as resin P in determining the labile P. The high coefficient of correlation between the isotope P and the resin P in the topsoil further enhances this belief (Table 5.3). However, in some of the soils the carrier P method could not be used because the P in solution was too low to detect or the $S_t > S_i$. Hence, the number of samples analyzed with the isotope carrier P method is lower (Table 5.3). Table 5.4 shows that the isotope method was ineffective in the subsoils; without any significant correlation with the resin method or other chemical extraction method; and was also unable to determine P in more than half the number of samples. In general, the coefficients of correlation for all the P extraction methods were lower in the subsoil. This is attributed to the lower range of P values in the subsoils as compared with the topsoils (Table 5.5 and 5.6).

The carrier method may give satisfactory labile P values for soils with low phosphate-fixing capacity, however, it is not recommended for highly weathered, high phosphate-fixing soils. Amer et al. (1969), Dalal and Hallsworth (1977), and Mekhael et al. (1965) recommended the use of inverse dilution method for high-medium P-fixing soils. Since the inverse dilution method requires determination of solution P both before and after the addition of the inactive carrier P it poses a problem in that the solution P values in most of the high P fixing

Table 5.3 Coefficient of correlation (r)[a] between different soil P extraction methods for topsoil samples.

	Resin P	Isotope P[b]	Mod. Truog P	Bray P	Double Acid P	H_2SO_4 P	Olsen P	Hydroxide P
Isotope P	0.82							
Mod. Truog P	0.85	0.78						
Bray P	0.88	0.87	0.85					
Double Acid P	0.85	0.74	0.74	0.84				
H_2SO_4 P	0.49	0.44	0.67	0.40	0.32**			
Olsen P	0.90	0.89	0.85	0.98	0.84	0.45		
Hydroxide P	0.39	0.37	0.44	0.34	--	0.81	0.40	
Solution P	0.92	0.98	0.92	0.97	0.91	0.45**	0.97	0.38**

a. ** signficant at $P \leq 0.01$ all other coefficients of correlation are significant at $P \leq 0.001$.
b. 77 observations for Isotope P and Solution P. The rest of the variables had 99 observations.

Table 5.4 Some significant coefficient of correlation (r)[a] between different soil P extraction methods for subsoil samples.

	Resin P	Isotope P[b]	Mod. Truog P	Bray P	Double Acid P	H_2SO_4 P	Olsen P
Isotope P	--						
Mod. Truog P	0.44	--					
Bray P	0.83	--	0.38				
Double Acid P	0.69	--	0.39	0.74			
H_2SO_4 P	0.33	--	0.70	0.30	0.24**		
Olsen P	0.75	--	0.53	0.77	0.56	0.52	
Hydroxide P	0.46	--	0.39	0.50	--	0.56	0.66
Solution P	0.71**	0.41*	--	--	--	--	--

a. *, ** significant at $P \leq 0.05$ and $P \leq 0.01$ respectively, all the other coefficients of correlation given are significant at $P \leq 0.001$.

b. 30 observations for Isotope P and Solution P. The rest of the variables had 142 observations.

Table 5.5 Number of observations, mean, range and standard deviation for soil test P and other soil properties in topsoils.

Soil property	Number of observations	Mean	Minimum	Maximum	Standard deviation
Soil P methods (mg/kg)					
Mod. Truog P	91	56.2	0.4	770.8	98.4
Bray I P	91	8.9	0.18	203.6	21.2
Olsen P	91	14.9	0.12	375.8	39.6
Double Acid P	91	5.0	0.13	81.5	10.5
Hydroxide-carb P	91	416.2	8.2	2580.4	603.9
Chloride-sulfate resin P	91	22.34	0.10	255.6	33.2
Chloride resin P	24	34.8	0.0	170.8	39.1
Isotope carrier P	77	16.2	0.0	324.9	41.5
Solution P	77	2.3	0.04	45.0	6.7
0.5 N H_2SO_4 P	91	350.7	16.0	1524.8	373.8
Organic P (mg kg^{-1})	91	402.2	1.4	1983.2	360.9
P Buffering Capacity (l kg^{-1})	66	5062	45	38340	7416
P sorption (mg kg^{-1}) at:					
0.02 mg P l^{-1}	59	162	-150	1065	214
0.10 mg P l^{-1}	63	303	-80	1840	44.2
Clay (%)	72	43.8[a]	2.5	85	44.2
pH	77	5.7	3.8	9.0	1.0
pH (KCl)	45	4.7	3.5	6.4	0.7
Organic C (%)	72	3.9	0.16	16.2	3.5

Table 5.5 (continued) Number of observations, mean, range and standard deviation for soil test P and other soil properties in topsoils.

Soil property	Number of observations	Mean	Minimum	Maximum	Standard deviation
Total N (%)	72	0.33	0.02	1.38	0.31
CEC (cmol(+)kg^{-1})	65	28.0	0.23	97.8	26.7
Base Saturation (%)	65	54.8	5.0	100.0	30.2
Exchangeable bases (cmol (+) kg^{-1})					
Ca	73	11.8	0.10	66.9	13.3
Mg	73	5.1	0.08	39.6	6.2
K	73	0.87	0.0	5.76	1.12
Na	73	0.69	0.0	6.20	1.08
Ex. Al (cmol (+) kg^{-1})	73	0.62	0.0	0.20	1.08
ECEC (cmol(+) kg^{-1})	73	19.3	1.8	104.0	1.17
Al Saturation (%)	73	10.1	0	89.8	19.9
Dith. Cit. extr. Fe (%)	50	6.1	0.13	33.0	5.7
Oxalate extr. Fe (%)	29	0.98	0.06	4.50	1.11
Phosphate retention (%)	36	54.1	1.00	100.0	27.4
Lime required (kg ha^{-1})	73	0.70	0	6.4	1.31
$CaCO_3$ (%)	91	0.79	0.0	33.0	4.73

[a] Log transformed mean re-expressed in terms of the original data using Equations (5.4 and 5.5) (Haan, 1977).

Table 5.6 Number of observations, mean, range and standard deviation for soil test P and other soil properties in subsoils.

Soil property	Number of observations	Mean	Minimum	Maximum	Standard deviation
Soil P methods (mg/kg)					
Mod. Truog P	142	17.1	0.20	194.1	25.3
Bray I P	142	2.1	0.02	13.4	2.9
Olsen P	142	4.4	0.10	41.9	5.7
Double Acid P	142	1.1	0.01	7.6	1.4
Hydroxide-carbonate P	142	160.4	2.1	3626.9	361.4
Choloride-sulfate resin P	142	6.0	0.10	45.5	9.0
Isotope carrier P	57	14.1	0.01	33.5	49.9
Solution P	39	0.23	0.02	0.68	0.17
0.5 N H_2SO_4 P	142	176.8	7.1	1256.2	210.3
Organic P (mg kg^{-1})	142	182.7	0.0	936.4	142.9
P Buffering Capacity (1 kg^{-1})	51	6319.0	131.0	33310.0	6878.0
P sorption (mg kg^{-1}) at:					
0.02 mg P l^{-1}	51	220.0	5.0	760.0	207.0
0.10 mg P l^{-1}	51	521.0	51.0	2000.0	468.0
Clay (%)	116	53.3[a]	0.7	88.7	46.2
pH	116	6.1	4.05	9.30	1.2
pH (KCl)	57	4.7	3.60	6.40	0.74
Organic C (%)	116	1.3	0.06	12.8	1.9

Table 5.6 (continued) Number of observations, mean, range and standard deviation for soil test P and other soil properties in subsoils.

Soil property	Number of observations	Mean	Minimum	Maximum	Standard deviation
Total N (%)	106	0.11	0.01	0.85	0.14
CEC (cmol(+)kg^{-1})	116	25.8	2.4	100.6	26.4
Base saturation (%)	116	61.2	1.0	100.0	33.3
Exchangeable bases (cmol(+) kg^{-1})					
Ca	116	11.9	0.0	69.2	16.1
Mg	116	7.7	0.0	45.2	11.04
K	116	0.32	0.0	2.8	0.53
Na	116	2.2	0.0	23.6	5.1
Exch. Al (cmol(+) kg^{-1})	116	0.56	0.0	7.2	1.15
ECEC (cmol(+)kg^{-1})	116	21.3	0.30	120.0	29.6
Al saturation (%)	116	13.9	0.0	91.7	25.7
Dith.Cit.extr.Fe (%)	88	5.2	0.10	31.0	4.6
Oxalate extr.Fe (%)	25	1.2	0.0	57.0	1.5
Phosphate retention (%)	52	53.1	0.0	100.0	26.6
Lime required (kg ha^{-1})	116	0.63	0.0	8.1	1.3
$CaCO_3$ (%)	116	4.0	0.0	61.0	13.5

[a] Log transformed mean re-expressed in terms of the original data using Equations (5.4 and 5.5) (Haan, 1977).

soils are very low and in many cases undetectable. Thus, the isotope method though designed to detect very low concentrations is far from that because of the need to determine P in solution. Because of these reasons, the ease of laboratory methodology and its relationship to other soil properties (as discussed later in this chapter) the chloride-sulfate anion exchange resin method was used to determine labile P (P_{il}).

Relating labile P to soil - P test methods

Labile P was linearly related to the amount of P extracted by modified Truog, Bray I, double acid, Olsen, hydroxide, sulfuric acid, solution (water), solution ($CaCl_2$), and isotope ^{33}P techniques in the topsoil (Table 5.7). In the subsoil samples the linear relationship also held for all the P extraction methods except for solution P and isotope P (Table 5.7). One reason for this difference is that P in solution could not be determined accurately for many of the subsoil samples because of the very low concentration of P in these samples. The subsoils with their high P sorption (discussed later in the chapter) would also give erroneous (overestimated) values for radiosotope exchangeable P (Amer et al. 1969; Dalal and Hallsworth, 1977).

Since a very wide range of soils were used, a more reliable, appropriate and chemically-based relationship would be obtained if the soils were categorized into similar groups. The volcanic ash soils (Andisols) and soils with free $CaCO_3$ were separated from the rest of the soils and put into two separate groups. If $CaCO_3$ was present in a given horizon, all the remaining samples from that pedon were also

Table 5.7 Relationship between labile P P_{il} and modified Truog P (MTP), Bray I P (BP), double acid P (DP), Olsen P (OP), hydroxide P (HP), water P (WP), and isotope P (IP).

Equation	Number of observations	Root mean square error	R^2 a
	Topsoil		
P_{il}= 0.28 MTP + 6.15	91	17.58	0.72
1.35 BP + 10.24	91	15.76	0.78
2.65 DP + 9.39	91	17.40	0.73
0.74 OP + 11.39	91	14.31	0.82
0.020 HP + 13.43	91	30.80	0.15
5.80 WP + 13.97	77	17.20	0.84
0.67 IP + 9.54	77	19.91	0.67
	Subsoil		
Pil= 016 MTP + 3.85	142	8.37	0.14
2.66 BP + 0.73	142	4.96	0.70
4.66 DP + 1.64	142	6.68	0.47
1.18 OP + 1.11	142	5.95	0.57
0.011 HP + 4.23	142	8.00	0.21
1.10 WP + 3.30	57	9.49	0.003^{ns}
-0.01 IP + 8.60	57	10.35	0.002^{ns}

ns: not significant at 95% level

classified as calcareous soils. The Andisols were separated because of their unique chemical and physical properties- high amorphous clay content, low bulk density and irreversible changes in physical and mechanical properties on drying (Warkentin and Maeda, 1980). The remaining (non calcareous and non-volcanic) soils were divided into two groups: slightly weathered and highly weathered soils according to Sharpley et al. (1984a). This classification improved the coefficient of determination for the regression equations and also reduced the errors in estimations. Further improvements were obtained when the separation of soils into weathering groups was based on CEC of 16 cmol(+) kg^{-1} clay. Soils with CEC less than 16 cmol(+) kg^{-1} clay in the subsoils and acidic ochrepts were classified as low activity clay or highly weathered soils and the remaining soils were the high activity clay or the slightly weathered soils. The mean, range and standard devitation for these four categories of soils are given in Appendix 5.2-5.5.

For the slightly weathered soils, all the P extraction methods used were linearly related to labile P. In the commonly used soil P test methods: modified Truog, Bray 1, double acid, Olsen, and solution P more than 75% of the variation in P_{il} was explained by the regression equations (Table 5.8). The strong extractants like 0.5 M H_2SO_4 and 0.25 M NaOH with 0.1 M Na_2CO_3 which assessed the quantity factor explained about 60% of the variation in P_{il}. In the highly weathered soils, the hydroxide extractable P was not related to labile P. The sulfuric acid extractant although highly significant ($P > 0.999$) explained only 29% of the variation in P_{il}. In the highly weathered

Table 5.8 Relationship between labile P P_{il} and modified Truog P (MTP), Bray I P (BP), double acid P (DP), Olsen P (OP), hydroxide P (HP), sulfuric acid P (SP), solution P (SOLP), water P (WP), and isotope P (IP).

Equation	Number of observations	Root mean square error	R^2 a
Slightly weathered soils			
P_{il}= 0.34 MTP + 3.35	120	8.91	0.91
1.37 BP + 6.77	120	13.71	0.78
2.71 DP + 5.82	120	14.65	0.76
0.76 OP + 6.53	120	12.45	0.83
0.07 HP + 1.49	120	18.38	0.61
0.08 SP + 3.89	120	18.65	0.60
5.97 WP + 9.03	68	14.02	0.86
0.80 IP + 6.92	68	15.75	0.82
187.30 SOLP + 11.87	73	19.70	0.69
Highly weathered soils			
P_{il}= 1.07 MTP - 1.49	70	5.14	0.85
2.88 BP - 0.30	70	3.71	0.92
5.97 DP - 0.21	70	3.41	0.93
2.50 OP - 2.19	70	4.85	0.86
0.094 SP + 1.29	70	11.08	0.29
2.36 IP + 3.89	44	9.23	0.50
658.98 SOLP + 10.70	15	8.23	0.59
Andisols			
P_{il}= 0.27 MTP - 0.73	21	5.19	0.92

Table 5.8 (continued) Relationship between labile P P_{i1} and modified Truog P (MTP), Bray I P (BP), double acid P (DP), Olsen P (OP), hydroxide P (HP), sulfuric acid P (SP), solution P (SOLP), water P (WP), and isotope P (IP).

Equation	Number of observations	Root mean square error	R^2 [a]
	Andisols		
2.88 BP - 2.11	21	9.16	0.74
4.52 DP + 6.67	21	16.12	0.21*
1.41 OP - 2.56	21	4.22	0.95
0.01 HP - 2.69	21	14.89	0.32
0.03 SP - 9.03	21	13.08	0.48
0.55 IP - 0.30	11	5.69	0.39*
	Calcareous soils		
P_{i1}=0.05 MTP + 1.27	22	6.46	0.26*
1.81 BP + 1.88	22	4.99	0.56
1.38 OP + 0.37	22	6.36	0.28**
0.048 HP + 3.20	22	5.02	0.55
5.92 WP + 0.09	10	4.51	0.78

a: *, ** significant at P<0.05 and P<0.01, respectively while all the other coefficients of determination are significant at P<0.001.

soils double acid method explained 93% of the variation in labile P. Fitts (1956) reported that the double acid method was much better correlated with A values or percent yields on soils which had predominantly kaolinitic clay minerals, than on soils which had 2:1 type clay minerals. The results in Table 5.8 further support the above statement, e.g. in calcareous soils (predominantly 2:1 minerals) the double acid method was not correlated with labile P. In the Andisols with amorphous mineralogy, the double acid P explained only 21% of the variation in labile P. Thus, the double acid extractant which was developed for the highly weathered soils in the southeastern United States could be used successfully with the highly weathered soils from the tropic but not on volcanic ash soils.

The Olsen's method which was designed for calcareous and slightly weathered soils is also as effective for Andisols and highly weathered soils (Table 5.8). Thomas and Peaslee (1973) have reported that the Olsen extractant is more universal or reacts more consistently across a wide range of soil types. Another extractant which could be applied on a wide range of soil types as evident from Table 5.8 and results of Sharply et al. (1984a) is the Bray I. The modified Truog extractant which is widely used in the tropics for noncalcareous weathered soils, explained more than 80% of the variations in labile P in these soils. Thus, there is no single extractant which is superior to the others under all soil conditions, however, there are some that could be used consistently across a wide range of soil types. Comparison of Tables 5.7 and 5.8 shows the usefulness and importance of dividing soils into appropriate groups to fully understand the reactions they undergo.

Relationships among soil P test values

The commonly used soil P test methods: modified Truog, Bray I, double acid, and Olsen were linearly related to each other. The coefficient of determination in the slightly weathered soils ranged from 0.72 to 0.96. The lower coefficients were obtained with the double acid extractant (Table 5.9). For the highly weathered soils the coefficents of determination (R^2) ranged from 0.84 to 0.91. Thus, as far as the noncalcareous and nonvolcanic ash soils are concerned, one could use any of the above soil P test methods quite satisfactorily. In the calcareous soils, however, the double acid extractant was not related to the other three soil P extractants. This further illustrates the nature of soils for which the double acid extractant was developed. Modified Truog P was the only method related to both the Olsen P and Bray P. In the Andisols modified Truog was the only extractant for which linear relationships were obtained with the other three extractants. The coefficient of determination ranged from 0.31 (with double acid) and 0.92 (with Olsen).

It is interesting to note that Olsen P was linearly related to sulfuric acid P and hydroxide P in all soil types. This points out the 'universal' nature of the Olsen extractant, its ability to consistently react on a wide range of soil types. The above relationship also points out that calcium phosphate (hydroxy-apatite) is not the only P form present in calcareous soils studied. Hydroxide ions have little effect on basic Ca-P, but will dissolve Fe-P and Al-P while hydroxyl ions greatly increase the solubility of Ca-P, yet both hydroxide P and sulfuric acid P were linearly related to Olsen P.

Table 5.9 Relationship between modified Truog (MTP), Bray I (BP), double acid (DP), Olsen (OP), hydroxide (HP), sulfuric acid (SP), water (WP), solution P (SOLP), and isotope (IP) (mg P/kg soil) soil P tests.

Equation	Number of observations	Root mean square error	R^2 [a]
	Slightly weathered soils		
MTP=401 BP + 10.84	120	31.1	0.86
7.36 DP + 9.54	120	4.54	0.72
2.16 OP + 10.47	120	31.1	0.87
0.19 HP - 3.47	120	51.8	0.62
0.24 SP - 21.73	120	50.3	0.64
17.40 WP + 17.17	68	33.8	0.90
2.29 IP + 3.17	68	35.1	0.88
BP= 0.22 MTP - 1.53	120	7.2	0.86
1.71 DP - 0.01	120	10.1	0.73
0.53 OP - 0.012	120	3.6	0.96
0.038 HP - 1.55	120	13.9	0.46
0.04 SP - 3.27	120	15.3	0.34
4.26 WP + 1.07	68	5.8	0.95
0.57 IP - 1.19	68	7.6	0.91
DP= 0.098 MTP + 0.059	120	5.2	0.72
0.43 BP + 0.92	120	5.0	0.73
0.23 DP + 0.89	120	5.1	0.72
0.016 HP + 0.23	120	7.8	0.34
0.018 SP - 0.84	120	8.1	0.29

Table 5.9 (continued) Relationship between modified Truog (MTP), Bray I (BP), double acid (DP), Olsen (OP), hydroxide (HP), sulfuric acid (SP), water (WP), solution P (SOLP), and isotope (IP) (mg P/kg soil) soil P tests.

Equation	Number of observations	Root mean square error	R^2 [a]
	Slightly weathered soils		
DP= 1.82 WP + 1.41	68	4.6	0.84
0.24 IP + 0.87	68	7.1	0.66
OP= 0.40 MTP - 2.68	120	13.4	0.87
1.82 BP + 0.41	120	6.8	0.96
3.18 DP + 0.24	120	19.0	0.72
0.074 HP - 3.32	120	25.0	0.50
0.077 SP - 6.58	120	28.4	0.36
7.95 WP + 0.88	68	9.8	0.96
1.10 IP - 2.79	68	11.2	0.94
HP= 3.23 MTP + 85.51	120	212.3	0.62
12.01 + 120.3	120	248.4	0.46
20.82 DP + 121.82	120	279.2	0.34
6.79 OP + 116.21	120	239.6	0.50
1.09 SP - 51.92	120	153.5	0.79
51.01 WP - 145.15	68	306.9	0.48
6.83 IP - 88.50	68	251.6	0.56

Table 5.9 (continued) Relationship between modified Truog (MTP), Bray I (BP), double acid (DP), Olsen (OP), hydroxide (HP), sulfuric acid (SP), water (WP), solution P (SOLP), and isotope (IP) (mg P/kg soil) soil P tests.

Equation	Number of observations	Root mean square error	R^2 a
Slightly weathered soils			
SP= 2.66 MTP + 140.59	120	166.9	0.64
8.49 BP + 172.21	120	223.4	0.34
15.53 DP + 175.25	120	235.6	0.29
4.70 OP + 172.85	120	221.0	0.36
0.73 HP + 83.34	120	125.5	0.79
36.14 WP + 202.3	68	258.1	0.39
4.61 IP + 142.94	68	191.6	0.49
WP= 0.14 IP - 0.35	68	1.18	0.97
Highly weathered soils			
MTP= 2.34 BP + 2.93	70	4.6	0.84
4.94 DP + 2.76	70	3.4	0.91
2.18 OP + 0.30	70	3.6	0.90
0.036 HP + 8.31	70	10.6	0.15
0.11 SP + 1.97	70	8.5	0.45
2.24 IP + 4.85	44	7.8	0.56
BP= 0.34 MTP - 0.28	70	1.73	0.84
1.86 DP + 0.34	70	1.35	0.90
0.79 OP - 0.44	70	1.64	0.85

Table 5.9 (continued) Relationship between modified Truog (MTP), Bray I (BP), double acid (DP), Olsen (OP), hydroxide (HP), sulfuric acid (SP), water (WP), solution P (SOLP), and isotope (IP) (mg P/kg soil) soil P tests.

Equation	Number of observations	Root mean square error	R^2 [a]
	Highly weathwered soils		
BP= 0.013 HP + 2.34	70	3.99	0.14
0.039 SP + 0.44	70	3.23	0.43
0.78 IP + 1.82	44	3.18	0.48
DP= 0.18 MTP - 0.31	70	0.65	0.91
0.48 BP + 0.064	70	0.69	0.90
0.41 OP - 0.31	70	0.79	0.87
0.017 SP + 0.39	70	1.84	0.30
0.42 IP + 0.65	44	1.45	0.56
OP= 0.41 MTP + 0.51	70	1.58	0.90
1.07 BP + 1.33	70	1.91	0.85
2.11 DP + 1.46	70	1.78	0.87
0.016 HP + 3.52	70	4.59	0.16
0.044 SP + 1.15	70	3.84	0.41
0.87 IP + 2.74	44	3.52	0.48
HP = 4.13 MTP + 100.9	70	112.8	0.15
10.80 BP + 106.1	70	116.3	0.14
9.92 OP + 93.51	70	114.9	0.16
1.43 SP - 1.94	70	71.0	0.68

Table 5.9 (continued) Relationship between modified Truog (MTP), Bray I (BP), double acid (DP), Olsen (OP), hydroxide (HP), sulfuric acid (SP), water (WP), solution P (SOLP), and isotope (IP) (mg P/kg soil) soil P tests.

Equation	Number of observations	Root mean square error	R^{2a}
	Highly weathered soils		
SP = 4.22 MTP + 53.81	70	53.3	0.45
11.04 BP + 60.64	70	54.2	0.43
17.63 DP + 73.41	70	59.8	0.30
9.19 OP + 53.34	70	55.5	0.41
0.47 HP + 35.66	70	40.9	0.68
8.57 IP + 80.20	44	63.5	0.22
	Andisols		
MTP =10.39 BP - 3.71	21	31.0	0.77
19.72 DP + 23.91	21	53.4	0.31**
4.97 OP + 3.88	21	17.9	0.92
0.11 SP - 30.26	21	44.9	0.51
BP = 0.07 MTP + 1.42	21	2.6	0.77
0.37 OP + 1.06	21	2.8	0.74
DP = 0.016 MTP + 0.44	21	1.5	0.31**
OP = 0.19 MTP + 1.52	21	3.5	0.92
1.97 BP + 0.64	21	6.4	0.74
0.0088 HP - 1.34	21	9.4	0.43
0.023 SP - 5.23	21	8.3	0.55

Table 5.9 (continued) Relationship between modified Truog (MTP), Bray I (BP), double acid (DP), Olsen (OP), hydroxide (HP), sulfuric acid (SP), water (WP), solution P (SOLP), and isotope (IP) (mg P/kg soil) soil P tests.

Equation	Number of observations	Root mean square error	R^{2a}
	Andisols		
HP= 48.66 OP + 820.47	21	698.4	0.43
1.83 SP + 76.48	21	563.1	0.64
SP= 4.50 MTP + 466.50	21	281.6	0.51
24.11 OP + 430.85	21	270.5	0.55
0.35 HP + 216.63	21	241.8	0.64
	Calcareous soils		
MTP=19.61 + 41.93	22	46.4	0.63
17.49 OP + 17.00	22	57.4	0.44
BP= 0.03 MTP - 0.69	22	1.88	0.63
DP= 0.0027 SP - 0.05	22	1.14	0.40
OP= 0.025 MTP + 1.52	22	2.17	0.44
0.015 HP + 2.86	22	2.34	0.35**
0.0057 SP + 0.56	22	2.13	0.46
HP= 23.86 OP - 41.61	22	94.5	0.35**
148.05 DP + 315.6	22	268.7	0.40
81.22 OP + 231.2	22	254.9	0.46

[a]: ** significant at $p \leq 0.01$ all other coefficients of determination are significant at $p \leq 0.001$.

5.3.2 Relating labile phosphorus, organic phosphorus, P availability index and P buffering capacity to soil chemical and physical properties

Labile P

A summary of selected soil properties for the four soil categories, viz., slightly weathered, highly weathered, Andisols and calcareous soils are given in Appendix 5.2-5.5. Even within a given soil category the soil properties vary considerably. This wide range of tropical soils was selected for the study with the assumption that regression models developed on these soils could be applied to other soils from the region.

Such properties as the CEC of the soils and the exchangeable bases (Ca, Mg, K, Na) were positively correlated with total N and organic carbon content in all the soils (Table 5.10). Similarly exchangeable bases were positively related to pH and negatively to KCl-extractable Al. As expected in the calcareous soils the effect of Al on pH was insignificant. In both the slightly and highly weathered soils pH (KCl) was positively related to free-iron oxide content and also to delta pH. Therefore, in these soils the zero point of charge increased due to the presence of free iron oxide. The higher iron oxide content also explained the higher P retention of these soils. However, in Andisols the phosphate retention was negatively correlated to free iron oxide content and positively to CEC. This may be due to the positive relationship between organic matter and phosphate retention. Several researchers have reported positive relationship between the organic matter contents of soils and P adsorption (Harter, 1969; Holford and

Table 5.10 Some significant (<0.01) coefficients of correlation (Pearson's t) between different soil properties.

	pH	Organic C	Total N	Base Saturation	CEC	KCl-Al	Dith-cit Fe	Phosphate retention	Exch. cations Ca	Mg	K	Na
			(%)		(cmol(+) kg^{-1})			(%)			(cmol(+) kg^{-1})	
Slightly weathered soils												
pH (KCl)	0.77	--	--	0.38	--	-0.48	0.56	--	0.37	--	0.42	--
pH	--	-0.25	-0.28	0.66	0.60	-0.45	--	--	0.73	0.68	0.25	0.48
Organic C	--	--	0.75	-0.26	0.28	--	--	0.42	--	--	--	--
Total N	--	--	--	--	0.26	--	--	0.38	--	--	--	--
Base saturation	--	--	--	--	0.38	-0.48	-0.40	-0.48	0.70	0.52	0.32	0.25
Delta pH	--	--	--	--	--	--	0.61	--	0.57	0.52	--	--
CEC	--	--	--	--	--	--	--	--	0.88	0.90	--	0.70
KCl extr. Al	--	--	--	--	--	--	--	--	-0.30	--	--	--
Dith.-cit. Extr. Fe	--	--	--	--	--	--	--	0.59	-0.29	-0.28	--	--
Exch Ca	--	--	--	--	--	--	--	--	--	0.86	--	0.57
Highly weathered soils												
pH (KCl)	0.64	--	--	--	--	-0.57	0.69	--	--	--	--	--
pH	--	-0.43	-0.49	0.52	--	-0.66	--	--	0.40	--	--	--
Organic C	--	--	0.92	--	0.81	--	--	--	--	--	--	--
Total N	--	--	--	--	0.84	--	--	--	--	--	0.53	--
Base saturation	--	--	--	--	--	-0.52	--	--	0.86	0.72	--	--
Delta pH	--	--	--	--	--	--	0.71	--	--	--	--	--
CEC	--	--	--	--	--	--	--	--	0.41	0.48	0.43	--
KCl extr. Al	--	--	--	--	--	--	--	--	-0.61	-0.51	--	--
Exch Ca	--	--	--	--	--	--	--	--	--	0.84	0.57	0.48
Exch Mg	--	--	--	--	--	--	--	--	--	--	0.53	0.54

Table 5.10 (continue) Some significant (<0.01) coefficients of correlation (Pearson's t) between different soil properties.

	pH	Organic C	Total N	Base Saturation	CEC	KCl-Al	Dith-cit Fe	Phosphate retention	Ca	Exch. cations Mg	K	Na
	(%)				(cmol(+) kg^{-1})		(%)		(cmol(+) kg^{-1})			
Andisols												
pH (KCl)	0.89	--	--	--	--	-0.81	-0.62	--	0.69	--	--	--
pH	--	--	--	0.84	0.71	-0.62	--	--	0.71	0.71	--	--
Organic C	--	--	0.90	--	0.83	--	--	0.60	0.75	0.70	--	--
Total N	--	--	--	--	0.70	--	--	--	0.65	0.63	--	--
Base saturation	--	--	--	--	0.70	--	--	--	0.86	0.85	--	--
CEC	--	--	--	--	--	--	--	0.82	0.90	0.77	--	--
KCl extr. Al	--	--	--	--	--	--	0.63	-0.88	-0.62	-0.52	--	--
Dith.-cit. Extr. Fe	--	--	--	--	--	--	--	-0.89	--	--	--	0.63
Exch Ca	--	--	--	--	--	--	--	--	--	0.88	--	--
Calcareous soils												
$CaCO_3$ (%)	--	-0.55	-0.51	--	-0.87	--	--	--	--	0.56	--	--
Organic C	--	--	0.92	--	0.61	--	--	--	--	0.53	--	--
Total N	--	--	--	--	0.51	--	--	--	--	--	--	--
Clay (%)	--	--	--	--	0.59	--	--	--	--	--	--	--
CEC	--	--	--	--	--	--	--	--	--	0.89	--	--

Mattingly, 1975). These relationships probably reflect the association of organic matter with cations such as Fe and Al. These cations are capable of adsorbing P while still associated with organic matter, and hence the positive relationship with organic matter would be expected (Sample et al., 1980). Thus, the dithionite-citrate extractable Fe was negatively correlated with phosphate retention because the Fe measured by this method reflect free iron oxide and not organically bound Fe.

Due to irreversible drying of Andisols, correlation of clay content with other soil properties is not shown in Table 5.10. In calcareous soils, the clay content was as important in determining CEC as the organic matter content. In contrast, the CEC of the more weathered soils were not significantly related to texture. The Pearson r for correlation between CEC and organic carbon increased from 0.28 in slightly weathered soils, 0.61 in calcareous soils and eventually to 0.81 in highly weathered and volcanic ash soils. Thus from foregoing cases the justification for dividing the soils into different weathering and chemicals groups is evident.

Labile P and chemically extractable P were positively related to exchangeable bases (Ca, Mg, K, or Na) in the noncalcareous soils (Table 5.11). Thus, the high base status soils would have higher labile P and vice versa. The labile P was negatively related to extractable Al and P buffering capacity in the more weathered soils. In such soils labile P would be lower because of precipitation reactions with Al (Sanchez and Uehara, 1980). Correlations between P fixation and exchangeable Al have been reported (Syers et al., 1971; Udo and Uzo. 1972). In the calcareous soils extractable P was positively related to cation

Table 5.11 Coefficients of correlation (r) between different soil P extraction technique, organic P, P availability index, buffering capacity and other soil properties.

	Resin P	Mod. Truog P	Bray P	Double acid P	Olsen P	Sulfuric acid P	Hydroxide P	Solution P	Isotope P	Organic P	F_1	Buffering capacity
Slightly weathered soils												
Clay	--	--	--	--	--	--	--	--	--	--	-0.32	--
Exch Ca	--	--	--	--	--	0.23	--	--	--	--	--	-0.28
Exch K	0.72	0.64	0.57	0.61	0.56	0.60	0.54	0.61	0.69	0.21*	--	--
pH (KCl)	0.38	0.35	--	0.41	0.26*	0.45	0.32	0.37	0.36*	--	--	--
pH	0.18*	--	--	--	--	0.28	--	--	--	-0.23*	--	-0.28*
Organic C	--	--	--	--	--	--	--	--	--	0.58	--	0.40*
Total N	--	--	--	--	--	--	--	--	--	0.53	--	--
Base saturation	0.21*	0.19*	--	--	--	0.21*	--	--	--	-0.29*	--	-0.61*
KCl-extr Al	--	--	--	--	--	-0.20*	--	--	--	--	--	--
Dith.-cit. Extr. Fe	--	--	--	--	--	--	0.28	--	--	0.33	--	0.37*
Phosphorus retention	--	--	--	--	--	--	--	--	--	--	-0.40	0.75
Organic P	0.35	0.36	0.26	--	0.22*	0.54	0.54	--	0.25*	1.00	--	0.34*
Buffering capacity	-0.22*	--	--	-0.23*	--	--	--	--	--	0.34	--	1.00
F_1	0.35	0.38	0.39	0.48	0.39	--	--	0.41	0.36	--	1.00	-0.32
Highly weathered soils												
Exch bases: Ca	0.77	0.57	0.75	0.73	0.59	--	--	--	0.55*	--	--	--
Mg	0.62	0.43*	0.54	0.54	0.40*	--	--	--	--	--	--	--
K	0.64	0.59	0.61	0.70	--	--	--	--	--	--	--	--
Na	0.59	0.57	0.51	0.48*	0.53	--	--	--	--	--	--	0.60*
Total N	--	--	0.39*	--	--	--	--	--	--	--	--	--
Base saturation	0.39*	--	--	--	--	--	--	--	--	-0.41	0.61*	-0.63*
KCl-extr Al	-0.40*	--	-0.44*	--	--	-0.38*	--	--	--	-0.38*	--	--
Organic P	--	--	--	--	--	0.61	0.69	--	--	1.00	--	--
Buffering capacity	-0.57*	--	-0.52*	-0.54*	--	--	-0.49	--	--	--	--	1.00
F_1	0.86	0.83	0.80	0.86	0.78	--	--	--	--	--	1.00	-0.74

Table 5.11 (continue) Coefficients of correlation (r) between different soil P extraction technique, organic P, P availability index, buffering capacity and other soil properties.

		Resin P	Mod. Truog P	Bray P	Double acid P	Olsen P	Sulfuric acid P	Hydroxide P	Solution P	Isotope P	Organic P	F_1	Buffering capacity
Andisols													
Exch bases:	Ca	--	--	--	--	--	0.55*	--	--	--	--	--	-0.54*
	Mg	0.45*	--	--	--	0.46*	0.53*	--	--	--	--	--	-0.57*
	K	--	--	--	--	--	--	--	--	--	0.73	0.87	-0.50*
	Na	0.45*	0.46*	0.44*	--	--	--	--	-0.77*	-0.78	--	--	--
Organic C		--	--	--	--	--	--	--	--	--	0.47*	--	--
Total N		--	--	--	--	--	--	--	--	--	0.58	--	--
Base saturation		--	--	--	--	--	0.50*	--	--	--	--	--	-0.62*
CEC		--	--	--	--	--	0.61	0.54*	--	--	--	--	--
Oxalate-Fe		--	--	--	--	--	--	--	--	--	--	-0.71*	0.79*
delta pH		-0.54*	--	--	--	--	--	--	--	--	--	--	0.82
Organic P		-0.42*	--	--	--	--	--	--	--	--	1.00	--	--
Calcareous soils													
Exch bases:	Mg	--	-0.44*	--	--	0.49*	-0.66	--	--	--	--	--	0.74*
	Na	-0.54	-0.53	-0.55	--	--	--	--	--	--	--	--	--
pH		--	--	--	--	-0.63	--	--	--	--	--	0.85	--
Organic C		--	--	--	0.42*	--	--	--	--	--	--	--	--
Total N		--	--	--	0.52*	--	--	--	--	--	--	--	--
$CaCO_3$		-0.57	--	-0.52	--	--	--	--	--	--	--	--	--
Clay		--	-0.63	--	-0.50*	-0.71	-0.81	--	-0.80	--	--	--	--
CEC		--	--	--	--	--	-0.68	--	--	--	--	--	0.82
CEC/% clay		0.66	0.48*	0.51*	--	--	-0.46*	0.43*	--	--	--	--	--
dith.-Fe		--	--	--	--	--	--	--	--	--	--	-0.97	--

* r signigicant at $\leq$5%, rest of the values presented are significant at $\leq$1% level.

exchange capacity:clay (%) ratio and negatively to clay content. Most of the soils in the calcareous group have similar mineralogy. It has been observed that among soils of similar clay mineralogy, P fixation increases with increasing clay content (Sanchez and Uehara, 1980). Thus, part of the positive relationship between labile P and CEC/clay (%) was related to clay content. The clays with higher CEC have more labile P because of their higher negative charge density and hence very little P sorption. In the Andisols labile P was negatively related to delta pH. The labile P content of the soil as expected would increase as the delta pH became more negative and hence the soil will be less P sorbing. This is reflected in Table 5.11 as buffering capacity is positively correlated to delta pH.

The relationships from Table 5.11 were used to improve the estimation of labile P form soil test P (Table 5.8). The modified equations are presented in Table 5.12. On incorporation of K into the equations for estimating labile P the R^2 values increased and the errors in estimation of P_{il} became smaller for the slightly weathered soils. Exchangeable K alone explained for more than 50% of the variation in labile P. The positive relationship between labile P and exchangeable K in slightly weathered soils cannot be explained solely on the basis of K retention on P application. In tile drainage studies, the concentrations of the two nutrients were also significantly correlated (Grant et al., 1982). In the remaining groups of soil estimation of labile P was not improved when other soil properties were incorporated with soil test P. In the highly weathered

Table 5.12 Relationship between labile P P_{il}, (mg P/kg soil), soil test P (mg P/kg soil), and soil properties in four groups of soil.

Equation		Number of observations	Root mean square error	R^2 [b]
	Slightly weathered soils			
P_{il}=	0.30 MTP[a] + 5.85 K + 1.48	120	7.96	0.93
	1.09 BP + 10.59 K + 2.71	120	11.39	0.85
	2.16 DP + 9.58 K + 2.42	120	13.03	0.81
	0.62 OP + 10.09 K + 2.62	120	10.02	0.89
	0.05 HP + 13.02 K - 2.16	120	15.26	0.73
	4.82 WP + 10.01 K + 4.12	68	11.06	0.91
	0.64 IP + 11.02 K + 2.49	68	14.20	0.85
	24.03 K^C + 1.67	120	20.56	0.52
	Highly weathered soils			
P_{il}=	2.32 Ca^2 - 5.32 Ca + 2.62	30	5.70	0.75
	15.70 CaK + 0.24	30	4.25	0.86
	51.05 K - 0.89	30	7.91	0.52
	Andisols			
P_{il}=	-11.97 + 60.37 ln(1 - ΔpH) -76.09 [Na x ln(1 - ΔpH)]*	13	8.91	0.53*

Table 5.12 (continued) Relationship between labile P P_{il}, (mg P/kg soil), soil test P (mg P/kg soil), and soil properties in four groups of soil.

Equation	Number of observations	Root mean square error	R^2 [b]
	Calcareous soils		
P_{il}= 0.074 CEC^d - 0.0032 x (Na x CEC) +0.20	22	2.82	0.73

a MTP= Modified Truog P, BP= Bray I P, DP= Double acid P, OP= Olsen P, HP= hydroxide P, SP= sulfuric acid P, WP= solution P and IP= isotope P.

b All coefficient of determination (r^2) are signifcant at $p \leq 0.001$.

c K, CA, Na in cmol (+) kg $soil^{-1}$

d CEC in cmol (+) kg $clay^{-1}$

* These variables are significant at $p \leq 0.05$, the remaining varible are significant at $p \leq 0.01$.

soils, Ca was non-linearly related to P_{il} and explained 75% of the variation in the labile P content of the soils. The interaction between Ca and K in these soils explained over 85% of the variation in P_{il}. In the Andisols, delta pH and the interaction between delta pH and Na explained slightly more than half of the variation in P_{il} (Table 5.12). This may be attributed to the fact that as delta pH became smaller i.e. more negative, the negative charge density on the colloids increased, lesser P was sorbed and hence there was an increase in P_{il}. In calcareous soils, CEC in cmol(+) kg clay^{-1} or CEC/%clay and the interaction between CEC/% clay and Na explained 73% of the variation in P_{il}. This as discussed earlier may be attributed to clay content and charge density.

The relationships between labile P and K in slightly weathered soils, and labile P an Ca or Ca x K interaction in highly weathered soils may be attributed to variable charge concept. In the slightly weathered soils with mixture of variable and permanent charge clays the effect is not as marked as in the highly weathered soils with predominantly variable charge clays. In the variable charge soils as the pH_o decreases the colloids may become more negatively charged if they were initially negatively charged or have lower charge density if colloids were initially positively charged (Eq.5.6).

$$\sigma_v = (2n\varepsilon kT/\pi)^{1/2} \sinh 1.15z(pH_o - pH) \qquad (5.6)$$

where σ_v = surface charge density for variable charge clloids in C/m^2

z = valence of counterion

n = ionic concentration in ions/m^3

ε = dielectric constant = 8.9 x 10^{-9} C^2/Jm

k = Boltzmann constant = 1.38 x 10^{-23} J/ion K

T = temperature in Kelvin, and

pH_o = pH at zero net surface charge = zero point of charge.

Thus, it would be possible to increase the cation retention of variable charged soil by lowering pH_o. This effect has been obtained on application of phosphate which resulted in increased negative surface charge density of a Gibbsihumox and a Hydrandept (El-Swaify and Saygeh, 1975) and Torrox (Wann and Uehara, 1978).

In highly weathered soils as the labile P content increases the cation retention also increased (Figure 5.1). Further, as expected from Eq.(5.6) a divalent ion (Ca) would be retained readily more than a monovalent ion (K) (Table 5.12). The regression model has a minimum P_{il} value at 0.7 cmol Ca /kg soil (Figure 5.1). This may reflect the point where the soils are at the zero point of charge (pH= pH_o). The negative slope is due to adsorption of P on positively charge colloids. Ayres and Hagihara (1953) showed that K retention was measurably reduced by prior application of phosphorus fertilizer to an Andisol (Typic Hydrandept). However, in the present study P_{il} in the Andisols were not correlated with either exchangeable K or Ca. On dehydration a surface with exchangeable or sorbed ions may coalesce with another suface thus occluding the retained/sorbed ions. Kanehiro and Sherman (1956) have reported a significant decrease in CEC when

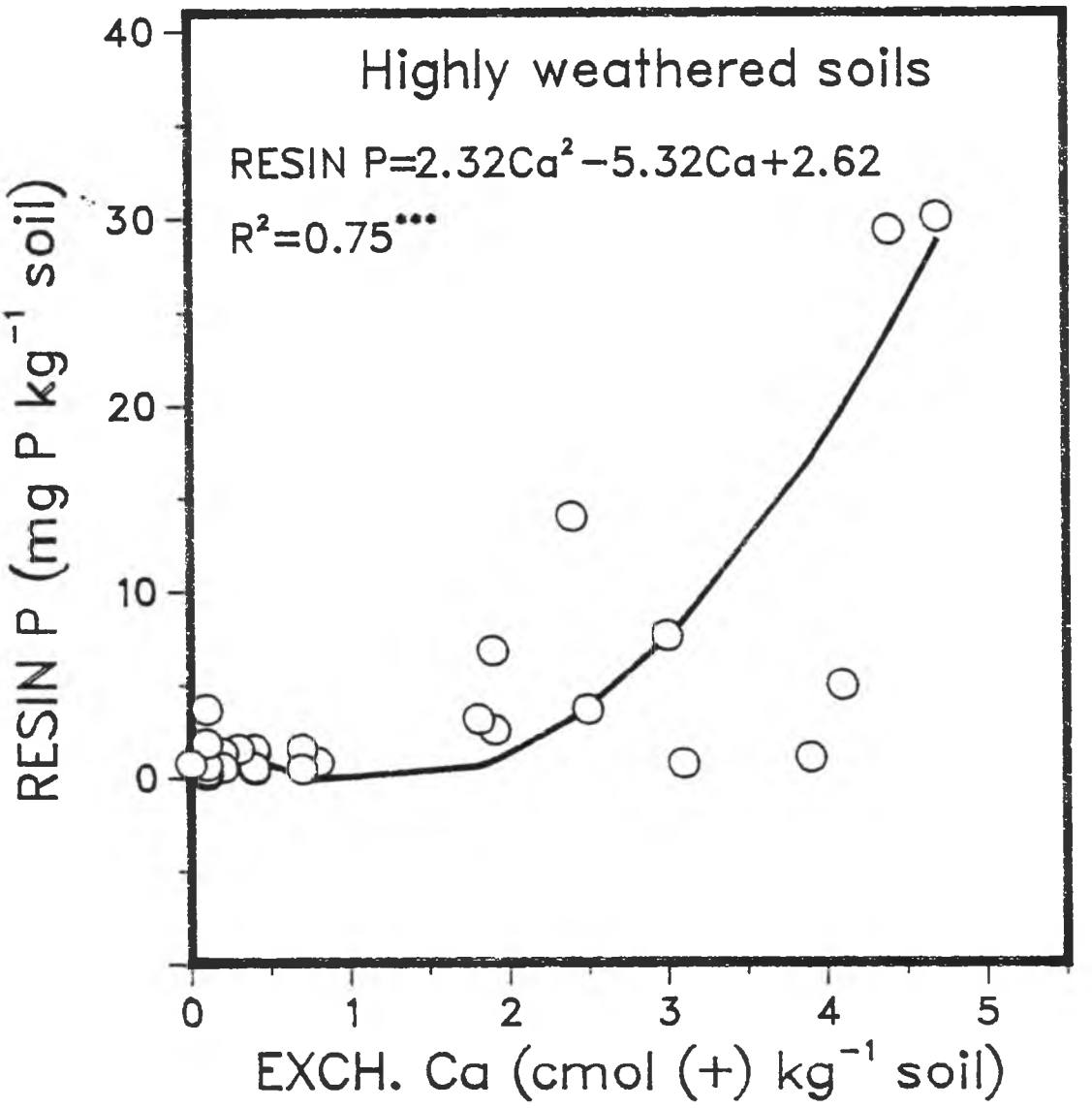


Figure 5.1 Relationship between labile phosphorus and exchangeable calcium.

volcanic ash soils were dehydrated. Recalling, all the physical and chemical analyses (except for P determination in the Andisols) were done on air-dried soils, suggests that some of the anomolous results may be attributed to irreversible drying of the Andisols.

This was shown to be the case when positive correlations were obtained between extractable P and exchangeable K and Ca on an independent set of data where the Andisols were not air-dried (Parra, 1983). Exchangeable Ca and Ca x K explained 37% of the variation in Olsen P,

$$\text{Olsen P} = 0.33*Ca + 0.26(Ca*K) - 1.58 \quad (R^2=0.37,\ P\geq 0.999,\ N=50)$$

Organic P

Preliminary investigation on selected soils with varying degree of weathering indicated that the extraction (Mehta et al. 1954) and the ignition (Walker and Adams, 1958) methods yielded similar quantities of organic P (P_o) (Table 5.13). It has been reported that the ignition procedure overestimates the organic P content in highly weathered soils (Williams et al. 1970). In such soils the solubility of Al- and Fe-bound P in 1 N H_2SO_4 after ignition at 550 C was increased and resulted in erraneously high P_o values. In the present study 0.5 N H_2SO_4 was used to minimize the above error. However, both the extraction and ignition procedures would underestimate the organic P content of soils because of acid hydrolysis during treatment of unignited samples (Olsen and Sommers, 1982). Because of the above reasons, the much simpler and less laborious ignition method was used for the remaining soils.

Table 5.13 Comparison of organic P content (mg P kg soil^{-1}) for selected soils as determined by ignition (Walker and Adams, 1958) and extraction (Mehta et al. 1954) methods.

Soil	Ignition	Extraction
Torroxic Haplustoll	126.0	144.1
Typic Eutrandept	917.3	885.4
Oxic Dystrandept	755.7	1173.6
Hydric Dystrandept	62.2	1094.5
Ustoxic Humitropept	832.0	706.5
Tropeptic Eutrustox	239.5	145.3
Typic Gibbsihumox	285.1	267.4
Typic Paleudult	75.6	92.6

The organic P content (mg P/kg soil) of the soils in this study was linearly related (R^2= 0.56, P>0.999) to total nitrogen (%) or organic carbon (%) in all groups of soils (N= 180) according to the following equations:

$$P_o = 754.5 * \text{Total N} + 122.8 \quad (5.7)$$

$$= 67.9 * \text{Organic C} + 110.3 \quad (5.8)$$

In the topsoil the relationship was also highly significant (R^2 = 0.51, P > 0.999, N = 75) to total N

$$P_o = 812.6 * \text{Total N} + 116.3 \quad (5.9)$$

or (R^2 = 0.50, P > 0.999, N = 75) to organic C

$$P_o = 71.4 * \text{Organic C} + 112.8 \quad (5.10)$$

Similarly, the organic P content in the subsoil was linearly related (R^2 = 0.42, P > 0.999, N = 105) to total N,

$$P_o = 754.5 * \text{Total N} + 114.8 \quad (5.11)$$

or to (R^2 = 0. , P > 0.999, N = 105) to organic C,

$$P_o = 64.7 * \text{Organic C} + 109.9 \quad (5.12)$$

These relationships are in agreement with the results obtained by Sharpley et al. (1984a) and other work cited by them.

Likewise for labile P, the separation of soils according to their weathering status and mineralogy would better explain the relationship between organic P content and other soil properties. Tiessen and

coworkers (1984) reported the relative proportions of available and stable as well as organic and inorganic P forms were dependent upon soil chemical properties and related to soil taxonomy.

In the slightly weathered soils organic carbon content alone explained 45% of the variation in organic P content (Table 5.14). Incorporation of K x Organic C interaction increased the coefficient of determination to 0.49. On the otherhand hydroxide extractable P and organic C content of the soils explained 55% of the variation in organic P level. In the slightly weathered soils total N and organic C behaved alike, however, the latter was used because it is more commonly measured and hence readily availble. In the highly weathered soils hydroxide- P (N = 70) and CEC/% clay (N = 28) explained 47% and 41% of the variation in P_o, respectively. Together the two (N = 28), explained 64% of the variation (Table 5.14). The R^2 of 0.47 may be preferred over R^2 = 0.64 because errors in estimation of P_o were smaller in the former and also variations were explained with larger number of observations. On the other hand K explained 54% and together with total N over 60% of variation in organic P content of the Andisols (Table 5.14). In calcareous soils organic P was not related to any of the soil properties (Table 5.11)

The foregoing discussion showed that the relationships obtained between organic P and total N (Eq. 5.7) or organic C (Eq. 5.8) were predominantly due to slightly weathered soils. In slightly weathered soils P_o was positively related to P_{il}, isotope P, and other soil test P as well as to buffering capacity (Table 5.11). Thus, in these soils organic P acts as a reservoir of P (Tiessen et al., 1984).

Table 5.14 Relationship between organic P P_o,(mg P kg $soil^{-1}$), hydroxide P (HP) (mg P kg $soil^{-1}$) and soil chemical properties.

Equation	Number of observations	Root mean square error	R^2 [a]
Slightly weathered soils			
P_o= 91.72 + 88.25 Org C - 4.32 x $(Org\ C)^2$	120	118.0	0.45
92.07 + 74.19 Org C - 3.94 x $(Org\ C)^2$ + 22.56(Org C x K)	120	114.3	0.49
74.47 + 80.94 Org C - 3.85 x $(Org\ C)^2$ + 0.17 HP	120	106.9	0.55
Highly weathered soils			
P_o= 0.48 HP + 117.20	70	63.9	0.47
10.19 CEC^b + 65.15	28	85.6	0.41
0.42 HP + 6.62 CEC + 58.5	28	67.8	0.64
Andisols			
P_o= 331.03 K + 608.91	20	310.1	0.54
266.21 K + 360.43 N* + 394.1	20	300.3	0.61

a All coefficients of determination are significant at 0.1% level.

* Variable N is nonsignificant at $p>0.05$, the remaining variable are all significant at $p<0.01$.

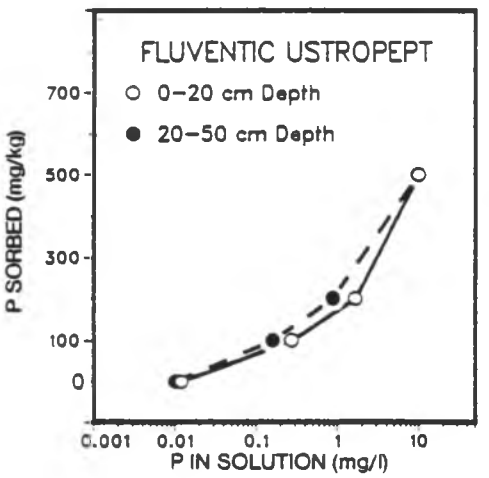
b CEC in cmol (+) kg $clay^{-1}$.

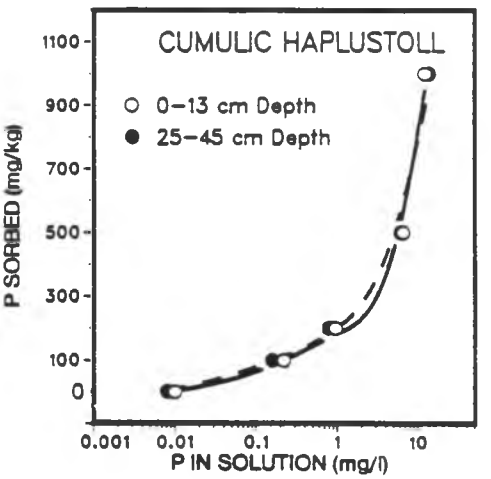
Similar relationship is expected on highly weathered soils where P_o was highly correlated with both sulfuric acid P and hydroxide P. As reported by Tiessen et al. (1984) available P in these soils may be largely controlled by mineralization of organic P. In the Andisols the stable P_o again appears to act as a sink since high content were associated with low labile P (resin P) (Table 5.11).

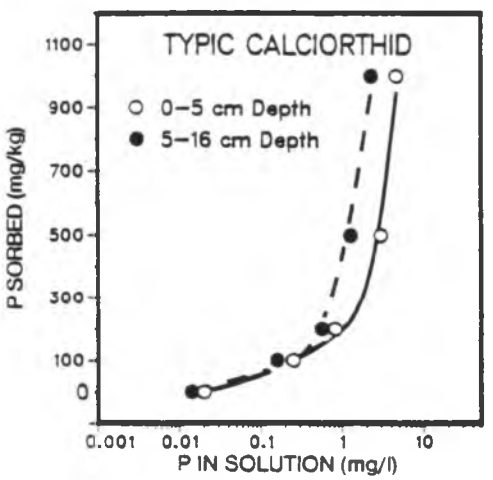
Buffering capacity and P availability index

The determination of P soption curve utilized the procedure of Fox and Kamprath (1970). A wide range of P sorption values ranging from -150 mg P kg $soil^{-1}$ to 1065 mg P kg $soil^{-1}$ were required to achieve a solution P level of 0.02 mg P l^{-1} (Table 5.5 and 5.6). The wide range is a reflection of different mineralogies, texture, and weathering status of the soils. Slightly weathered soils with predominantly 2:1 clay minerals were low in P sorption (Figure 5.2). Highly weathered soils with 1:1 clay minerals and more so with short order minerals (amorphous) were highly P sorbing, e.g., Typic Hydrandept (Figure 5.3).

In general subsoils sorb more P than topsoils (Figures 5.2-5.3). Topsoils have lower P fixation, mainly due to organic matter which can block exposed hydroxyls on the surfaces of Fe and Al oxides. Such relationships have been reported by Fox and Kamprath (1970), Holford and Mattingly (1975), and Sample et al. (1980). Also, among soils of similar clay mineralogy, P fixation increases with increasing clay content. Topsoils generally have lower clay content. However, in some water-logged soils, e.g., Andaqueptic Haplaquoll, the subsoil may sorb less P because the Fe in reduced form is more soluble (Sanchez, 1976).







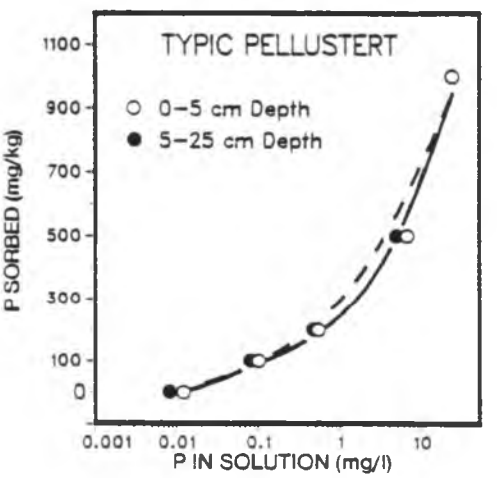


Figure 5.2 P sorption curves of soils with low P-fixing capacity.

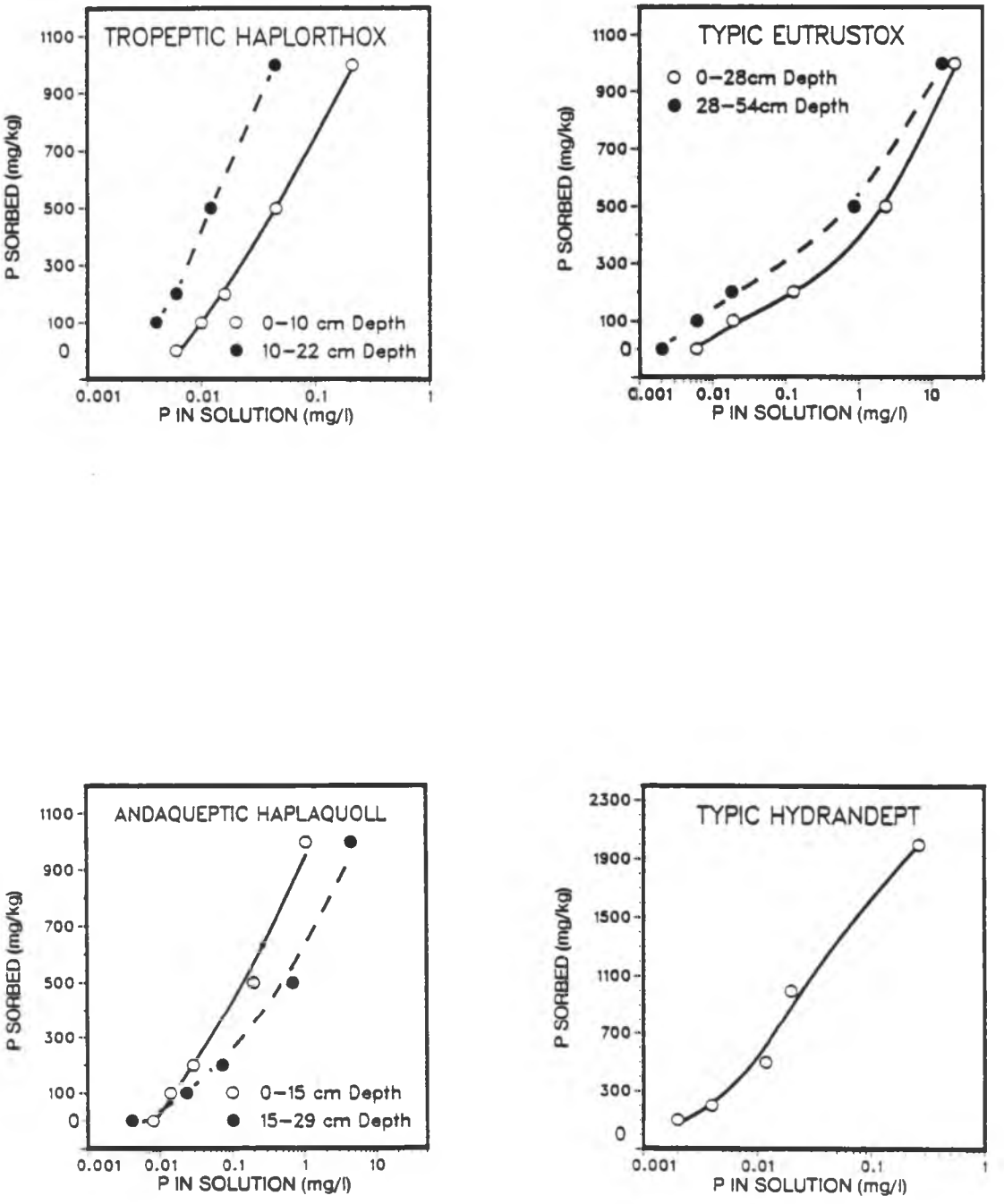


Figure 5.3 P sorption curves of soils with high P-fixing capacity.

Buffering capacity (l/kg) were determined from the slopes of the sorption curve, $\Delta Q/\Delta I$. Since the external P requirement of many of the agronomically important crops is between 0.01 to 0.1 mg P kg $soil^{-1}$, the buffering capacity was determined from this range of P in solution. The concentration of 10^{-4} M phosphate as suggested by Bache and Williams (1971) is not practical for tropical soils as such concentration is not easily reached in these soils. The fraction of added fertilizer P remaining as P in solution (F_1 in kg/l) was also determined at the above range of P in solution. The availability index of P for all soils ranged from 2.61×10^{-5} to 0.02 kg l^{-1} (Appendix 5.3-5.6). The calcareous soils (mean = 3.26×10^{-3} kg l^{-1}) in general had the highest P availability as P in solution per unit of P fertilizer applied while the Andisols (mean = 9.65×10^{-5} kg l^{-1}) had the lowest P availability. The higher P fixation in Andisols have been attributed to x-ray amorphous colloid content and with large surface area (Sanchez and Uehara, 1980). The lower P fixation in calcareous soils is due to the fact that P is less strongly bound to $CaCO_3$ than to hydrous oxides (Sample et al., 1980).

In slightly weathered soils the P availability index was positively related to labile P and extractable P (Table 5.11). The index was not related to sulfuric acid- or hydroxide- P because these methods also extract P which is not available to plants. As expected the F_1 was negatively related to buffering capacity. In these soils P_{il} (mg P kg $soil^{-1}$) and phosphate retention (%) explained 64% (N = 48) of the variation in P availability (Table 5.15). The positive correlation with labile P is consistent with previous studies which have shown that

Table 5.15 Relationship between availability index (F_1) (kg/1), buffering capacity (1/kg) and soil properties.

Equation	Number of observations	Root mean square error	R^2 [a]
Slightly weathered soils			
$F_1 = 0.0000354\ P_{il} + 0.0000435\ PR + 0.026$	48	0.0013	0.64^{***}
$= 0.0000356\ P_{il} + 0.0000138 BS + 0.000011\ CEC^2 - 0.000114$	76	0.0016	0.49^{***}
$BC = 131.9\ PR - 78.92\ BS + 190.82$	48	2990.0	0.70^{***}
$= 541.7$ Org C $- 324.9\ BS + 2.13\ BS^2 + 12900$	76	3336.0	0.54^{***}
$= 253.7 CEC - 318.3 BS + 1.92\ BS^2 - 2.48\ CEC^2 + 10660$	76	191.0	0.59^{***}
Highly weathered soils			
$F_1 = 0.0000185\ P_{il} + 0.00000318\ BS + 0.00000581$	13	0.00012	0.78^{***}
$BS = 21311.9\ Na - 408.46\ P_{il} + 5125.4$	13	3874.0	0.56^{**}
Andisols			
$F_1 = 0.000128 \ln(1 - \Delta pH) + 0.0000678\ K - 0.0000301$	12	0.000036	0.87^{***}
$BC = 48200 \ln(1 - \Delta pH) - 4380\ K + 45300$	12	3717.0	0.90^{***}
Calcareous soils			
$F_1 = 0.00724\ pH - 0.055$	9	0.002	0.73^{**}
$0.0186 - 0.0109\ Fe$	9	0.0014	0.94^{**}
$0.0185 - 0.0088\ Fe - 0.003$ Org C	9	0.0008	0.99^{**}
$BC = 14.04\ CEC - 41.64\ P_{il} + 263.27$	9	150.0	0.85^{**}

*** Significant at $p \leq 0.001$.

** Significant at $p \leq 0.01$.

P sorption is reduced by additions of fertilizer P (Barrow, 1974). Since phosphate retention is not routinely measured for slightly weatherd soils, F_1 was related to CEC. For these soils an increase in P_{il} and CEC was associated with an increase in F_1 (Table 5.15). These results are consistent with those of Sharpley et al. (1984a). The buffering capacity of slightly weathered soils was also related to CEC, base saturation, as well as organic carbon (Table 5.15). Buffering capacity has been positively correlated with organic C (Harter, 1969) and negatively with base saturation (Brown and Loewenstein, 1978).

For the highly weathered soils fertilizer P availability increased with an increase in labile P, organic C and base saturation (Table 5.15). Likewise, in the slightly weathered soils, F_1 in the highly weathered soils also showed high correlation with soil test P and not with sulfuric acid- or hydroxide- extractable P. The buffering capacity in these soils was negatively related with labile P.

In Andisols, the P availability after fertilizer application as well as the buffering capacity was explained by ΔpH of the soils and exchangeable K content (cmol(+) kg $soil^{-1}$). A decrease in ΔpH and an increase in K was associated with an increase in F_1. In Andisols F_1 was also negatively related with oxalate extractable Fe (Table 5.11). The oxalate extraction method depends mainly on the complexing affinity of oxalate at pH 3.25 to extract colloid complexes (Searle and Daly, 1977). The reagent dissolves such forms as amorphous oxides and hydrous oxides which play a major part in cation and anion retention and other surface phenomena. Thus, the P sorption in Andisols is highly correlated with amorphous oxides and hydrous oxides of Fe.

A decrease in ΔpH in variable charge colloids is associated with an increase in negative charge and hence lower phosphate fixation (Uehara and Gillman, 1981). Additions of fertilizer P have been reported to reduce P sorption capacity (Barrow, 1974) as well as increase K retention particularly in variable charge clays (Ayres and Hagihara, 1953). As expected buffering capacity was positively associated with ΔpH and negatively with exchangeable K.

In calcareous soils P availability index, F_1, was positively related to pH (Tables 5.11 and 5.15). Dithionite-citrate extractable Fe alone explained 94% of the variation in P availability and together with CEC explained 99% of the variation. Similar relationship was obtained with iron and organic C (Table 5.15). (Note organic C and CEC were highly correlated in calcareous soils Table 5.10). Buffering capacity on the other hand was positively related to CEC and negatively to labile P.

Previous studies have shown that fertilizer P availability increases with decreasing $CaCO_3$ content (Larson and Widdowson, 1970; Sharpley et al., 1984). However, in the present study there was no correlation with $CaCO_3$. The results from this study could be explained by the findings of Holford and Mattingly (1975), where high-energy adsorption surfaces in 24 calcareous soils were closely related to dithionite-citrate soluble iron. Their study indicated that even in calcareous soils hydrous oxides are important in the adsorption of P. The low-energy adsorption was highly correlated with $CaCO_3$ surface areas and organic matter content, but not with the $CaCO_3$ content. The high coefficient of determination and low estimation

error for P availability index (F_1) with Fe and organic C (or CEC) in this study confirms their finding (Table 5.15). In the calcareous soils dithionite extractable iron content ranged from 0-1.7% (Appendix 5.6). Despite the low concentration, the positive relationship between fertilizer P availability and pH may also be attributed to precipitation/complexing of dithionite extractable iron into inactive forms.

For each of the four soil categories regression equations were developed to predict the amount of fertilizer P (mg P kg $soil^{-1}$) required to achieve a P in solution of 0.02 mg P l^{-1} (PS02) and 0.10 mg P l^{-1} (PS10) (Table 5.16)

The regression models developed in this section would be useful for predictive purposes and as input to a phosphorus simulation model once they are validated and tested with independent sets of data. The next section considers that aspect of model development.

5.3.3 Validation of P regression models

Labile P

Some of the relationships presented in Table 5.8 were validated on independent sets of data from Sharpley et al. (1984 a, b) and Tiessen et al. (1984). In both the studies labile P, Bray I P, and double acid P were determined on the same soils. In addition, P was also extracted by Texas A & M technique (extracting P by shaking 25 ml of 1.43 M NH_4OAc (pH 4.2) and 0.025 M EDTA for 30 min.) (Sharpley et al. 1984a).

Table 5.16 Estimating fertilizer P requirement to achieve P concentrations of 0.02 mg P/1 (PSO2) and 0.10 mg P/1 (PS10) from buffering capacity and soil properties

Equation	Number of observations	Root mean square error	R^2 a
Slightly weathered soils			
PSO2=0.024 BC + 45.78	72	100.47	0.58
1.90 BS + 4.18 PR + 48.46	44	116.03	0.58
1.638 + 5.19 PR - 20.25 Org C* + 37.55	44	111.92	0.62
PS10=0.074 BC + 77.01	75	143.66	0.86
9.08 BS + 5.51 CEC + 782.69	75	293.74	0.44
5.54 BS + 12.12 PR + 112.73	47	243.80	0.72
Highly weathered soils			
PSO2=0.037BC-11.08	15	79.8	0.87
1048.94 Na - 16.51 P_{il} + 154.09	12	126.6	0.72
PS10=0.065 BC - 81.86	15	84.0	0.95
1572.23 Na - 29.17 P_{il} + 418.33	12	205.98	0.72
1302.96 Na - 4.82 BS - 23.00 P_{il}	12	192.38	0.80
Andisols			
PSO2=0.025BC + 51.82	15	92.40	0.90
-1224.99 ln ΔpH - 147.21 K + 1246.57	12	102.80	0.90
PS10=0.1040 BC + 442.90	15	271.78	0.74
-2174.26 ln ΔpH - 272.75 K + 2535.89	12	224.42	0.86
Calcareous Soils			
PS10=0.41 CEC + 50.07	9	3.22	0.56*
PS10=0.038 BC + 47.67	9	14.52	0.46*

* Significant at $p \leq 0.05$

Sharpley and his group determined labile P with 4 g sample of 60 mesh soil while Tiessen et al. (1984) used 0.5 g of <100 mesh soil sample. In the present study labile P was determined on <50 mesh size soil sample using $NaCl-Na_2SO_4$ resin instead of $NaHCO_3$ resin. These differences in procedure reflect the need for standardization of resin technique. The shaking time in Bray I P also differed, 5 min. in their studies and 1 min. in the present. The terms highly weathered and slightly weathered soils as used by Sharpley et al. (1984 a) was based on soil taxonomy. For the validation exercise their data was regrouped according to CEC/% clay and soil taxonomy, the criteria used in the present study to define the weathering status.

In slightly weathered and calcareous soils, predicted labile P values from Olsen P agreed with actual values (Figure 5.4). The differences due to resin procedure is reflected in highly weathered soils (Figure 5.4c). In these soils chloride-sulfate form of the resin extracted more P. In soils where P was available to plants, e.g., Typic Gibbsihumox (R.L. Fox, pers comm.) bicarbonate form of the resin could not be used to extract P. The chloride-sulfate form of the resin and the chloride-sulfate solution were more effective in extracting P from the soil and the resin, respectively (Figure 5.4c). In calcareous soils, maximum Olsen P value used in developing the regression model was 10.4 mg P/kg soil (Appendix 5.5). The model accurately predicted labile P from Olsen P values up to 37 mg P/kg soil (Figure 5.4b).

For the Bray I P the predictions were off in all three groups of soil, viz., calcareous, slightly weathered and highly weathered soils (Figure 5.5). However, the bias was in the expected direction. For a

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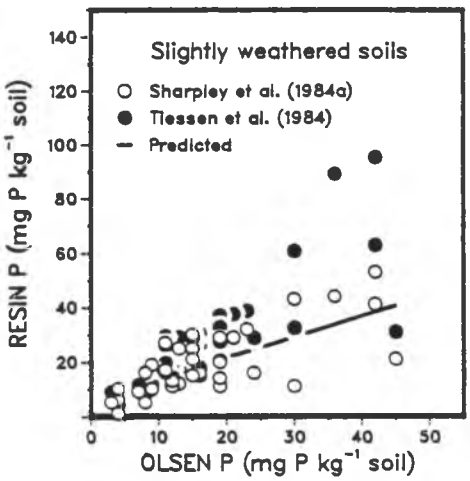

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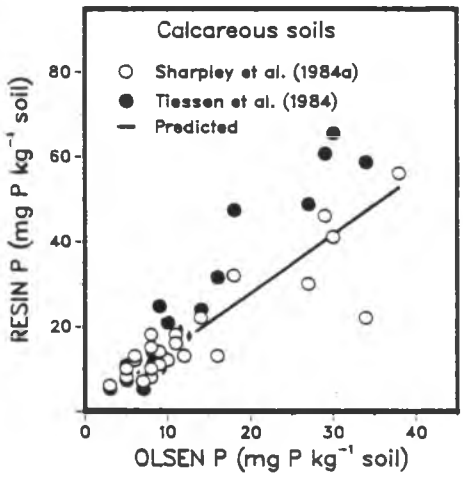

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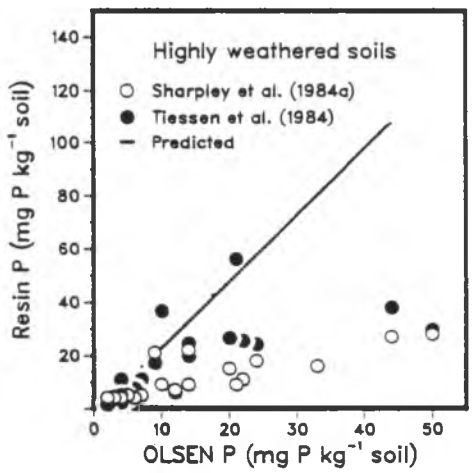

Figure 5.4 Validation of the relationship between Olsen P and labile P for the (A) slightly weathered, (B) calcareous, and (C) highly weathered soils.

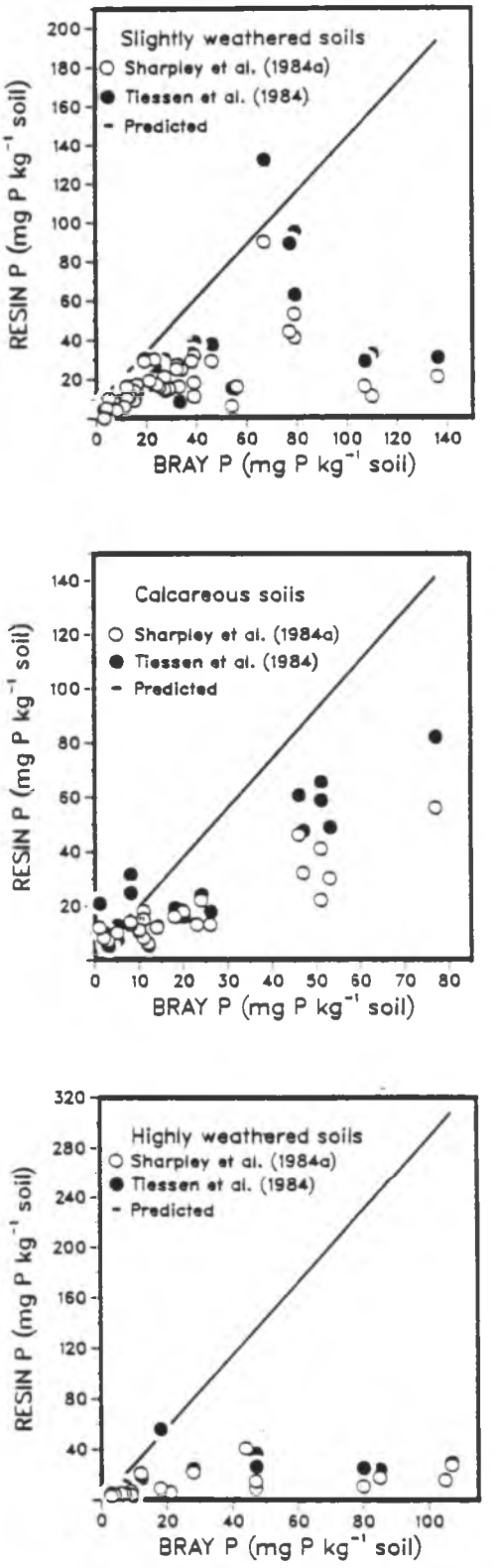

Figure 5.5 Validation of the relationship between Bray I P and labile P for the slightly weathered, calcareous, and highly weathered soils.

given P_{il} the model predicted lower Bray I value because of the shaking-time difference during P extraction. This is evident in highly weathered soils where longer shaking time led to dissolution of Al- and Fe- bound P, thereby releasing P which is not readily available to plants. Another reason for the difference as discussed before was the inability of bicarbonate resin to extract P in highly weathered, variable charged soils.

The relationship between double acid P and labile P (Table 5.7) when tested on data from Sharpley et al. (1984a) and Tiessen et al. (1984) overestimated the labile P content. The maximum double acid P value used in developing the model was 81 and 7 mg P/kg soil (Appendix 5.2 and 5.3) compared with 240 and 102 mg P/kg soil in their data for slightly weathered and highly weathered soils, respectively (Figure 5.6).

Texas A & M P has been suggested as a suitable fertility test in highly weathered soils (Sharpley et al., 1984 b). In the present study modified Truog P was considered suitable for a wide range of soils particularly the highly weathered soils. The two methods extract similar amounts of P in these soils (Figure 5.7a). In Figure 5.7a regression model developed for predicting P_{il} from modified Truog P was compared with the relationship between P_{il} and Texas A & M P.

Soil test P

Some of the soil test P relationships presented in Table 5.9 were tested on independent data. The model tend to underestimate the Bray I P content in highly weathered soils when the relationship between Bray

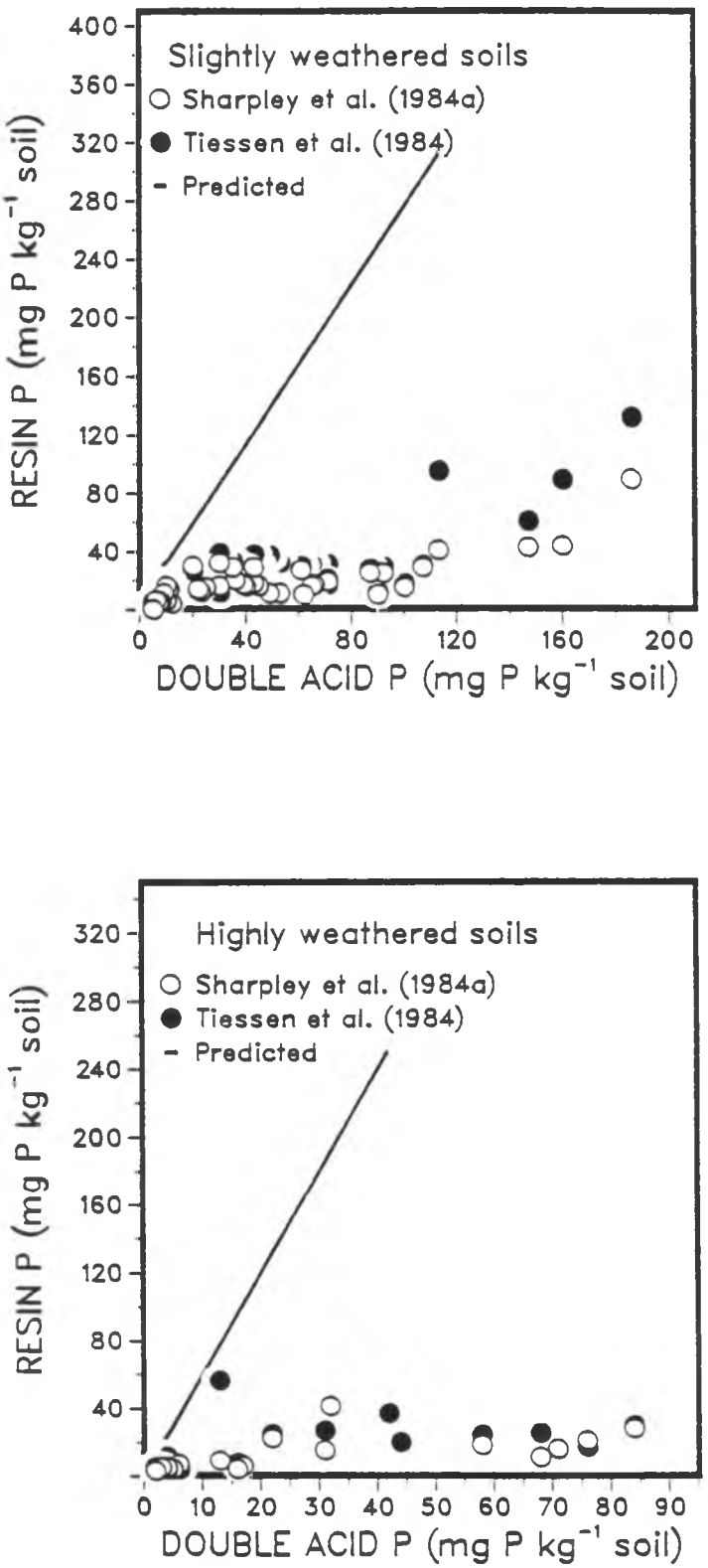

Figure 5.6 Validation of the relationship between double acid P and labile P for the slightly weathered and highly weathered soils.

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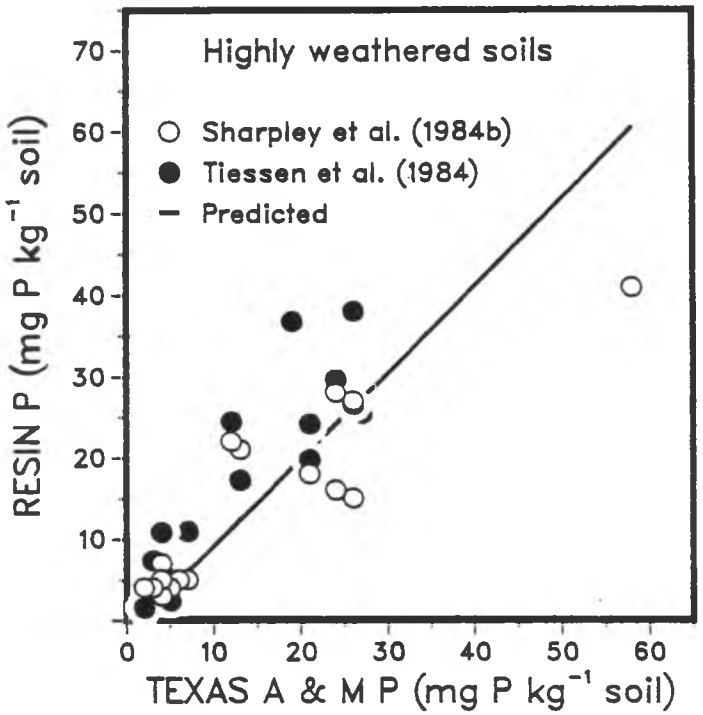

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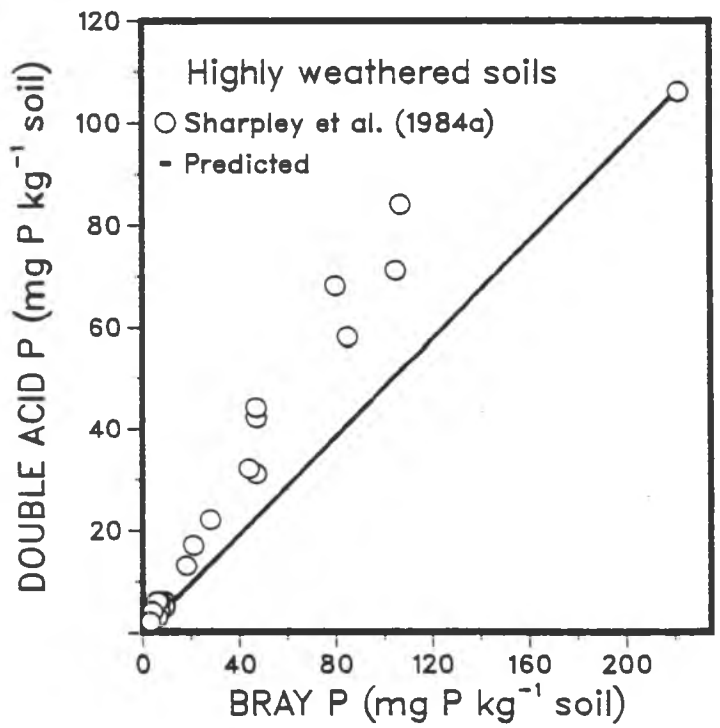


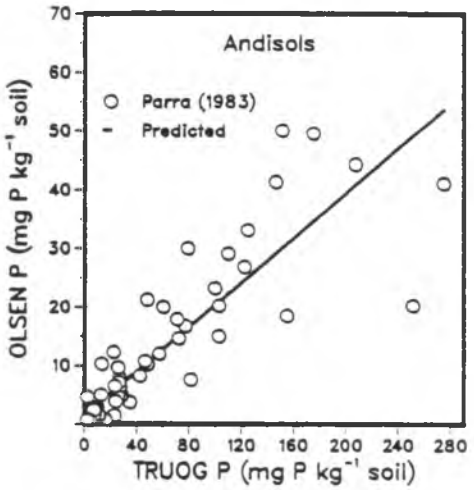
Figure 5.7 Comparing the relationship between (A) modified Truog P and labile P, and Texas A & M P with labile P on two independent data, and (B) validating the relationship between Bray I P and double acid P.

I P and double acid P was tested (Figure 5.7b). This as discussed earlier is due to dissimilar procedures in the current study and that used by Sharpley et al. (1984a).

For Andisols the predicted soil test P values and measured values were in close agreement (Figure 5.8). The soil P extraction methods used on this independent set of data (Parra, 1983) were identical to the present study. Hence, the data set was ideal for validation purposes.

The regression model was also tested on two sets of data from erosion plots with maize crop (S.A. El-Swaify, unpublished data). The treatments were three rates of erosion and three level of fertility. At the end of first cropping the model underestimated Olsen P level or overpredicted modified Truog P values while at the end of fourth crop the predictions were reversed (Figure 5.9a). The simple regression models in the present study were developed from undisturbed soils, where there was equilibrium between different P forms. These simplistic models did not include the dynamic nature of soil reactions during cultivation and erosion. This further enhances the need for simulation models to study soil, plant and environment interactions. However, when the highest P fertilizer rates (approximately 400 kg P/ha and 200 kg P/ha prior to the first and fourth plantings, respectively) were not considered the predictons were reasonable especially at the end of fourth cropping (Figures 5.9b). Thus as expected the model performance was unsatisfatory under non-equilibrium conditions (recently disturbed and highly fertilized soils).

A



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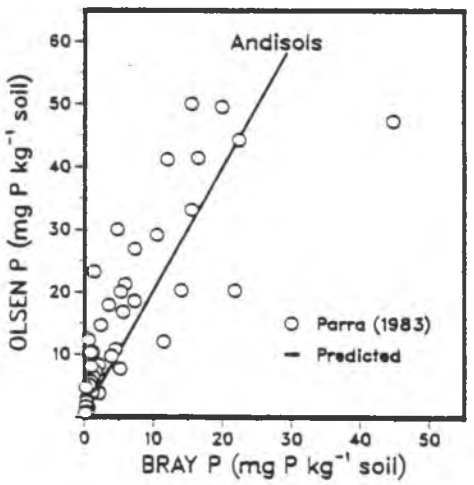

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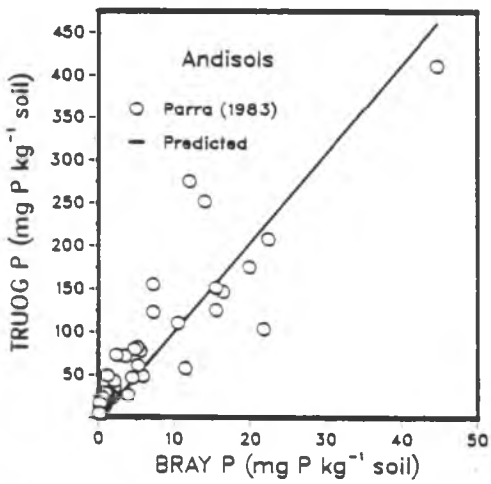
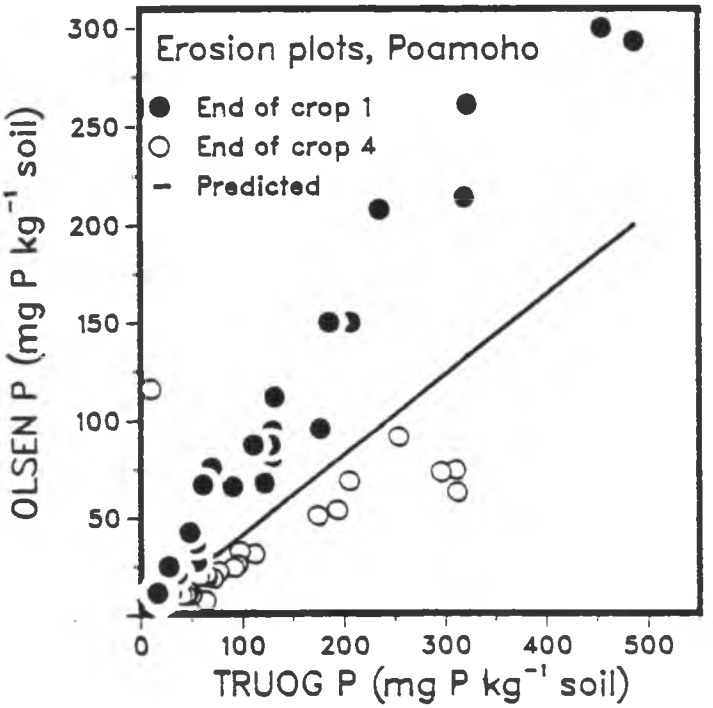


Figure 5.8 Validation of the relationship between (A) modified Truog P and Olsen P, (B) Bray I P and Olsen P, and (C) Bray I P and modified Truog P for the Andisols.

A



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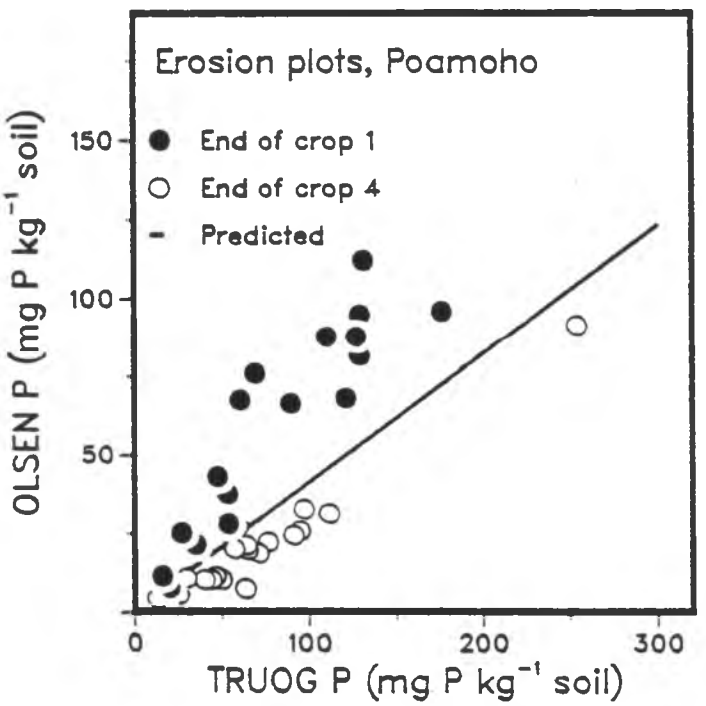

Figure 5.9 Validation of the relationship between modified Truog P and Olsen P for the highly weathered soils on erosion plots at Poamoho, Hawaii.

Organic P

The relationships presented in Table 5.14 for slightly weathered and highly weathered soils were tested on data from Sharpley et al. (1984a). A quadratic model with organic carbon as the independent variable and a linear model with CEC/% clay as independent variable were used for slightly weathered and highly weathered soils, respectively (Figure 5.10).

In general there was greater variability in slightly weathered soils than in highly weathered soils. This may be attributed to a wide range of soils categorized as slightly weathered (all soils except acidic ochrepts and soils with CEC/% clay < 16).

Phosphorus sorption

The relationships between P in solution (Fox and Kamprath, 1970) and anion exchange resin P (Table 5.8) were used to re-express the data of Sharpley et al. (1984a) in terms of solution P. The relationships presented in Table 5.15 for slightly weathered (multiple regression model with P_{il}, CEC and $(CEC)^2$ as independent variables) and highly weathered soils (with P_{il} and base saturation as independent variables) were then tested on their data.

The model predictions were generally in agreement with the actual values (Figure 5.11). Perhaps a better fit would have been obtained if the model were fitted on the raw data.

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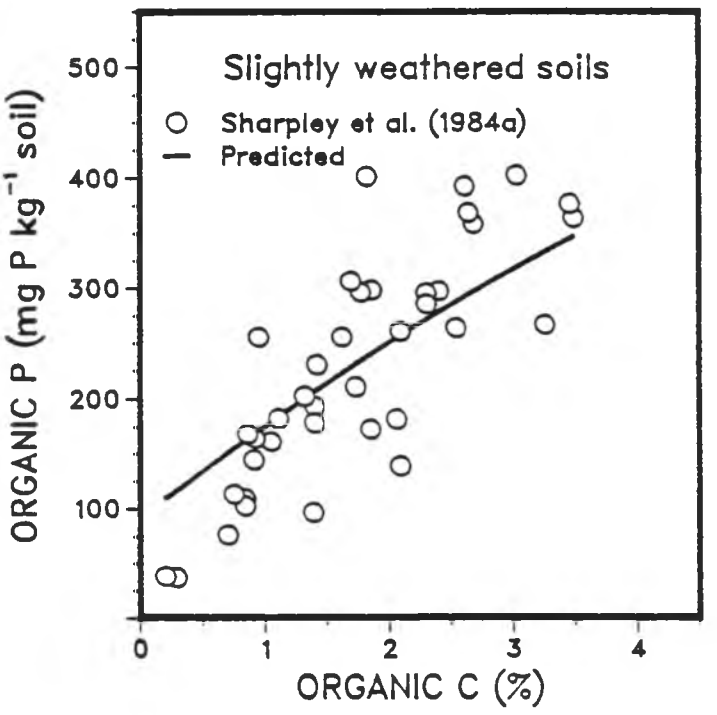

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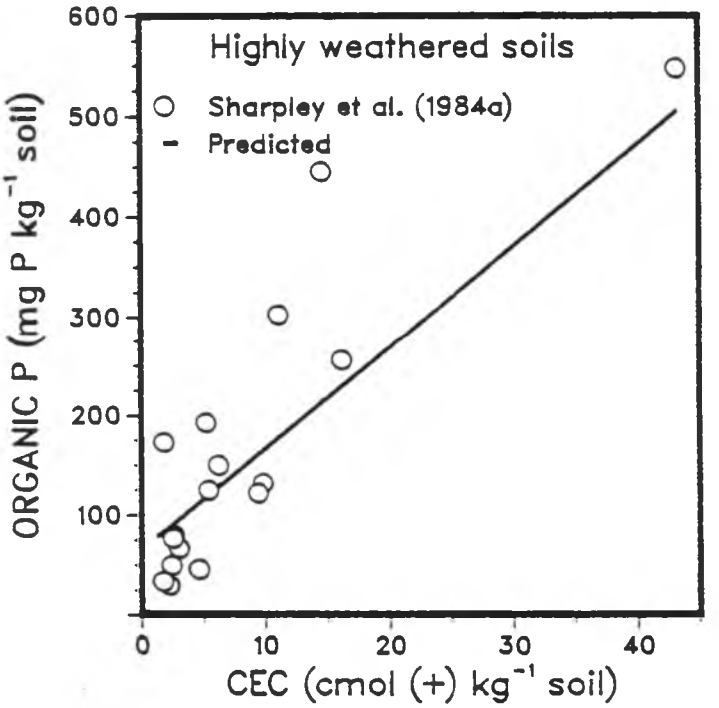


Figure 5.10 Validation of the relationships between (A) organic C and organic P for the slightly weathered and (B) CEC and organic P for the highly weathered soils.

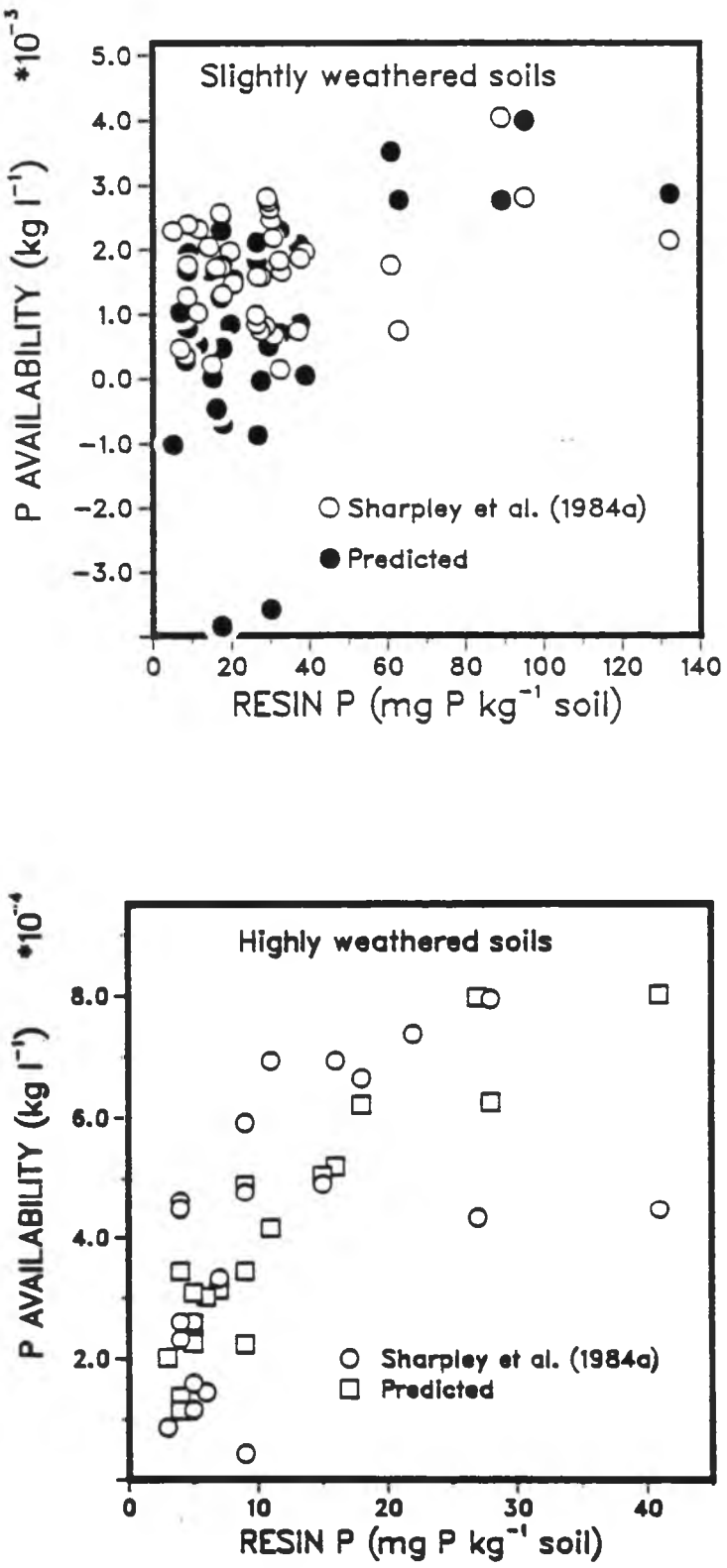


Figure 5.11 Validation of the relationship between labile P and P availability index for the slightly weathered and the highly weathered soils.

5.4 Conclusions

1. Regression models were developed to determine labile P, organic P, buffering capacity, and availability index of P from readily available soil test P methods and soil physical and chemical properties. These simple models are are useful in generating input data for simulation models where measured data is not available or too time consuming and costly to determine.

2. Stratification of soils into different categories, viz., calcareous, Andisols, low activity clays, and high activity clays reduced the errors in estimation. Although the stratification was chemically-based, a recent study has shown reduced variability in soil physical properties as well (Soekardi, 1985). Stratifying soils into the above groups helped to understand the soil chemical reactions. Simple correlation between organic carbon and CEC: 0.25 on slightly weathered soils (high activity clays), 0.61 on calcareous soils, 0.81 on highly weathered soils (low activity clays), and 0.83 on Andisols illustrated the nature of the four groups of soil. In essence the CEC for low activity clays and Andisols is highly dependent on organic carbon content.

3. Stratification of soils also delineated the best soil P extraction method for a specified soil. Olsen P applied consistently across a wide range of soils. Modified Truog P was best suited for Andisols and highly weathered soils as evident from the very high correlation with resin P in these soils.

4. The chloride sulfate form of the anion exchange resin was used to determine labile P. This non-chemical method of P extraction also applied on a wide range of soils. The labile P was linearly related to all common soil test P methods on slightly weathered and highly weathered soils, and Andisols. However, on calcareous soils P_{il} was not related to double acid P.

5. Labile P was postively correlated with exchangeable bases. On slightly weathered soils, exchangeable K alone explained more than 50 % of the variation in P_{il}. On low activity clays K x Ca interaction explained more than 85 % of variability in P_{il}. Approximately 35 % of variation in labile P was explained by Ca and Ca x K interaction on field- moist Andisols. For the air-dried samples pH and pH x exchangeable Na interaction explained over 50 % of the variation in labile P. Over 70 % of the variability in P_{il} was explained by CEC/% clay and CEC/% clay x Na interaction on the calcareous soils.

6. Organic P was positively related to total N, organic C, and hydroxide - extractable P on slightly weathered soils, CEC/% clay and hydroxide - extractable P on highly weathered soils, and exchangeable K and total N on air-dried Andisols. Organic P was not significantly related to other soil properties on calcareous soils.

7. P availability index or its reciprocal, buffering capacity was related to labile P and CEC on slightly weathered soils. On highly weathered soils the relationship between P_{il} and base saturation explained over 75 % of variation in P availabilty. Similarly on

Andisols the relationship between exchangeable K and pH with P availability index gave R^2 of 0.90. On calcareous soils organic C and dithionite extractable Fe explained most of the variability associated with P availability index.

8. The P regression models were validated on independent sets of data. Lack of standardized laboratory techniques for P analyses was evident from these data. Regression models are not suitable for extrapolative predictions for they may not perform as anticipated. Similarly these models should not be used for conditions/cases they were not developed for, e.g., non-equilibrium conditions.

VI. TESTING OF PHOSPHORUS MODEL

6.1 Introduction

Dynamic phosphorus simulation models consider the effect of soil phosphorus status, plant status, growth rate yield throughout the growth period. Empirical approach of relating soil P status and using Mitscherlich equation (Bennett, 1975) or a linear response and a plateau function is still widely used. Those models represent an over-simplification of a complex pattern of nutrient supply and demand which varies throughout the growing period.

The main drawback of some of the simulation models is the large number of input parameters required to run the model. The soil and plant phosphorus model developed at Grassland Soil, and Water Research Laboratory, Temple, Texas is a simpler model that runs on a daily time step (Jones et al., 1984).

The phosphorus model simulates P uptake and the transformations in up to ten soil layers of variable thickness, and is sensitive to soil chemical and physical properties, crop phosphorus requirements, tillage practice, fertilizer rate, soil temperature and soil water content. Although the model oversimplifies soil phosphorus transformations model parameter can be obtained from limited soil data, the model is sensitive to soil properties, and has high overall accuracy (Jones et al., 1984b).

Labile P and P availability index in the phosphorus model was determined by rapid P adsorption method of Sharpley et al. (1984a). The soils in their study were from temperate region. As evident from

the previous chapter the relationship between labile P and soil physical and chemical properties were different in highly-weathered "tropical" soils from temperate region soils. Similar difference was also observed when relating P availability index to soil physical and chemical properties.

The P availability index as used in the phosphorus model is the fraction of fertilizer P which is labile after six-month incubation period. The P availability index as used in the previous chapter is the fraction of fertilizer P determined as P in solution (kg l^{-1}) after six-day incubation (Fox and Kamprath, 1970).

The objective of the present study was to: (i) modify the equations relating labile P and P availability index in the phosphorus model, and (ii) utilize simpler P sorption method to simulate the flux between labile P pool and active pool (Figure 6.1).

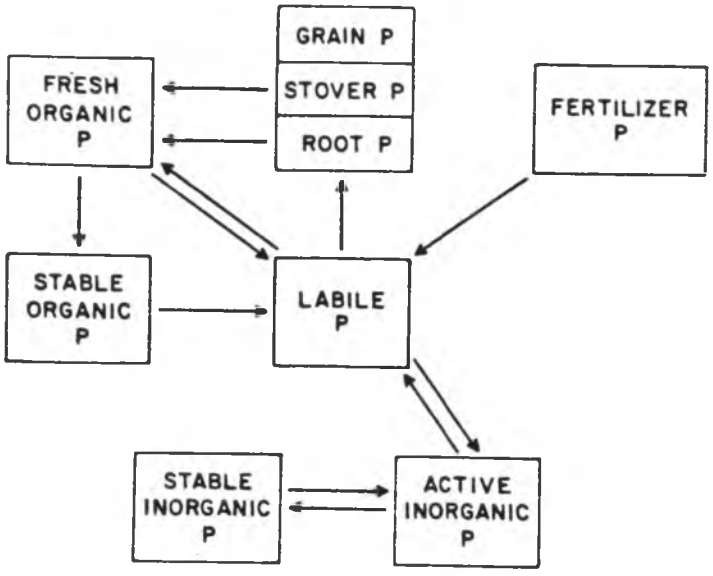


Figure 6.1 Pools and flows of phosphorus in the EPIC model. Source: Jones et al. (1984a).

6.2 Materials and Methods

6.2.1 Phosphorus Model

The phosphorus model was designed for use in the Erosion-Productivity Impact Calculator (EPIC) crop management model (Williams et al., 1983). The model contains pools of soil inorganic and organic P, plant residue P, and plant shoot, root, and grain P (Figure 6.1).

The P model accounts for the initial rapid decrease in soil solution P (Rajan and Fox, 1972; Barrow and Shaw, 1975). The labile P and P availability index is determined by rapid P adsorption method as described by Sharpley et al. (1984 a).

The movement of P between labile P pool (P_{il}) and a hypothetical "active" mineral P pool (Pia) is simulated as:

$$R_{la} = 0.1[P_{il} - P_{ia}\S F_l/(1-F_l)\dagger]F_{im}F_{it} \qquad (6.1)$$

The initial size of P_{ia} is estimated as:

$$P_{ia} = P_{il}(1-F_l) \qquad (6.2)$$

The rate of P movement from P_{il} to P_{ia} (R_{la}) has a rate constant of 0.1 d^{-1} under optimum temperature and moisture (Rajan and Fox, 1972). The two pools are at equilibrium when:

$$P_{il} = P_{ia}F_l/(1-F_l) \qquad (6.3)$$

In the above equations F_l is the fraction of fertilizer P (P_f) which is labile after the incubation period:

$$F_l = (P_{ilf} - P_{ili})/P_f$$

P_{ili} and P_{ilf} are labile P value prior to and after fertiization, respectively. In Equation (6.1) F_{it} and F_{im} are temperature and moisture factors.

The slow decrease in extractable P in residual P fertilizer experiments have been described with a simple exponential function whose rate constant varies among soils (Cox et al., 1981). When not in equilibrium, the rate of movement (R_{as}) of P between active mineral pool (P_{ia}) and stable mineral pool (P_{is}) is:

$$R_{as} = K_{as}(4P_{ia} - P_{is}) \qquad (6.4)$$

Equation(6.4) assumes that at equilibrium, P_{is} is four times as large as P_{ia}. From results of Cox et al. (1981), Jones and coworkers (1984a) assumed the value for rate constant, K_{as} to by 0.00076 d^{-1} in all calcareous soils. They also reanalyzed available data on noncalcareous soils (Cox et al., 1981; Yost et al, 1981; Russel, 1973) and came up with:

$$K_{as} = \exp(-1.77F_1 - 7.05) \qquad (6.5)$$

In their model the immobilization of labile P and mineralization of organic P is similar to the N minerilization- immobilization routine of PAPRAN (Seligman and Van Keulen, 1981). PAPRAN allows the availability of inorganic N and P_i to affect the rates of organic N, organic P, and crop residue transformations. In contrast to PAPRAN, the P model (Jones et al., 1984a) divides stable organic matter into mineralizable and nonmineralizable pools.

On a given day the rate of P uptake is controlled either by plant demand or by its abitlity to take up P from the soil. The plant demand or by its ability to take up P from the soil. The plant demand for P is the difference in the actual plant P content of a plant of identical biomass at an optimum plant P concentration. The model assumes potential plant uptake of labile P from a soil layer is a linear function of labile P concentration up to a user-specified critical concentration.

For maize the P model uses P_{ilc} (critical) value of 20 mg kg^{-1}. The potential rate of P adsorption from a layer is assumed to be 1.5 times that needed to maintain the optimum plant P concentration when adsorption is not limited by soil moisture or labile P. When P uptake is inadequate to maintain optimum plant P content a plant P stress factor is used in conjunction with other plant stress factors to affect daily crop growth in the Erosion-Productivity Impact calculator (EPIC) model (Williams et al. 1983 a,b).

6.2.2 Testing of the phosphorus model

The phosphorus model was tested with the data from Benchmark Soils Project. Firstly, the simulation runs were made to calibrate the existing model so that it simulated maize responds to phosphorus accurately. Seven experiments were used for the calibration purpose. Only the high N treatment (+.85 or 186 kg N ha^{-1}) experiments were used for simulation. The phosphorus treatments ranged from 25 kg P ha^{-1} to 1200 kg ha^{-}in some experiments.

Next, the model was run with: (i) initial soil P expressed as labile P (determined using anion-exchange resin); and (ii) P availability index determined from P sorption isotherms. The labile P values for these experiments were obtained using the regression equations relating modified Truog soil phosphorus values to labile P (Table 5.8). The P availability index, F_1, determined from the above method (P sorption) was expressed as a function of chemical and physical soil properties (Table 5.15). The relationship between soil solution P and anion exchange P (labile P) based on Table 5.8 was used as a calibration factor on the model. The calibration factor was further modified such that the simulated results were reasonable for the seven sites tested (Table 6.1)

Table 6.1 Experiments used to test the soil and plant phosphorus model.

Site/block	Type of Experiment	Soil
HAL-B21	P-residual	Hydric Dystrandept
KUK-A21	P-residual	Hydric Dystrandept
KUK-C11	P-residual	Hydric Dystrandept
KUK-C12	P-residual	Hydric Dystrandept
KUK-D11	P-residual	Hydric Dystrandept
KUK-D20	P-applied	Hydric Dystrandept
MOL-A10	P-applied	Tropeptic Eutrustox

6.3 Results and Discussion

After calibrating the phosphorus model, runs were made on data from seven Benchmark Soils Project experiments on Hydric Dystrandept and Tropeptic Eutrustox. The same data were then rerun on the P model with modifications from the previous chapter. These simulation runs are presented in Table 6.2 as Simulation 1 and Simulation 2, respectively.

The calibrations were made so that most of the simulated results were within one standard deviation of the observed mean. The model predictions in residual phosphorus experiments were as good as in experiments where P had been applied. In general, simulated yields were greater than the observed yields particularly at the highest P treatment.

Like the CERES maize model the EPIC model does not consider the effect of insects and diseases. Similarly the assumption that water and other nutrients are non-limiting may not be true in all cases.

The main difference between Simulation 1 and Simulation 2 occurs at the lowest rate of P. In six out of seven experiments the modified P model predicted higher yields than the original model. This may be due to lower accuracy of the P availability index at low levels of P in solution. Nevertheless, the predictions of both models were similar at low levels of P.

The simulation exercise showed that P soil test values from modified Truog P extraction method may be related to labile P by regression equations and then successfully utilized in the P model.

Table 6.2 Comparison of observed and simulated grain yield on seven Benchmark Soils Project experiments in Hawaii

Site/Block		Phosphorus Applied (Coded level)		
		-.85	Opt	+.85
HAL-B21[a]	Observed	7697±525	8194±264	8169±815
	Simulation 1	7100	8210*	8848*
	Simulation 2	7950*	8002*	8600*
KUK-A21[a]	Observed	6039±917	6993±607	7852±1591
	Simulation 1	5780*	7004*	8692*
	Simulation 2	5284*	6190	7408*
KUK-C11[a]	Observed	7123±539	8917±100	8768±433
	Simulation 1	6004	8991*	9179
	Simulation 2	6775*	9213	9213
KUK-C12[a]	Observed	8462±697	9230±550	9262±509
	Simulation 1	8972*	10009	10009
	Simulation 2	9327	10031	10031
KUK-D11[a]	Observed	7003±1132	7937±835	8471±354
	Simulation 1	7450*	9460	9700
	Simulation 2	7933*	9340	9582
KUK-D20	Observed	6751±1200	8212±533	8828±365
	Simulation 1	5200	7942*	9802
	Simulation 2	7697*	8519*	9904
MOL-A10	Observed	8451±477	9887±478	10460±650
	Simulation 1	7780	9723*	11034*
	Simulation 2	8600*	9948*	11018*

[a] Phosphorus - residual experiments.

* Within ± one standard deviation of the observed mean yield.

Likewise, the P sorption method (Fox and Kamprath, 1970) may be used in the P model instead of the P sorption method requiring six-month incubation.

In the present study P availability index (kg l^{-1}) as determined by P in solution was related to P availability index as determined by anion exchange method using regression equations relating P in solution to labile P. This step may be eliminated and the error reduced if the P model was modified to utilize P sorption results directly.

6.4 Conclusions

1. Modified Truog P and the P availability index as determined by P in solution when used in the P model predicted maize grain yields with reasonable accuracy.

2. Phosphorus model prediction may be improved if P availability index (kg l^{-1}), fraction of P in solution after P application, is used in the model parameter development. More date can be generated on P sorption isotherms than on the P incubation studies requiring six months.

3. Phosphorus isotherm data (P in solution, buffering capacity) could also be used in modeling phosphorus gradients in the rhizosphere.

VII. SUMMARY

The Crop Environment Resource Synthesis model was verified on low nitrogen and water stress conditions. Thus, ensuring that yields obtained were logical when plants were exposed to unfavorable conditions prevalent in the tropics.

The CERES maize model was calibrated on experimental data from two soil families: Tropeptic Eutrustox and Hydric Dystrandept in Hawaii. Genetic coefficients of two maize cultivars, X304C and H610 were adjusted to simulate field response accurately in both of the above soil families. Due to lack of field level information on intermediate stages of crop growth and initial soil conditions many of the model components were not tested on these data.

Changes in leaf area index, leaf weight, above ground biomass with time and occurrence of phenological events were tested on one experiment on the Tropeptic Eutrustox site. The simulated and observed plant components were then compared with the actual values. The model was calibrated such that simulated yields were higher than the observed mean yield. This calibration was based on the assumption that in most cases the field experiment had unfavorable condition that prevented the yield from being the maximum.

Adjustments were made for: (i) thermal time computation; (ii) maize genotype coefficients; (iii) optimum temperature for photosynthesis; (iv) the effect of minimum temperature on grain filling; (v) effect of N deficiency and water stress on grain numbers;

(vi) N mineralization constant for Tropeptic Eutrustox and Hydric Dystrandept sites; and (vii) an interactive term to accommodate the effect of other nutrients on crop growth when both water and nitrogen is limiting.

The CERES model was then run on independent data sets from Hawaii, the Philippines, and Indonesia. The model predictions for phenological development, kernel weights, kernels ear^{-1} and grain yield were nonsite-specific. The CERES model was able to perform equally well on a wide range of agroenvironments. The sites ranged from 5°S latitude to 21° N latitude and 77 to 800 meters above sea level. The soils included Oxisol, Ultisol, and Mollisol. The observed grain yields ranged from 2000 to 11500 kg ha^{-1} and days to anthesis ranged from 48 to 100 days after planting (DAP) and physiological maturity range was 97 to 176 DAP.

The model simulated the effects of nitrogen application, planting density, and seasonal variation with reasonable accuracy. Unmeasured and unknown environmental and management variables caused considerable differences between the simulated and observed values. These variables affected the yield predictions as well as the phenological development.

A sensitivity analysis of the maize model showed that it was capable of mimicking the high sensitivity of maize to temperature and solar radiation. The model accurately predicted days to anthesis as late as 100 DAP and physiological maturity as early 97 DAP.

The CERES maize model simulated latitudinal difference seasonal variation, altitudinal difference, response to nitrogen application, and effect of planting density. The CERES maize model therefore has considerable potential as a tool for agrotechnology transfer among a wide range of agroenvironments in the tropics.

The model currently does not simulate the effect of phosphorus on plant development and yield. Phosphorus in many tropical soils is the major nutrient limiting crop growth.

Regression models were developed to determine labile phosphorus, organic phosphorus, buffering capacity, and phosphorus availability index from readily available soil test P methods and soil physical and chemical properties. These models are useful in generating input data for simulation models where the measured data is not available or too time consuming and costly to determine. These regression equations were developed by stratification of soils into four groups: calcareous, andisols, low activity clays, and high activity clays. The stratification of soils delineated the best soil P extraction method for a specified soil. The Olsen P method applied across a wide range of soils while for the Andisols and the highly weathered soils modified Truog P method is the best.

Regression analysis indicated that on high activity clays exchangeable potassium alone explained more than 50% of the variation in labile P. On low activity clays K x Ca interaction explained more than 85% of the variability in labile P. Approximately 35% of the variation of labile P was explained by Ca and the Ca x K interaction on

field moist Andisols. This indicates that P simulation models should also incorporate the effect of potassium and calcium on labile P.

The P regression models when validated on independent sets of data indicated the lack of standardized laboratory technique. Validation also showed that regression models are not suitable for extrapolative prediction. Regression equations performed best when applied to the conditions for which they were developed.

The regression models developed for andisols and low activity clays when incorporated in the phosphorus model (Jones et al., 1984a) predicted maize grain yields accurately (within one standard deviation of the observed means).

Appendix 3.1 Program listing of CERES maize model.

```
00010 C ---- TROPMODL ---- FEBRUARY 9, 1985
00020 C
00030 C
00040 C     C E R E S   C O R N   N I T R O G E N   M O D E L
00050 C
00060 C
00070 C     CERES CORN MODEL
00080 C     DEVELOPED BY RITCHIE,KINIRY,GODWIN,JONES,KNIEVEL AND OTHERS
00090 C
00100 C     NITROGEN ROUTINES DEVELOPED BY GODWIN,JONES,YOUNGDAHL ET AL
00110 C     RESIDUE DECOMPOSITION BASED ON THE METHOD OF SELIGMAN AND
00120 C     VAN KEULEN 1981
00130 C
00140 C     DENITRIFICATION ROUTINE BASED ON THE METHOD OF ROLSTON AND
00150 C     SHARPLEY 1980
00160 C
00170 C     ADAPTED FOR THE TROPICS BY U.SINGH
00180 C
00190       REAL LAT,LAI,LL,LFWT,NDEM,NDEF1,NDEF2,NDEF3,NDEF4,INSOIL
00200       COMMON /PARAM/ ISOIL,IIRR,IWETH,ISOW,PLANTS,KOUTGR,KOUTWA,SDEPTH,
00210      1  LAT,KVARTY,KIRR,KSOIL,IQUIT,NEWSOL,NEWWET,MULTYR,ISWSWB
00220      2  ,PHINT,KNIT,IODATE,XYIELD,XGRWT,XGPSM,XGPE,XLAI,XBIOM,ISLKJD,
00230      3 MATJD,INSOIL
00240       COMMON /YLDS/ YIELD
00250       COMMON /GENET/ P1,P2,P3,P5,G2,G3
00260       COMMON /SOILI/ SALB,U,SWCON,DLAYR(10),DUL(10),LL(10),SW(10),
00270      1 SAT(10),DEPMAX,TDUL,NLAYR,SMX,WF(10),WR(10),RWU(10),SWEF,CN2
00280       COMMON /IRRIG/ NIRR,JDAY(26),AIRR(26)
00290       COMMON /TITL/ TITLE(20)
00300       COMMON /CLIMT/ TEMPMN,TEMPMX,RAIN,SOLRAD,TMFAC(8)
00310       COMMON /DATEC/ MO,ND,IYR,JDATE,JDATEX,IDIM(12),NYRS
00320       COMMON /WATER/ SUMES1,SUMES2,T,TLL,PESW,TSW,CUMDEP,ESW(10),
00330      1    CSD1,CSD2,SI1(6),SI2(6),ICSDUR,ES,EP,ET,EO,CES,CEP,CET,
00340      1    RLV(10),PRECIP,CRAIN,DRAIN,IDRSW,RTDEP,SWDF1,SWDF2,
00350      1    SWDF3,TRWU,RWUMX
00360       COMMON /WRITS/ AES,AEP,AET,AEO,ASOLR,ATEMX,ATEMN,ARUNOF,
00370      1  ADRAIN,APRECP,ASWDF1,ASWDF2,IOUTGR,IOUTWA,JHEAD,KHEAD,
00380      2  TPRECP,RUNOFF
00390       COMMON /PHENL/ P9,CUMDTT,TBASE,SUMDTT,S1,C1,ISTAGE,
00400      1  DTT,IDUR,SIND,TEMPM
00410       COMMON /GROTH/ GPSM,GPP,GRORT,PTF,LAI,DM,BIOMAS,PLA,SENLA,
00420      1  LFWT,SEEDRV,REGM,XPLANT,WIDTL,EMAT,SLW,PLAY,PLAMX,
00430      1  RTWT,STMWT,GRNWT,SWMIN,LN,EARWT,TLNO,SWMAX,FACLI,
00440      1RWID,SUMP,IDURP,PLAG,EGFT,GROSTM,CARBO,BLAMX(35),GBLA(35),
00450      1 SLA(35),NL1,NLMAX,EARS
00460       COMMON /NCTRL/ KOUTMN,IOUTMN,KOUTNU,IOUTNU,MINCK,NHDMN,NHDUP,
00470      1  IFERT,KFERT,ISWNIT,DMOD,XSTRAW,GRPCTN,GRPTN,XTOTNP,XAPTNP
00480      2,XGNUP
00490       COMMON /NFERTB/ JFDAY(10),AFERT(10),DFERT(10),NFERT,IFTYPE(10)
00500       COMMON /NROOT/ RNFAC(10),RNLOSS(10),JJ
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
00510       COMMON /NSPOOL/ SNH4(10),SNO3(10),NH4(10),NO3(10),FAC(10),
00520      1   BD(10),PH(10)
00530       COMMON /NPLANT/ GRAINN,ROOTN,STOVN,PDWI,STOVWT,PGRORT,NDEM
00540       COMMON /NWRITP/ ATANC,ATCNP,ARANC,ARCNP,ANDEM2,ATNUP,ARTN,ASTOVN,
00550      1  AGRN,CTNUP,TNUP,APTNUP
00560       COMMON /NCONC/ TANC,TCNP,RCNP,RANC,TMNC,VANC,VMNC,XSTAGE
00570 10    CALL PROGRI
00580 40       REWIND IWETH
00590       IYR = 1
00600       JJ = ISOW - 10
00610       IF (ISWSWB.NE.0) CALL SOILRI
00620       NYRS = MULTYR + 1
00630       IF (ISWNIT.NE.0) CALL SOILNI
00640 50       READ (IWETH,120,END=90) IYR,JDATE,SOLRAD,TEMPMX,TEMPMN,RAIN
00650          IF (JDATE.EQ.ISOW.AND.IIRR.EQ.99) RAIN=100.
00670           IF(JDATE.NE.ISOW-10)GO TO 60
00680           DO 61 L=1,NLAYR
00690 61        SW(L)=DUL(L)
00700 60       IF (JDATEX.EQ.367) CALL CALDAT
00710          IF (ISWNIT.NE.0) CALL MINIMO
00720          IF (ISWSWB.NE.0) CALL WATBAL
00730          IF (JDATE.EQ.ISOW.OR.ISTAGE.NE.7) CALL PHENOL (*10)
00740          IF (ISTAGE.LT.6) CALL GROSUB
00750          IF (ISWNIT.NE.0) CALL NWRITE
00760          CALL WRITE
00770           GO TO 50
00780 90    IF (IQUIT.NE.999) GO TO 10
00790       WRITE (6,130)
00800       STOP
00810 C
00820 120   FORMAT (7X,I2,1X,I3,3X,F4.0,3F6.1)
00830 130   FORMAT (6X,'END OF WEATHER DATA')
00840       END
00850 C
00860 C     ****************************** PROGRAM INITIALIZATION
00870 C
00880       SUBROUTINE PROGRI
00890       REAL LAT,LAI,LL,LFWT,NDEM,NDEF1,NDEF2,NDEF3,NDEF4,INSOIL
00900       COMMON /TITL/ TITLE(20)
00910       COMMON /PARAM/ ISOIL,IIRR,IWETH,ISOW,PLANTS,KOUTGR,KOUTWA,SDEPTH,
00920      1  LAT,KVARTY,KIRR,KSOIL,IQUIT,NEWSOL,NEWWET,MULTYR,ISWSWB
00930      2  ,PHINT,KNIT,IODATE,XYIELD,XGRWT,XGPSM,XGPE,XLAI,XBIOM,ISLKJD,
00940      3 MATJD,INSOIL
00950       COMMON /GENET/ P1,P2,P3,P5,G2,G3
00960       COMMON /CLIMT/ TEMPMN,TEMPMX,RAIN,SOLRAD,TMFAC(8)
00970       COMMON /DATEC/ MO,ND,IYR,JDATE,JDATEX,IDIM(12),NYRS
00980       COMMON /WATER/ SUMES1,SUMES2,T,TLL,PESW,TSW,CUMDEP,ESW(10),
00990      1    CSD1,CSD2,SI1(6),SI2(6),ICSDUR,ES,EP,ET,EO,CES,CEP,CET,
01000      1    RLV(10),PRECIP,CRAIN,DRAIN,IDRSW,RTDEP,SWDF1,SWDF2,
01010      1    SWDF3,TRWU,RWUMX
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
01020       COMMON /WRITS/ AES,AEP,AET,AEO,ASOLR,ATEMX,ATEMN,ARUNOF,
01030      1  ADRAIN,APRECP,ASWDF1,ASWDF2,IOUTGR,IOUTWA,JHEAD,KHEAD,
01040      2  TPRECP,RUNOFF
01050       COMMON /PHENL/ P9,CUMDTT,TBASE,SUMDTT,S1,C1,ISTAGE,
01060      1  DTT,IDUR,SIND,TEMPM
01070       COMMON /GROTH/ GPSM,GPP,GRORT,PTF,LAI,DM,BIOMAS,PLA,SENLA,
01080      1  LFWT,SEEDRV,REGM,XPLANT,WIDTL,EMAT,SLW,PLAY,PLAMX,
01090      1  RTWT,STMWT,GRNWT,SWMIN,LN,EARWT,TLNO,SWMAX,FACLI,
01100      1RWID,SUMP,IDURP,PLAG,EGFT,GROSTM,CARBO,BLAMX(35),GBLA(35),
01110      1 SLA(35),NL1,NLMAX,EARS
01120       COMMON /NCTRL/ KOUTMN,IOUTMN,KOUTNU,IOUTNU,MINCK,NHDMN,NHDUP,
01130      1  IFERT,KFERT,ISWNIT,DMOD,XSTRAW,GRPCTN,GRPTN,XTOTNP,XAPTNP
01140      2,XGNUP
01150       COMMON /NDFPG/ NDEF1,NDEF2,NDEF3,NDEF4,GNP,CNSD1,CNSD2
01160       COMMON /NWRITP/ ATANC,ATCNP,ARANC,ARCNP,ANDEM2,ATNUP,ARTN,ASTOVN,
01170      1  AGRN,CTNUP,TNUP,APTNUP
01180       COMMON /NCONC/ TANC,TCNP,RCNP,RANC,TMNC,VANC,VMNC,XSTAGE
01190       COMMON /NPLANT/ GRAINN,ROOTN,STOVN,PDWI,STOVWT,PGRORT,NDEM
01200       COMMON /NROOT/ RNFAC(10),RNLOSS(10),JJ
01210       COMMON /NSPOOL/ SNH4(10),SNO3(10),NH4(10),NO3(10),FAC(10),
01220      1   BD(10),PH(10)
01230       DIMENSION VARTY(5)
01240       NAMELIST /FARM/ ISOIL,IIRR,IWETH,ISOW,PLANTS,SDEPTH,
01250      1  LAT,KVARTY,KIRR,KSOIL,IQUIT,NEWSOL,NEWWET,MULTYR,
01260      2  KOUTWA,KOUTGR,ISWSWB,ISWNIT,PHINT,KNIT,U
01270      3 ,IODATE,XYIELD,XGRWT,XGPSM,XGPE,XLAI,XBIOM,ISLKJD,MATJD,INSOIL
01280       NAMELIST /NPARM/KOUTMN,IOUTMN,KOUTNU,IOUTNU,MINCK,
01290      1 IFERT,KFERT,DMOD,XSTRAW,GRPCTN,GRPTN,XTOTNP,XAPTNP,XGNUP
01300       READ (13,80) TITLE
01310       WRITE (6,90) TITLE
01320       READ (13,PARM,END=10)
01330 10    READ (13,NPARM,END=20)
01340 20    IF (IQUIT.EQ.999) GO TO 70
01350       IF (NEWWET.EQ.0) REWIND IWETH
01360       IF (NEWWET.EQ.0) NEWWET=2
01370       DO 11 L=1,10
01380        RNFAC(L)=1.0
01390        RNLOSS(L)=0.0
01400        SNH4(L)=1.0
01410  11   CONTINUE
01420        GRAINN=1.0
01430        APTNUP=0.0
01440        TMNC=0.0045
01450       S1=SIN(LAT*0.01745)
01460       XPLANT=PLANTS
01470       XSTAGE=0.1
01480       DO 12 I=1,8
01490 12    TMFAC(I)=0.931+0.114*I-0.0703*I**2+0.0053*I**3
01500       C1=COS(LAT*0.01745)
01510       ISTAGE=7
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
01520       TBASE=10.
01530       LAI=0.
01540       SWDF1=1.0
01550       SWDF2=1.0
01560       SWDF3=1.0
01570       ICSDUR=0
01580       JHEAD=0
01590       KHEAD=0
01600       NDEF1=1.0
01610       NDEF2=1.0
01620       NDEF3=1.0
01630       NDEF4=1.0
01640       TANC=0.0
01650       RANC=0.0
01660       STOVN=0.0
01670       ROOTN=0.0
01680       GNP=1.0
01690       TNUP=0.0
01700       NHDMN=0
01710       NHDUP=0
01720       IF (ISWNIT.EQ.0) GO TO 30
01730       CALL OUTNU
01740       CALL OUTMN
01750 30      IF(ISWSWB.EQ.0)KOUTWA=0
01760       IF (KOUTWA.NE.0) CALL OUTWA
01780       IF (KOUTGR.NE.0) CALL OUTGR
01790       JDATEX=367
01800       CUMDTT=0.
01810       SUMDTT=0.
01820       DTT=0.
01830       CRAIN=0.
01840       PRECIP=0.
01850       REWIND 12
01860 40    READ (12,110,END=50) IVARTY,(VARTY(NN),NN=1,4),P1,P2,P5,G2,G3
01870       IF (IVARTY.NE.KVARTY) GO TO 40
01880       GO TO 60
01890 50    WRITE (6,120) KVARTY
01900       STOP
01910 60    CONTINUE
01920       WRITE (6,130) IVARTY,(VARTY(NN),NN=1,4)
01930       WRITE (6,100) LAT,SDEPTH,PLANTS
01940       WRITE (6,140) P1,P2,P5,G2,G3
01950       RETURN
01960 70    WRITE (6,150)
01970       STOP
01980 C
01990 80    FORMAT (20A4)
02000 90    FORMAT (1H1,20X,20A4//)
02010 100   FORMAT (/1X,5X,'LATITUDE =',F6.1,' , SOWING DEPTH = ',F4.0,
02020      1  ' CM , PLANT POPULATION = ',F6.2,'PLANTS PER SQ METER')
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
02030 110   FORMAT (1X,I4,1X,4A4,F6.2,F6.4,F6.2,F6.2,F6.3)
02040 120   FORMAT (' CROP VARIETY INFORMATION IS MISSING FOR',I5)
02050 130   FORMAT (6X,'VARIETY NUMBER ',I4,'  VARIETY NAME  ',5A4)
02060 140   FORMAT (/1X,5X,'GENETIC SPECIFIC CONSTANTS',3X,'P1 =',F6.2,2X,
02070      1  'P2 =',F6.4,2X,'P5=',F6.2,2X,'G2 =',F6.2,2X,'G3 =',F6.3)
02080 150   FORMAT ('  CROP MATURE FOR SINGLE YEAR RUN')
02090       END
02100 C
02110 C     ********** SUBROUTINE TO READ AND INITIALIZE SOIL INFORMATION ****
02120 C
02130       SUBROUTINE SOILRI
02140       REAL LAT,NOUT,NUP,LL,LAI,LFWT,INSOIL
02150       COMMON /PARAM/ ISOIL,IIRR,IWETH,ISOW,PLANTS,KOUTGR,KOUTWA,SDEPTH,
02160      1  LAT,KVARTY,KIRR,KSOIL,IQUIT,NEWSOL,NEWWET,MULTYR,ISWSWB
02170      2  ,PHINT,KNIT,IODATE,XYIELD,XGRWT,XGPSM,XGPE,XLAI,XBIOM,ISLKJD,
02180      3 MATJD,INSOIL
02190       COMMON /SOILI/ SALB,U,SWCON,DLAYR(10),DUL(10),LL(10),SW(10),
02200      1 SAT(10),DEPMAX,TDUL,NLAYR,SMX,WF(10),WR(10),RWU(10),SWEF,CN2
02210       COMMON /IRRIG/ NIRR,JDAY(26),AIRR(26)
02220       COMMON /WATER/ SUMES1,SUMES2,T,TLL,PESW,TSW,CUMDEP,ESW(10),
02230      1    CSD1,CSD2,SI1(6),SI2(6),ICSDUR,ES,EP,ET,EO,CES,CEP,CET,
02240      1    RLV(10),PRECIP,CRAIN,DRAIN,IDRSW,RTDEP,SWDF1,SWDF2,
02250      1    SWDF3,TRWU,RWUMX
02260       COMMON /NSPOOL/ SNH4(10),SNO3(10),NH4(10),NO3(10),FAC(10),
02270      1   BD(10),PH(10)
02280       COMMON /PHENL/ P9,CUMDTT,TBASE,SUMDTT,S1,C1,ISTAGE,
02290      1  DTT,IDUR,SIND,TEMPM
02300       COMMON /GROTH/ GPSM,GPP,GRORT,PTF,LAI,DM,BIOMAS,PLA,SENLA,
02310      1  LFWT,SEEDRV,REGM,XPLANT,WIDTL,EMAT,SLW,PLAY,PLAMX,
02320      1  RTWT,STMWT,GRNWT,SWMIN,LN,EARWT,TLNO,SWMAX,FACLI,
02330      1RWID,SUMP,IDURP,PLAG,EGFT,GROSTM,CARBO,BLAMX(35),GBLA(35),
02340      1 SLA(35),NL1,NLMAX,EARS
02350       COMMON /NMOVE/ FLUX(10),SWX(10),FLOW(10),MU,NOUT(10),NUP(10)
02360       COMMON /NSTEMP/ ST(10),ANG,TMN,AMP
02370       COMMON /NROOT/ RNFAC(10),RNLOSS(10),JJ
02380       IF (NEWSOL.EQ.0) GO TO 60
02390       REWIND ISOIL
02400 10    READ (ISOIL,200,END=20) NSOIL,SALB,U,SWCON,CN2
02410       IF (NSOIL.NE.KSOIL) GO TO 10
02420       WRITE (6,120) SALB,U,SWCON,CN2
02430       GO TO 30
02440 20    WRITE (6,210)
02450 30    DEPMAX=0.
02460       CUMDEP=0.
02470       DO 40 NLAYR=1,10
02480          READ (ISOIL,130) DLAYR(NLAYR),LL(NLAYR),DUL(NLAYR),SAT(NLAYR),
02490      1     WR(NLAYR)
02500       IF(INSOIL.LE.1.0) GO TO 37
02510 38    IF(DLAYR(NLAYR).GT.0.) READ (13,134) SW(NLAYR)
02520       GO TO 39
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
02530 37     SW(NLAYR)=LL(NLAYR)+(DUL(NLAYR)-LL(NLAYR))*INSOIL
02540        CUMDEP=CUMDEP+DLAYR(NLAYR)
02550        IF(CUMDEP.LE.110.) GO TO 39
02560        DLL=0.008*(CUMDEP-110.)*(DUL(NLAYR)-LL(NLAYR))+LL(NLAYR)
02570        IF(SW(NLAYR).LT.DLL) SW(NLAYR)=DLL
02580 39     CONTINUE
02590           DEPMAX=DEPMAX+DLAYR(NLAYR)
02600           IF (DLAYR(NLAYR).LE.0.) GO TO 50
02610 40     CONTINUE
02620        GO TO 60
02630 50     NLAYR=NLAYR-1
02640 60     IF (IIRR.EQ.0.OR.IIRR.EQ.99) GO TO 81
02650        WRITE (6,140)
02660        J=1
02670        NIRR=0
02680 70     READ(IIRR,135,END=80) LIRR
02690        IF(LIRR.NE.KIRR) GO TO 70
02700 75     READ (IIRR,150) JDAY(J),AIRR(J)
02710        IF (JDAY(J).EQ.0) GO TO 80
02720        WRITE (6,160) JDAY(J),AIRR(J)
02730        J=J+1
02740        NIRR=NIRR+1
02750        GO TO 75
02760  80    REWIND IIRR
02770   81    CONTINUE
02780        SWR=(SW(1)-LL(1))/(DUL(1)-LL(1))
02790        IF (SWR.LT.0.) SWR=0.
02800        IF (SWR.GE..9) GO TO 90
02810        SUMES2=25-27.8*SWR
02820        SUMES1=U
02830        T=(SUMES2/3.5)**2
02840        GO TO 100
02850 90     SUMES2=0.
02860        SUMES1=100-SWR*100
02870        T=0.
02880 100    CONTINUE
02890        WRITE (6,180)
02900        XX=0.
02910        TSW=0.
02920        TPESW=0.
02930        TDUL=0.
02940        TLL=0.
02950        TSAT=0.
02960        CUMDEP=0.
02970        DL1=0.
02980        IDRSW=0
02990        DO 110 L=1,NLAYR
03000           DL2=DL1+DLAYR(L)
03010           ESW(L)=DUL(L)-LL(L)
03020           WRITE (6,190) DL1,DL2,LL(L),DUL(L),SAT(L),ESW(L),SW(L),WR(L)
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
03030           DL1=DL2
03040           CUMDEP=CUMDEP+DLAYR(L)
03050           TSW=TSW+SW(L)*DLAYR(L)
03060           TPESW=TPESW+ESW(L)*DLAYR(L)
03070           TLL=TLL+LL(L)*DLAYR(L)
03080           TDUL=TDUL+DUL(L)*DLAYR(L)
03090           TSAT=TSAT+SAT(L)*DLAYR(L)
03100          IF(SW(L).GT.DUL(L))IDRSW=1
03110           WX=1.016*(1.-EXP(-4.16*CUMDEP/DEPMAX))
03120           WF(L)=WX-XX
03130           XX=WX
03140           RWU(L)=0.0
03150           FLUX(L)=0.0
03160           IF (L.LE.5) FLOW(L)=0.0
03170 110     CONTINUE
03180         RTDEP=DEPMAX
03190         WRITE (6,170) RTDEP,TLL,TDUL,TSAT,TPESW,TSW
03200         CN1=-16.91+1.348*CN2-0.01379*CN2**2+0.0001172*CN2**3
03210         SMX=254.*(100./CN1-1.)
03220         SWEF=0.9-0.00038*(DLAYR(1)-30.)**2
03230         CET=0.
03240         CES=0.
03250         CEP=0.
03260         CRAIN=0.
03270         APESW=TPESW/DEPMAX
03280         RWUMX=0.03
03290         RETURN
03300 C
03310 120     FORMAT (1X,5X,'SOIL ALBEDO= ',F4.2,2X,'U=',F5.1,2X,'SWCON=',F6.2,
03320        1  '   RUNOFF CURVE NO.=',F6.1)
03330 130     FORMAT (4F10.3,10X,F10.3)
03340 134     FORMAT (1X,F10.3)
03350 135     FORMAT(I3)
03360 140     FORMAT (/6X,'JULIAN DAY    IRRIGATION(MM)')
03370 150     FORMAT (7X,I3,1X,F5.2)
03380 160     FORMAT (8X,I5,7X,F5.0)
03390 170     FORMAT (/1X,8X,6F9.1,'   TOTAL FOR PROFILE',/)
03400 180     FORMAT (1HO,6X,'DEPTH-CM',6X,'LOW LIM',3X,' UP LIM',3X,'SAT SW',
03410        1  3X,'EXT SW',3X,'INIT SW',4X,'WR',/)
03420 190     FORMAT (1H ,3X,F6.0,'-',F6.0,2X,6F9.3)
03430 200     FORMAT(I4,34X,2F6.2,6X,2F6.2)
03440 210     FORMAT (' SOIL DATA IS MISSING')
03450         END
03460 C
03470 C       ********** OUTPUT SUBROUTINE FOR WATER BALANCE*********************
03480 C
03490         SUBROUTINE OUTWA
03500         COMMON /TITL/ TITLE(20)
03510         COMMON /PARAM/ ISOIL,IIRR,IWETH,ISOW,PLANTS,KOUTGR,KOUTWA,SDEPTH,
03520        1  LAT,KVARTY,KIRR,KSOIL,IQUIT,NEWSOL,NEWWET,MULTYR,ISWSWB
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
03530      2  ,PHINT,KNIT,IODATE,XYIELD,XGRWT,XGPSM,XGPE,XLAI,XBIOM,ISLKJD,
03540      3 MATJD,INSOIL
03550       COMMON /SOILI/ SALB,U,SWCON,DLAYR(10),DUL(10),LL(10),SW(10),
03560      1 SAT(10),DEPMAX,TDUL,NLAYR,SMX,WF(10),WR(10),RWU(10),SWEF,CN2
03570       COMMON /DATEC/ MO,ND,IYR,JDATE,JDATEX,IDIM(12),NYRS
03580       COMMON /WATER/ SUMES1,SUMES2,T,TLL,PESW,TSW,CUMDEP,ESW(10),
03590      1    CSD1,CSD2,SI1(6),SI2(6),ICSDUR,ES,EP,ET,EO,CES,CEP,CET,
03600      1    RLV(10),PRECIP,CRAIN,DRAIN,IDRSW,RTDEP,SWDF1,SWDF2,
03610      1    SWDF3,TRWU,RWUMX
03620       COMMON /WRITS/ AES,AEP,AET,AEO,ASOLR,ATEMX,ATEMN,ARUNOF,
03630      1  ADRAIN,APRECP,ASWDF1,ASWDF2,IOUTGR,IOUTWA,JHEAD,KHEAD,
03640      2  TPRECP,RUNOFF
03650       COMMON /NROOT/ RNFAC(10),RNLOSS(10),JJ
03660       DIMENSION AVEARG(10)
03670       EQUIVALENCE (AVEARG(1),AES)
03680       IF (JHEAD.EQ.1) GO TO 10
03690       IF (KOUTWA.NE.0) WRITE (10,50) TITLE
03700       IF (KOUTWA.NE.0) WRITE (10,60)
03710       JHEAD=1
03720       GO TO 30
03730 10    DAWA=FLOAT(IOUTWA)
03740       DO 20 I=1,7
03750          AVEARG(I)=AVEARG(I)/DAWA
03760 20    CONTINUE
03770       CALL CALDAT
03780       WRITE (10,70) MO,ND,IYR,JDATE,AVEARG,SW,PESW
03790 30    DO 40 I=1,10
03800          AVEARG(I)=0.
03810 40    CONTINUE
03820       IOUTWA=0
03830       RETURN
03840 C
03850  50    FORMAT (1H1,20X,20A4//)
03860  60    FORMAT (1H ,9X,'JUL',2X,12('-'),' AVERAGE ',12('-'),2X,
03870      1  '---- PERIOD ----',2X,8('-'),' SOIL WATER CONTENT ',
03880      2  'WITH DEPTH ',9('-'),T123,'TOTAL',/,4X,'DAY',3X,'DAY',3X,'ES',
03890      3  3X,'EP',3X,'ET',3X,'EO',2X,'SR   MAX  MIN RUNOFF',
03900      4  ' DRAIN PREC  SW1  SW2  SW3  SW4  SW5  SW6  SW7  SW8  SW9 SW10
03910      5    PESW')
03920  70    FORMAT (1X,I2,'/',I2,'/',I2,I4,4F5.1,F5.0,2F5.1,F6.2,2F6.2,10(1X,
03930      1  F4.2),3X,F7.1)
03940       END
03950 C
03960 C     ****************OUTPUT SUBROUTINE FOR GROWTH**********************
03970 C
03980       SUBROUTINE OUTGR
03990       REAL LAT,LL,LAI,LFWT
04000       COMMON /TITL/ TITLE(20)
04010       COMMON /CLIMT/ TEMPMN,TEMPMX,RAIN,SOLRAD,TMFAC(8)
04020       COMMON /PARAM/ ISOIL,IIRR,IWETH,ISOW,PLANTS,KOUTGR,KOUTWA,SDEPTH,
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
04030      1  LAT,KVARTY,KIRR,KSOIL,IQUIT,NEWSOL,NEWWET,MULTYR,ISWSWB
04040      2 ,PHINT,KNIT,IODATE,XYIELD,XGRWT,XGPSM,XGPE,XLAI,XBIOM,ISLKJD,
04050      3 MATJD,INSOIL
04060       COMMON /WATER/ SUMES1,SUMES2,T,TLL,PESW,TSW,CUMDEP,ESW(10),
04070      1    CSD1,CSD2,SI1(6),SI2(6),ICSDUR,ES,EP,ET,EO,CES,CEP,CET,
04080      1    RLV(10),PRECIP,CRAIN,DRAIN,IDRSW,RTDEP,SWDF1,SWDF2,
04090      1    SWDF3,TRWU,RWUMX
04100       COMMON /DATEC/ MO,ND,IYR,JDATE,JDATEX,IDIM(12),NYRS
04110       COMMON /WRITS/ AES,AEP,AET,AEO,ASOLR,ATEMX,ATEMN,ARUNOF,
04120      1  ADRAIN,APRECP,ASWDF1,ASWDF2,IOUTGR,IOUTWA,JHEAD,KHEAD,
04130      2  TPRECP,RUNOFF
04140       COMMON /PHENL/ P9,CUMDTT,TBASE,SUMDTT,S1,C1,ISTAGE,
04150      1  DTT,IDUR,SIND,TEMPM
04160       COMMON /GROTH/ GPSM,GPP,GRORT,PTF,LAI,DM,BIOMAS,PLA,SENLA,
04170      1  LFWT,SEEDRV,REGM,XPLANT,WIDTL,EMAT,SLW,PLAY,PLAMX,
04180      1  RTWT,STMWT,GRNWT,SWMIN,LN,EARWT,TLNO,SWMAX,FACLI,
04190      1RWID,SUMP,IDURP,PLAG,EGFT,GROSTM,CARBO,BLAMX(35),GBLA(35),
04200      1 SLA(35),NL1,NLMAX,EARS
04210       COMMON /NROOT/ RNFAC(10),RNLOSS(10),JJ
04220       IF (KHEAD.EQ.1) GO TO 10
04230       IF (KOUTGR.NE.0) WRITE (9,30) TITLE
04240       IF (KOUTGR.NE.0) WRITE (9,40)
04250       KHEAD=1
04260       GO TO 20
04270 10    DAGR=FLOAT(IOUTGR)
04280       ASWDF1=ASWDF1/DAGR
04290       ASWDF2=ASWDF2/DAGR
04300       CALL CALDAT
04310       WRITE (9,50) MO,ND,IYR,JDATE,BIOMAS,LN,LAI,SUMDTT,TRWU,RTWT,
04320      1  STMWT,GRNWT,LFWT,SENLA,ASWDF1,ASWDF2,RTDEP,PTF,RLV(1),RLV(2),
04330      2  RLV(3),RLV(4),RLV(5),RLV(6),RLV(7),RLV(8)
04340 C      WRITE(22,60) JDATE,BIOMAS,LAI
04350  20   ASWDF1=0.
04360       ASWDF2=0.
04370       IOUTGR=0
04380       RETURN
04390 C
04400 30    FORMAT (1H1,20X,20A4//)
04410 40    FORMAT (1H ,4X,'DATE  JUL  BIO  LEAF  LAI SUMDTT TRWU',2X,
04420      1  'ROOT   STEM  GRAIN  LEAF    SEN  SW  SW  ROOT    ',5X,
04430      2  'ROOT LENGTH VOLUME',/,11X,'DAY MASS  NO.',21X,'WT',5X,'WT',4X,
04440      3  'WT',5X,'WT    LFA  DF1 DF2 DPTH PTF   L1  L2  L3',2X,
04450      4  'L4  L5  L6  L7  L8',/)
04460 50    FORMAT (1X,I2,'/',I2,'/',I2,I4,1X,F5.0,I4,1X,F5.2,1X,F5.0,F6.1,
04470      1  4(1X,F6.1),1X,F5.0,2(1X,F3.1),1X,F4.0,F5.2,8(1X,
04480      2  F3.1))
04490 C  60 FORMAT (1X,I3,F9.3,F6.3)
04500       END
04510 C
04520 C     ********** SUBROUTINE TO CONVERT JULIAN DAY TO CALENDAR DATE *****
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
04530 C
04540       SUBROUTINE CALDAT
04550       COMMON /DATEC/ MO,ND,IYR,JDATE,JDATEX,IDIM(12),NYRS
04560       IF (JDATE.GE.JDATEX) GO TO 20
04570       DO 10 I=1,12
04580          IDIM(I)=31
04590 10    CONTINUE
04600       IDIM(4)=30
04610       IDIM(6)=30
04620       IDIM(9)=30
04630       IDIM(11)=30
04640       IDIM(2)=28
04650       IF (MOD(IYR,4).EQ.0) IDIM(2)=29
04660       IF (JDATEX.EQ.367) WRITE (6,50) JDATE
04670 20    MO=1
04680       ND=31
04690 30    IF (ND.GE.JDATE) GO TO 40
04700       MO=MO+1
04710       ND=ND+IDIM(MO)
04720       GO TO 30
04730 40    ND=JDATE-ND+IDIM(MO)
04740       JDATEX=JDATE
04750       RETURN
04760 C
04770 50    FORMAT (/12X,'THE PROGRAM STARTED ON JULIAN DATE',2X,I3,/)
04780       END
04790 C
04800 C     ********** WATER BALANCE SUBROUTINE ********************************
04810 C
04820       SUBROUTINE WATBAL
04830       REAL LAT,LL,LAI,LFWT,NOUT,NUP
04840       COMMON /PARAM/ ISOIL,IIRR,IWETH,ISOW,PLANTS,KOUTGR,KOUTWA,SDEPTH,
04850      1  LAT,KVARTY,KIRR,KSOIL,IQUIT,NEWSOL,NEWWET,MULTYR,ISWSWB
04860      2 ,PHINT,KNIT,IODATE,XYIELD,XGRWT,XGPSM,XGPE,XLAI,XBIOM,ISLKJD,
04870      3 MATJD,INSOIL
04880       COMMON /SOILI/ SALB,U,SWCON,DLAYR(10),DUL(10),LL(10),SW(10),
04890      1 SAT(10),DEPMAX,TDUL,NLAYR,SMX,WF(10),WR(10),RWU(10),SWEF,CN2
04900       COMMON /IRRIG/ NIRR,JDAY(26),AIRR(26)
04910       COMMON /CLIMT/ TEMPMN,TEMPMX,RAIN,SOLRAD,TMFAC(8)
04920       COMMON /DATEC/ MO,ND,IYR,JDATE,JDATEX,IDIM(12),NYRS
04930       COMMON /WATER/ SUMES1,SUMES2,T,TLL,PESW,TSW,CUMDEP,ESW(10),
04940      1    CSD1,CSD2,SI1(6),SI2(6),ICSDUR,ES,EP,ET,EO,CES,CEP,CET,
04950      1    RLV(10),PRECIP,CRAIN,DRAIN,IDRSW,RTDEP,SWDF1,SWDF2,
04960      1    SWDF3,TRWU,RWUMX
04970       COMMON /WRITS/ AES,AEP,AET,AEO,ASOLR,ATEMX,ATEMN,ARUNOF,
04980      1  ADRAIN,APRECP,ASWDF1,ASWDF2,IOUTGR,IOUTWA,JHEAD,KHEAD,
04990      2  TPRECP,RUNOFF
05000       COMMON /PHENL/ P9,CUMDTT,TBASE,SUMDTT,S1,C1,ISTAGE,
05010      1  DTT,IDUR,SIND,TEMPM
05020       COMMON /GROTH/ GPSM,GPP,GRORT,PTF,LAI,DM,BIOMAS,PLA,SENLA,
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
05030      1  LFWT,SEEDRV,REGM,XPLANT,WIDTL,EMAT,SLW,PLAY,PLAMX,
05040      1  RTWT,STMWT,GRNWT,SWMIN,LN,EARWT,TLNO,SWMAX,FACLI,
05050      1RWID,SUMP,IDURP,PLAG,EGFT,GROSTM,CARBO,BLAMX(35),GBLA(35),
05060      1 SLA(35),NL1,NLMAX,EARS
05070       COMMON /NCTRL/ KOUTMN,IOUTMN,KOUTNU,IOUTNU,MINCK,NHDMN,NHDUP,
05080      1  IFERT,KFERT,ISWNIT,DMOD,XSTRAW,GRPCTN,GRPTN,XTOTNP,XAPTNP
05090      2,XGNUP
05100       COMMON /NMOVE/ FLUX(10),SWX(10),FLOW(10),MU,NOUT(10),NUP(10)
05110       COMMON /NROOT/ RNFAC(10),RNLOSS(10),JJ
05120       COMMON /NSPOOL/ SNH4(10),SNO3(10),NH4(10),NO3(10),FAC(10),
05130      1   BD(10),PH(10)
05140       DIMENSION RLDF(10)
05150       ICSDUR=ICSDUR+1
05160       PRECIP=0.
05170       TAIR=0.
05180       IOFF=0
05190       IF (IIRR.EQ.0) GO TO 20
05200       IF (IIRR.EQ.99) GO TO 15
05210       DO 10 J=1,NIRR
05220          IF (JDATE.EQ.JDAY(J)) PRECIP=AIRR(J)
05230 10    IOFF=1
05240       GO TO 20
05250 15    IF(SWDF3.GE.0.9) GO TO 20
05260        DO 99 L=1,NLAYR
05270          TAIR=TAIR+(DUL(L)-SW(L))*DLAYR(L)*10
05280 99    CONTINUE
05290 20    PRECIP=PRECIP+RAIN+TAIR
05300       TPRECP=PRECIP
05321       DRAIN=0.
05322       PINF=0.
05330       RUNOFF=0.
05340       WINF=0.
05350       IF (PRECIP.EQ.0.) GO TO 70
05360 C     **CALCULATE RUNOFF BY WILLIAMS -SCS CURVE NO. TECHNIQUE********
05370       SUM=0.
05380       DO 50 L=1,NLAYR
05390          SUM=SUM+WF(L)*(SW(L)-LL(L))/ESW(L)
05400 50    CONTINUE
05410       R2=SMX*(1.-SUM)
05420       IF (R2.LE.2.54) R2=2.54
05430       PB=PRECIP-0.2*R2
05440       IF (PB.LE.0.) GO TO 60
05450       RUNOFF=PB*PB/(PRECIP+.8*R2)
05460        IF(IOFF.EQ.1)RUNOFF=0.
05470 60    PINF=PRECIP-RUNOFF
05480 C     **CALCULATE DRAINAGE AND SOIL WATER REDISTRIBUTION*************
05490       WINF=PINF
05500       FLUX(1)=PINF*0.1
05510       IDRSW=1
05520 70    IF (IDRSW.EQ.0) GO TO 130
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
05530       IDRSW=0
05540       DO 110 L=1,NLAYR
05550          IF (FLUX(L).EQ.0.) GO TO 80
05560          HOLD=(SAT(L)-SW(L))*DLAYR(L)
05570          IF (FLUX(L).LE.HOLD) GO TO 80
05580          DRAIN=SWCON*(SAT(L)-DUL(L))*DLAYR(L)
05590          SW(L)=SAT(L)-DRAIN/DLAYR(L)
05600          FLUX(L)=FLUX(L)-HOLD+DRAIN
05610          IDRSW=1
05620          GO TO 100
05630 80       SW(L)=SW(L)+FLUX(L)/DLAYR(L)
05640          IF (SW(L).LT.DUL(L)+0.003) GO TO 90
05650          DRAIN=(SW(L)-DUL(L))*SWCON*DLAYR(L)
05660          SW(L)=SW(L)-DRAIN/DLAYR(L)
05670          FLUX(L)=DRAIN
05680          IDRSW=1
05690          GO TO 100
05700 90       FLUX(L)=0.
05710 100      IF (L.LT.NLAYR) FLUX(L+1)=FLUX(L)
05720 110   CONTINUE
05730       IF (L.GE.NLAYR) L=NLAYR
05740       DRAIN=FLUX(L)*10.0
05750       IF (ISWNIT.NE.0.AND.IDRSW.EQ.1) CALL NFLUX (0)
05760       IF (ISWNIT.NE.0.AND.IDRSW.EQ.1) CALL DNIT
05770       DO 120 L=1,NLAYR
05780          FLUX(L)=0.0
05790 120   CONTINUE
05800 C     ********************POTENTIAL EVAPORATION ROUTINE*****************
05810 130   TD=0.60*TEMPMX+0.40*TEMPMN
05820       ALBEDO=SALB
05830       IF (ISTAGE.LT.5.) ALBEDO=0.23-(0.23-SALB)*EXP(-0.75*LAI)
05840       EEQ=SOLRAD*(2.04E-4-1.83E-4*ALBEDO)*(TD+29.)
05850       EO=EEQ*1.1
05860       IF (TEMPMX.GT.35.) EO=EEQ*((TEMPMX-35.)*0.05+1.1)
05870       IF (TEMPMX.LT.5.0) EO=EEQ*0.01*EXP(0.18*(TEMPMX+20.))
05880       EOS=EO*(1.-0.43*LAI)
05890       IF (LAI.GT.1.) EOS=EO/1.1*EXP(-0.4*LAI)
05900 C     ***********************SOIL AND PLANT EVAPORATION ROUTINE**********
05910       IF (SUMES1.GE.U.AND.WINF.GE.SUMES2) GO TO 150
05920       IF (SUMES1.GE.U.AND.WINF.LT.SUMES2) GO TO 160
05930       IF (WINF.GE.SUMES1) GO TO 190
05940       SUMES1=SUMES1-WINF
05950       GO TO 200
05960 150   IF (WINF.LT.SUMES2) GO TO 160
05970       WINF=WINF-SUMES2
05980       SUMES1=U-WINF
05990       T=0.
06000       IF (WINF.GT.U) GO TO 190
06010       GO TO 200
06020 160   T=T+1.
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
06030       ES=3.5*T**0.5-SUMES2
06040       IF (WINF.GT.0.) GO TO 170
06050       IF (ES.GT.EOS) ES=EOS
06060       GO TO 180
06070 170   ESX=0.8*WINF
06080       IF (ESX.LE.ES) ESX=ES+WINF
06090       IF (ESX.GT.EOS) ESX=EOS
06100       ES=ESX
06110 180   CONTINUE
06120       SUMES2=SUMES2+ES-WINF
06130       T=(SUMES2/3.5)**2
06140       GO TO 220
06150 190   SUMES1=0.
06160 200   SUMES1=SUMES1+EOS
06170       IF (SUMES1.GT.U) GO TO 210
06180       ES=EOS
06190       GO TO 220
06200 210   ES=EOS-0.4*(SUMES1-U)
06210       SUMES2=0.6*(SUMES1-U)
06220       T=(SUMES2/3.5)**2
06230 220   SW(1)=SW(1)-ES*.1/DLAYR(1)
06240        IF(SW(1).GE.LL(1)*SWEF)GO TO 192
06250        ES1=(LL(1)*SWEF-SW(1))*DLAYR(1)*10.
06260        SW(1)=LL(1)*SWEF
06270        ES=ES-ES1
06280 192    NIND=NLAYR-1
06290       DO 250 L=1,NLAYR
06300          FLOW(L)=0.0
06310          SWX(L)=SW(L)
06320 250   CONTINUE
06330       IST=1
06340       IF (DLAYR(1).EQ.5.0) IST=2
06350       DO 260 L=IST,NIND
06360          MU=L+1
06370          THET1=SW(L)-LL(L)
06380          IF (THET1.LT.0.) THET1=0.
06390          THET2=SW(MU)-LL(MU)
06400          DBAR=0.88*EXP(35.4*(THET1+THET2)*0.5)
06410          IF (DBAR.GT.100.) DBAR=100.
06420          FLOW(L)=DBAR*(THET2-THET1)/((DLAYR(L)+DLAYR(MU))*0.5)
06430         WAT1=DUL(1)-SW(1)
06440         IF(FLOW(1).GT.WAT1)FLOW(1)=WAT1
06450         IF(WAT1.LT.0.0)FLOW(1)=0.0
06460          SWX(L)=SWX(L)+FLOW(L)/DLAYR(L)
06470          SWX(MU)=SWX(MU)-FLOW(L)/DLAYR(MU)
06480 260   CONTINUE
06490       IF (ISWNIT.NE.0) CALL NFLUX (1)
06500       DO 270 L=1,MU
06510          SW(L)=SWX(L)
06520 270   CONTINUE
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
06530       CES=CES+ES
06540       EP=0.
06550       IF (ISTAGE.GE.6) GO TO 280
06560       IF (LAI.LE.3.0) EP=EO*(1.-EXP(-LAI))
06570       IF (LAI.GT.3.0) EP=EO
06580       IF (EP+ES.GT.EO) EP=EO-ES
06590       GO TO 300
06600 280   ET=ES
06610       CET=CET+ET
06620       TSW=0.
06630       DO 290 L=1,NLAYR
06640          TSW=TSW+SW(L)*DLAYR(L)
06650 290   CONTINUE
06660       PESW=TSW-TLL
06670       RETURN
06680 C        ***************ROOT GROWTH AND DEPTH ROUTINE*****************
06690 300   IF (GRORT.EQ.0.) GO TO 340
06700       RLNEW=GRORT*0.80*PLANTS
06710       TRLDF=0.
06720       CUMDEP=0.
06730       SWDF3=0.0
06740       DO 310 L=1,NLAYR
06750          L1=L
06760          CUMDEP=CUMDEP+DLAYR(L)
06770          SWDF=1.
06780          IF (SW(L)-LL(L).LT.0.25*ESW(L)) SWDF=4.*(SW(L)-LL(L))/
06790      1     ESW(L)
06800          IF (SWDF.LT.0.) SWDF=0.
06810          RLDF(L)=AMIN1(SWDF,RNFAC(L))*WR(L)
06820          IF (CUMDEP.LT.RTDEP) GO TO 3100
06830          RTDEP=RTDEP+DTT*0.22*AMIN1((SWDF1*2.0),SWDF)
06840          IF (RTDEP.GT.DEPMAX) RTDEP=DEPMAX
06850          RLDF(L)=RLDF(L)*(1.-(CUMDEP-RTDEP)/DLAYR(L))
06860          TRLDF=TRLDF+RLDF(L)
06870          GO TO 320
06880  3100    SWDF3=SWDF3+(SW(L)-LL(L))/(DUL(L)-LL(L))*DLAYR(L)
06890 310   TRLDF=TRLDF+RLDF(L)
06900 320      SWDF3=SWDF3/CUMDEP
06910         IF (TRLDF.LT.RLNEW*0.00001) GO TO 340
06920       RNLF=RLNEW/TRLDF
06930       DO 330 L=1,L1
06940          RLV(L)=RLV(L)+RLDF(L)*RNLF/DLAYR(L)-0.005*RLV(L)
06950          IF(RLV(L).LT.0)RLV(L)=0.
06960          IF(RLV(L).GT.5.0)RLV(L)=5.0
06970          SNH4(L)=SNH4(L)+RNLOSS(L)*PLANTS*10.0
06980 330   CONTINUE
06990 C     ********** CALCULATE WATER UPTAKE AND SOIL DEFICIT FACTORS *******
07000 340   IF (EP.EQ.0.) GO TO 390
07010       EP1=EP*0.1
07020       TRWU=0.
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
07030        DO 350 L=1,NLAYR
07040           IF (RLV(L).EQ.0.0) GO TO 360
07050           RWU(L)=2.67E-3*EXP(62.*(SW(L)-LL(L)))/(6.68-ALOG(RLV(L)))
07060           IF (RWU(L).GT.RWUMX) RWU(L)=RWUMX
07080           RWU(L)=RWU(L)*DLAYR(L)*RLV(L)
07090           TRWU=TRWU+RWU(L)
07100 350    CONTINUE
07110 360    WUF=1.
07120        IF (EP1.LE.TRWU) WUF=EP1/TRWU
07130        TSW=0.
07140        DO 370 L=1,NLAYR
07150           RWU(L)=RWU(L)*WUF
07151           IF (SW(L).LE.1.0*LL(L)) RWU(L)=0.0
07160           SW(L)=SW(L)-RWU(L)/DLAYR(L)
07170           TSW=TSW+SW(L)*DLAYR(L)
07180 370    CONTINUE
07190        PESW=TSW-TLL
07200        SWDF2=1.
07210        IF (TRWU/EP1.LT.1.50) SWDF2=0.67*TRWU/EP1
07220        IF (ISTAGE.GE.2) GO TO 380
07230 380    SWDF1=1.
07240        IF (TRWU/EP1.GT.1.0) GO TO 390
07250        SWDF1=1.00*TRWU/EP1
07260        EP=TRWU*10.
07270 390    ET=ES+EP
07280        CEP=CEP+EP
07290        CET=CET+ET
07300        CSD1=CSD1+1.0-SWDF1
07310        CSD2=CSD2+1.0-SWDF2
07320        RETURN
07330        END
07340 C
07350 C      ********** SUBROUTINE TO CALCULATE PHENOLOGICAL STAGE ************
07360 C
07370        SUBROUTINE PHENOL (*)
07380        REAL LAT,NFAC,NDEF1,NDEF2,NDEF3,NDEF4,LL,LAI,LFWT,NDEM,MAXLAI,
07390       1SWMAX,FACLI
07400        COMMON /PARAM/ ISOIL,IIRR,IWETH,ISOW,PLANTS,KOUTGR,KOUTWA,SDEPTH,
07410       1  LAT,KVARTY,KIRR,KSOIL,IQUIT,NEWSOL,NEWWET,MULTYR,ISWSWB
07420       2 ,PHINT,KNIT,IODATE,XYIELD,XGRWT,XGPSM,XGPE,XLAI,XBIOM,ISLKJD,
07430       3 MATJD,INSOIL
07440        COMMON /YLDS/ YIELD
07450        COMMON /GENET/ P1,P2,P3,P5,G2,G3
07460        COMMON /SOILI/ SALB,U,SWCON,DLAYR(10),DUL(10),LL(10),SW(10),
07470       1 SAT(10),DEPMAX,TDUL,NLAYR,SMX,WF(10),WR(10),RWU(10),SWEF,CN2
07480        COMMON /DATEC/ MO,ND,IYR,JDATE,JDATEX,IDIM(12),NYRS
07490        COMMON /WATER/ SUMES1,SUMES2,T,TLL,PESW,TSW,CUMDEP,ESW(10),
07500       1    CSD1,CSD2,SI1(6),SI2(6),ICSDUR,ES,EP,ET,EO,CES,CEP,CET,
07510       1    RLV(10),PRECIP,CRAIN,DRAIN,IDRSW,RTDEP,SWDF1,SWDF2,
07520       1    SWDF3,TRWU,RWUMX
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
07530       COMMON /WRITS/ AES,AEP,AET,AEO,ASOLR,ATEMX,ATEMN,ARUNOF,
07540      1  ADRAIN,APRECP,ASWDF1,ASWDF2,IOUTGR,IOUTWA,JHEAD,KHEAD,
07550      2  TPRECP,RUNOFF
07560       COMMON /PHENL/ P9,CUMDTT,TBASE,SUMDTT,S1,C1,ISTAGE,
07570      1  DTT,IDUR,SIND,TEMPM
07580       COMMON /GROTH/ GPSM,GPP,GRORT,PTF,LAI,DM,BIOMAS,PLA,SENLA,
07590      1  LFWT,SEEDRV,REGM,XPLANT,WIDTL,EMAT,SLW,PLAY,PLAMX,
07600      1  RTWT,STMWT,GRNWT,SWMIN,LN,EARWT,TLNO,SWMAX,FACLI,
07610      1RWID,SUMP,IDURP,PLAG,EGFT,GROSTM,CARBO,BLAMX(35),GBLA(35),
07620      1 SLA(35),NL1,NLMAX,EARS
07630       COMMON /CLIMT/ TEMPMN,TEMPMX,RAIN,SOLRAD,TMFAC(8)
07640       COMMON /NCONC/ TANC,TCNP,RCNP,RANC,TMNC,VANC,VMNC,XSTAGE
07650       COMMON /NDFPG/ NDEF1,NDEF2,NDEF3,NDEF4,GNP,CNSD1,CNSD2
07660       COMMON /NPLANT/ GRAINN,ROOTN,STOVN,PDWI,STOVWT,PGRORT,NDEM
07670       COMMON /NWRITP/ ATANC,ATCNP,ARANC,ARCNP,ANDEM2,ATNUP,ARTN,ASTOVN,
07680      1  AGRN,CTNUP,TNUP,APTNUP
07690       COMMON /OUTER/ISUMO
07700       COMMON /NCTRL/ KOUTMN,IOUTMN,KOUTNU,IOUTNU,MINCK,NHDMN,NHDUP,
07710      1  IFERT,KFERT,ISWNIT,DMOD,XSTRAW,GRPCTN,GRPTN,XTOTNP,XAPTNP
07720      2,XGNUP
07730       COMMON /NNN/ NFAC,DSTOVN
07740       COMMON /NSTEMP/ ST(10),ANG,TMN,AMP
07741       DIMENSION SI3(6), SI4(6)
07750       TEMPM=0.4*TEMPMX+0.6*TEMPMN
07751       IF (ISTAGE.LE.2.OR.ISTAGE.GT.6) GO TO 19
07760       DTT=TEMPM-TBASE
07770       IF(TEMPMX.GT.TBASE) GO TO 31
07780       DTT=0.
07790       GO TO 20
07800    31 IF(TEMPMN.GE.TBASE) GO TO 20
07810       TCOR=(TEMPMX-TBASE)/(TEMPMX-TEMPMN)
07820       DTT=(TEMPMX-TBASE)/2.*TCOR
07861       GO TO 20
07862 C     **ST IS SOIL TEMPERATURE AND TBASE IS BASE TEMPERATURE**
07871    19 DTT=ST(1)-TBASE
07872       IF (ST(1).LT.TBASE) DTT=0.0
07878 20    IF(SOLRAD.LT.300.) DTT=DTT*SOLRAD/300.
07880         SUMDTT=SUMDTT+DTT
07890       CUMDTT=CUMDTT+DTT
07900       GO TO (1,2,3,4,5,6,7,8,9), ISTAGE
07910 C     **********************DETERMINE SOWING DATE************************
07920     7 CALL CALDAT
07930       WRITE (6,300)
07940       WRITE (6,290) MO,ND,IYR,JDATE,CUMDTT
07950       WRITE (6,210)
07960       NDAS=0.
07970       CALL PHASEI
07980       IF (ISWSWB.EQ.0) RETURN
07990       CUMDEP=0.
08000       DO 30 L=1,NLAYR
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
08010           CUMDEP=CUMDEP+DLAYR(L)
08020           IF (SDEPTH.LT.CUMDEP) GO TO 40
08030     30 CONTINUE
08040     40  LO=L
08050         RETURN
08060 C        **************DETERMINE GERMINATION DATE**********************
08070      8 IF (ISWSWB.EQ.0) GO TO 50
08080         IF (SW(LO).GT.LL(LO)) GO TO 50
08090         SWSD=(SW(LO)-LL(LO))*0.65+(SW(LO+1)-LL(LO+1))*0.35
08100         NDAS=NDAS+1
08110         IF(NDAS.LT.40) GO TO 45
08120         ISTAGE=5
08130         PLANTS=0.01
08140         GPP=1.
08150         GRNWT=0.
08160         WRITE(6,340)
08170         RETURN
08180     45 IF(SWSD.LT.0.02) RETURN
08190     50 CALL CALDAT
08200         WRITE (6,290) MO,ND,IYR,JDATE,CUMDTT
08210         WRITE (6,220)
08220         IF(ISWSWB.NE.0)WRITE(6,330) NFAC,CES,CEP,CRAIN,PESW
08230         CALL PHASEI
08240         RETURN
08250 C        *****************DETERMINE SEEDLING EMERGENCE DATE**************
08260      9 RTDEP=RTDEP+0.15*DTT
08270         IF (SUMDTT.LT.P9) RETURN
08320         CALL CALDAT
08330         WRITE (6,290) MO,ND,IYR,JDATE,CUMDTT
08340         WRITE (6,230)
08350         IF (ISWSWB.NE.0.) WRITE (6,330) NFAC,CES,CEP,CRAIN,PESW
08360         CALL PHASEI
08370         RETURN
08380 C        ********************DETERMINE END OF JUVENILE STAGE *************
08390     1   XSTAGE=SUMDTT/P1
08400         IF (SUMDTT.LT.P1) RETURN
08410         CALL CALDAT
08420         WRITE (6,290) MO,ND,IYR,JDATE,CUMDTT
08430         WRITE (6,240)
08440          GO TO 150
08450 C        ******************DETERMINE DATE OF TASSEL INITIATION *********
08460     2   XSTAGE=1.0+0.5*SIND
08470         DEC=0.4093*SIN(0.0172*(JDATE-82.2))
08480         DLV=(-S1*SIN(DEC)-0.1047)/(C1*COS(DEC))
08490         IF(DLV.LT.-.87) DLV=-.87
08500         HRLT=7.639*ARCOS(DLV)
08510 C        IF(HRLT.LT.12.5)FACLI=1.0-(12.5-HRLT)*0.05
08511         IF (HRLT.LT.12.5) HRLT=12.5
08520         RATEIN=1./(4.+P2*(HRLT-12.5))
08540         SIND=SIND+RATEIN
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
08550       IF (SIND.LT.1.0) RETURN
08560       CALL CALDAT
08570       WRITE (6,290) MO,ND,IYR,JDATE,CUMDTT
08580       WRITE (6,250)
08590       GO TO 150
08600 C     **************DETERMINE END OF LEAF GROWTH AND SILKING **********
08610     3 XSTAGE=1.5+3.0*SUMDTT/P3
08691       IF (SUMDTT.LT.P3) RETURN
08692       CALL CALDAT
08693       ISDATE=JDATE
08694       MAXLAI=LAI
08695       WRITE (6,290) MO,ND,IYR,JDATE,CUMDTT
08696       WRITE (6,260) TLNO
08697       GO TO 150
08698 C     *****DETERMINE BEGINNING OF EFFECTIVE GRAIN FILLING PERIOD ******
08700     4 XSTAGE=4.5+1.5*SUMDTT/(P5*.95)
08710       IF (SUMDTT.LT.P5*0.25) RETURN
08720       CALL CALDAT
08730       PSKER=SUMP*1000/IDURP
08731       GPP=G2*PSKER/7500.+50.
08732       IF (GPP.GT.G2) GPP=G2
08740       GPP=GPP*AMIN1(NDEF3,SWDF1)
08750       IF(GPP.LE.50.0) GPP=50.0
08760       EARS=PLANTS
08770 C     ******************* DETERMINE BARRENNESS *********************
08780       IF(GPP.LT.G2*0.25) EARS=PLANTS*((GPP-50.)/(G2-50.))**0.33
08790       IF(EARS.LT.0.0) EARS=0.0
08800       GPSM=GPP*EARS
08810       WRITE (6,290) MO,ND,IYR,JDATE,CUMDTT
08820       WRITE (6,270) GPSM
08830       GO TO 150
08840 C     ***********DETERMINE END OF EFFECTIVE FILLING PERIOD ************
08850     5 XSTAGE=6.0+4.0*SUMDTT/P5
08860       IF (SUMDTT.LT.P5*0.95) RETURN
08870       CALL CALDAT
08880       WRITE (6,290) MO,ND,IYR,JDATE,CUMDTT
08890       WRITE (6,275)
08900       GO TO 150
08910 C     ***************** DETERMINE PHYSIOLOGICAL MATURITY ***************
08920     6 IF (DTT.LT.2.0)SUMDTT=P5
08930       IF(SUMDTT.LT.P5) RETURN
08940       CALL CALDAT
08950       MDATE=JDATE
08960       WRITE (6,290) MO,ND,IYR,JDATE,CUMDTT
08970       WRITE(6,280)
08980       YIELD=GRNWT*10.*EARS
08990       SKERWT=GRNWT/GPP
09000       GPSM=GPP*EARS
09010       STOVER=BIOMAS*10.-YIELD
09020       YIELD=YIELD/0.845
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
09030        YIELDB=YIELD/62.8
09040        XGNP=(GRAINN/GRNWT)*100.0
09050        XPTN=XGNP*5.80
09060        GNUP=GRAINN*EARS*10.
09070        TOTNUP=GNUP+APTNUP
09080        IF(ISLKJD.EQ.0) PLSEMS=0.0
09090        IF(ISLKJD.NE.0) PLSEMS=ISLKJD-ISOW
09100        IF(PLSEMS.LT.0) PLSEMS=365.-ISOW+ISDATE
09110        PLSEPR=ISDATE-ISOW
09120        IF(PLSEPR.LT.0)PLSEPR=365.-ISOW+ISLKJD
09130        IF(MATJD.EQ.0.OR.ISLKJD.EQ.0) SEMSMS=0.0
09140        IF(MATJD.NE.0.AND.ISLKJD.NE.0) SEMTMS=MATJD-ISLKJD
09150        IF(SEMTMS.LT.0) SEMTMS=365.-ISDATE+MDATE
09160        SEMTPR=MDATE-ISDATE
09170        IF(SEMTPR.LT.0) SEMTPR=365.-ISLKJD+MATJD
09180 150    SI1(ISTAGE)=CSD1/ICSDUR
09190        SI2(ISTAGE)=CSD2/ICSDUR
09200        SI3(ISTAGE)=CNSD1/ICSDUR
09210        SI4(ISTAGE)=CNSD2/ICSDUR
09220        XANC=(STOVN+GRAINN)/(STOVWT+GRNWT)*100.
09230        IF (ISWSWB.NE.0) WRITE (6,320) BIOMAS,LAI,APTNUP,XANC,
09240       1  NFAC,CES,CEP,CRAIN,PESW
09250          PLANTS=XPLANT
09260        IF(ISTAGE.EQ.6) GO TO 160
09270        IF(JDATE.NE.IODATE) GO TO 159
09280         XDM=BIOMAS
09290         XXLAI=LAI
09300         XTANC=TAND*100.
09310   159  CONTINUE
09320        CALL PHASEI
09330        RETURN
09340   160  WRITE (6,305)
09350        WRITE(6,310) ISDATE,ISLKJD,MDATE,MATJD,YIELD,XYIELD,SKERWT,XGRWT,
09360       1GPSM,XGPSM,GPP,XGPE,MAXLAI,
09370       2XLAI,DM,XBIOM,STOVER,XSTRAW,XGNP,GRPCTN,XPTN,GRPTN,TOTNUP,
09380       3XTOTNP,APTNUP,XAPTNP,GNUP,XGNUP
09390        WRITE (6,190)
09400 C       WRITE(17,311) KVARTY,YIELD,XYIELD,GPP,XGPE,PLSEPR,PLSEMS,SEMTPR,
09410 C      1SEMTMS
09420        DO 170 I=1,5
09430           WRITE (6,200) I,SI1(I),SI2(I),SI3(I),SI4(I)
09440 170    CONTINUE
09450        IF (IYR.EQ.NYRS) RETURN 1
09460         CALL PHASEI
09470        RETURN
09480 190    FORMAT (/,1X,'GROWTH STAGE',6X,'CSD1',6X,'CSD2',5X,'CNSD1',5X,
09490       1  'CNSD2')
09500 200    FORMAT (1X,I12,4F10.2)
09510 210    FORMAT (1H+,21X,'SOWING',20X,'BIOMASS',5X,'LAI',6X,'NUPTK',4X,
09520       1  'XANC',5X,'NFAC',6X,'ES',7X,'EP',6X,'PREC',5X,'PESW'/)
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
09530 220   FORMAT (1H+,21X,'GERMINATION')
09540 230   FORMAT (1H+,21X,'EMERGENCE')
09550 240   FORMAT (1H+,21X,'END JUVENILE STAGE')
09560 250   FORMAT (1H+,21X,'TASSEL INITIATION')
09570 260   FORMAT (1H+,21X,'SILKING       LEAF NO =  ',F4.1)
09580 270   FORMAT (1H+,21X,'BEGIN GRAIN FILL---GPSM=',F6.0)
09590 275   FORMAT (1H+,21X,'END GRAIN FILL')
09600 280   FORMAT (1H+,21X,'PHYSIOLOG. MAT.')
09610 290   FORMAT (1X,I2,'/',I2,'/',I2,1X,I3,2X,F5.0)
09620 300   FORMAT (1H ,10X,'JUL',4X,'CUM',81X,'WATER BALANCE COMPONENTS',/,
09630      1  4X,'DAY',4X,'DAY',4X,'DTT',10X,'PHENOLOGICAL STAGE',51X,
09640      2  'CUMULATIVE',' AFTER GERMINATION',/)
09650 305   FORMAT (1X,/,26X,'PREDICTED VALUES',5X,'MEASURED VALUES',/)
09660 310   FORMAT (1X,'SILKING DATE',21X,I3,15X,I3,/,1X,'MATURITY DATE',
09670      *20X,I3,15X,I3,/,1X,'GRAIN YIELD  KG/HA (15.5%)',3X,F7.0,11X,F7.0,
09680      */,1X,'KERNAL WEIGHT  (G)',2(11X,F7.4),/,1X,'FINAL GPSM',19X,F7.0,
09690      *11X,F7.0,/,1X,'GRAINS/EAR',20X,F6.0,12X;F6.0,/,1X,'MAX. LAI',24X,
09700      *F6.2,12X,F6.2,/,1X,'BIOMASS KG/HA',17X,F7.1,10X,F7.0,/,1X,'STOVER
09710      *KG/HA',17X,
09720      *F8.1,10X,F8.1,/,1X,'GRAIN N%',25X,F5.2,13X,F5.2,/,1X,'GRAIN PTN%',
09730      *22X,F5.1,13X,F5.1,/,1X,'TOTAL N UPTAKE KG/HA',9X,F8.1,10X,F8.1,/,
09740      *1X,'STOVER N UPTK. KG/HA',9X,F8.1,10X,F8.1,/,1X,'GRAIN N UPTAKE KG
09750      */HA',9X,F8.1,10X,F8.1,/)
09760 320   FORMAT (1H+,51X,F5.0,3X,F5.2,3X,F5.1,3X,F5.2,3X,F6.1,3X,F6.1,3X,
09770      1  F6.1,3X,F6.1,3X,F6.1)
09790 330   FORMAT (1H+,83X,F6.1,3X,F6.1,3X,F6.1,3X,F6.1,3X,F6.1)
09800  340  FORMAT(1X,'CROP FAILURE BECAUSE OF LACK OF GERMINATION',
09810      1' WITHIN 40 DAYS OF SOWING')
09820       END
09830 C
09840 C     ***JULY 13 1984*************** GROWTH SUBROUTINE *****************
09850 C
09860       SUBROUTINE GROSUB
09870       REAL LAT,LL,LAI,LFWT,NDEF1,NDEF2,NDEF3,NDEF4,NDEM,NSINK,NPOOL1,
09880      1  NPOOL2,NPOOL,NSDR,NFAC,INSOIL
09890       COMMON /NNN/ NFAC,DSTOVN
09900       COMMON /CLIMT/ TEMPMN,TEMPMX,RAIN,SOLRAD,TMFAC(8)
09910       COMMON /PARAM/ ISOIL,IIRR,IWETH,ISOW,PLANTS,KOUTGR,KOUTWA,SDEPTH,
09920      1  LAT,KVARTY,KIRR,KSOIL,IQUIT,NEWSOL,NEWWET,MULTYR,ISWSWB
09930      2 ,PHINT,KNIT,IODATE,XYIELD,XGRWT,XGPSM,XGPE,XLAI,XBIOM,ISLKJD,
09940      3 MATJD,INSOIL
09950       COMMON /GENET/ P1,P2,P3,P5,G2,G3
09960       COMMON /PHENL/ P9,CUMDTT,TBASE,SUMDTT,S1,C1,ISTAGE,
09970      1  DTT,IDUR,SIND,TEMPM
09980       COMMON /GROTH/ GPSM,GPP,GRORT,PTF,LAI,DM,BIOMAS,PLA,SENLA,
09990      1  LFWT,SEEDRV,REGM,XPLANT,WIDTL,EMAT,SLW,PLAY,PLAMX,
10000      1  RTWT,STMWT,GRNWT,SWMIN,LN,EARWT,TLNO,SWMAX,FACLI,
10010      1RWID,SUMP,IDURP,PLAG,EGFT,GROSTM,CARBO,BLAMX(35),GBLA(35),
10020      1 SLA(35),NL1,NLMAX,EARS
10030       COMMON /WATER/ SUMES1,SUMES2,T,TLL,PESW,TSW,CUMDEP,ESW(10),
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
10040      1    CSD1,CSD2,SI1(6),SI2(6),ICSDUR,ES,EP,ET,EO,CES,CEP,CET,
10050      1    RLV(10),PRECIP,CRAIN,DRAIN,IDRSW,RTDEP,SWDF1,SWDF2,
10060      1    SWDF3,TRWU,RWUMX
10070       COMMON /NCTRL/ KOUTMN,IOUTMN,KOUTNU,IOUTNU,MINCK,NHDMN,NHDUP,
10080      1  IFERT,KFERT,ISWNIT,DMOD,XSTRAW,GRPCTN,GRPTN,XTOTNP,XAPTNP
10090      2,XGNUP
10100       COMMON /NDFPG/ NDEF1,NDEF2,NDEF3,NDEF4,GNP,CNSD1,CNSD2
10110       COMMON /NCONC/ TANC,TCNP,RCNP,RANC,TMNC,VANC,VMNC,XSTAGE
10120       COMMON /NPLANT/ GRAINN,ROOTN,STOVN,PDWI,STOVWT,PGRORT,NDEM
10130       COMMON /DATEC/ MO,ND,IYR,JDATE,JDATEX,IDIM(12),NYRS
10140       COMMON /NROOT/ RNFAC(10),RNLOSS(10),JJ
10150       IF(ISWNIT.NE.0) CALL NFACTO
10160       CLG=3.2
10170       PAR=0.02*SOLRAD
10180       F=1.0
10190       IF(ISTAGE.GT.4) F=(SUMDTT-0.25*P5)/(0.7*P5)
10200       IF(ISTAGE.GT.4) F=1.0-0.41*F
10220       IF(F.LT.0.) F=0.0
10230       PCARB=3.4*F*PAR/PLANTS*(1.-EXP(-0.65*LAI))
10240       PRFT=1.-0.0025*((0.25*TEMPMN+0.75*TEMPMX)-30.)**2
10250       IF (PRFT.LT.0.) PRFT=0.
10260       CARBO=PCARB*AMIN1(PRFT,SWDF1*NDEF1*1.2,SWDF1,NDEF1)
10270       TEMPM=(TEMPMN+TEMPMX)/2
10280       IF(ISTAGE.GT.3) GO TO 12
10290       EGFT=0.
10300       SLFT=1.0
10310 C     *******DRY MATTER PARTIONING BETWEEN SHOOTS AND ROOTS********
10320       IF (ISTAGE.LE.2)PCTSK=CUMDTT/900.
10330       IF (ISTAGE.GE.3)PCTSK=CUMDTT/(((TLNO-2.)*42.9)+96.)
10340       PTF = 1.100*PCTSK/(0.259 + PCTSK)
10350       IF (PCTSK.GE.1.0)PTF=1.0
10360     12 GO TO (1,2,3,4,5),ISTAGE
10370      1 IF(SEEDRV.GT.0)CARBO=CARBO+0.04
10380        SEEDRV=SEEDRV-0.04
10390        GRORT=CARBO*(1.- PTF)
10400        CARBO=CARBO-GRORT
10410        CALL LEAF
10420        RTWT=RTWT + GRORT
10430        GO TO 40
10460      2 GRORT=CARBO*(1.- PTF)
10470        CARBO=CARBO-GRORT
10480        CALL LEAF
10490        RTWT=RTWT + GRORT
10500        GO TO 40
10501      3 GRORT=(1.- PTF)*CARBO
10502        CARBO=CARBO-GRORT
10503        IF (SUMDTT.LT.0.33)GO TO 25
10504        IF (STMWT.EQ.0.0)STMWT=0.40
10505        GROSTM=CARBO
10506        GROSTM = ((SUMDTT/P3)*0.921 - 0.0668)*PTF*CARBO
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
10507       IF (GROSTM.LT.0.0)GROSTM=0.0
10510       CARBO=CARBO-GROSTM
10520       IF(CARBO.GE.0.0)GO TO 30
10530       GROSTM=GROSTM+CARBO
10540       CARBO=0.0
10550    30 CONTINUE
10560    25 CALL LEAF
10570       RTWT=RTWT+GRORT
10580       STMWT=STMWT+GROSTM
10590       GO TO 40
10600     4  GROSTM=CARBO
10610       SUMP=SUMP+CARBO
10620       IDURP=IDURP+1
10630       STMWT=STMWT+GROSTM
10640        IF (STMWT.GT.SWMAX) STMWT=SWMAX
10650       GO TO 40
10660     5 IF (PLANTS.EQ.0.01) RETURN
10670        GROSTM=CARBO
10691       RGFILL=0.052*TEMPMN-0.09
10700       IF (TEMPMN.LE.24.0.AND.SOLRAD.GT.300.) GO TO 241
10710       RGFILL=0.050*TEMPMN-0.09
10730 241        IF (RGFILL.LT.0.) RGFILL=0.
10740       IF (RGFILL.GT.1.10) RGFILL=1.10
10750       GROGRN=RGFILL*GPP*G3*0.001
10760       STMWT=STMWT + GROSTM - GROGRN
10770       IF (STMWT.GT.SWMAX) STMWT=SWMAX
10780       IF (STMWT.GE.SWMIN)GO TO 240
10790       GROGRN = GROGRN + STMWT - SWMIN
10800       STMWT=SWMIN
10810  240  GRNWT=GRNWT+GROGRN
10820       IF(GROGRN/GPP.GT.0.0010)GO TO 300
10830       EMAT=EMAT+1
10840       IF(EMAT.EQ.1)GO TO 301
10850       SUMDTT=P5
10860       WRITE(6,605)JDATE
10870  605  FORMAT(2X,'CROP MATURE ON JD',I4,' BECAUSE OF SLOWED GRAIN
10880      1FILLING')
10890  300  EMAT=0
10900  301  CONTINUE
10910       IF (ISWNIT.EQ.0) GO TO 41
10920 C*****GRAIN N ALLOWED TO VARY BETWEEN .01 AND .018.
10930 C*****HIGH TEMP., LOW SOIL WATER, AND HIGH N INCREASE GRAIN N
10940       TFAC=0.69+.0125*TEMPM
10950       SFAC=1.125-.125*SWDF2
10960       GNP=(.008+.010*NDEF4)*AMAX1(TFAC,SFAC)
10970       NSINK=GROGRN*GNP
10980       IF (NSINK.EQ.0.0) GO TO 100
10990       RMNC=0.75*RCNP
11000       VANC=STOVN/STOVWT
11010       NPOOL1=STOVWT*(VANC-VMNC)
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
11011        IF (RANC.LT.RMNC) RANC=RMNC
11020        NPOOL2=RTWT*(RANC-RMNC)
11030        NPOOL=NPOOL1+NPOOL2
11040        NSDR=NPOOL/NSINK
11050        IF (NSDR.LT.1.0) GROGRN=GROGRN*NSDR
11051 C      IF (NSDR.LT.2.0.AND.NSDR.GE.1.0) GROGRN=GROGRN*0.5*NSDR
11060 C      NSINK=GROGRN*GNP
11070        IF (NSINK.LE.NPOOL1) GO TO 90
11080        VANC=VMNC
11090        STOVN=STOVWT*VANC
11100        NPOOL2=NPOOL2-(NSINK-NPOOL1)
11110        IF (NPOOL2.LT.0.) NPOOL2=0.
11113        NPOOL1=0.0
11120        ROOTN=RTWT*RMNC+NPOOL2
11130        RANC=ROOTN/RTWT
11140        GO TO 100
11150 90     NPOOL1=NPOOL1-NSINK
11160        STOVN=NPOOL1+VMNC*STOVWT
11170        VANC=STOVN/STOVWT
11180 100    GRAINN=GRAINN+NSINK
11190  40    PDWI=PCARB*PTF
11200        PGRORT=PCARB*(1.0-PTF)
11210        CALL NUPTAK
11220         GO TO 42
11230  41     NFAC=1.
11240    42 SLFW=0.95+0.05*SWDF1
11250        SLFN=0.95+0.05*NDEF4
11260        SLFC=1.0
11270        IF(LAI.GT.4.)SLFC=1.-0.025*(LAI-4.)
11280        IF(SLFC.LT.0.)SLFC=0.
11290        SLFT=1.
11300        IF(TEMPMN.GT.0.)GO TO 50
11310        SLFT=1.-0.0015*(TEMPMN+TEMPM+20.)**2
11320        IF(SLFT.LT.0.)SLFT=0.
11330    50  IF (ISTAGE.GE.4.AND.SUMDTT.LT.0.95*P5)PLA=PLAMX*(1.-
11340       1SUMDTT/(0.95*P5))**0.21*(AMIN1(SLFC,SLFT))**0.10
11350        IF (PLA.GT.PLAY.AND.ISTAGE.GE.4)PLA=PLAY
11360        IF(ISTAGE.GT.4) LFWT=LFWT-(PLAY-PLA)/600.
11370        PLAY=PLA
11380        LAI=PLA*PLANTS*0.0001
11390        BIOMAS=(LFWT+STMWT+GRNWT)*PLANTS
11400        DM=BIOMAS*10.
11410        STOVWT=LFWT+STMWT
11420      6 RETURN
11430        END
11440 C
11450 C      ******************************** WRITE SUBROUTINE ******************
11460 C
11470        SUBROUTINE WRITE
11480        COMMON /PHENL/ P9,CUMDTT,TBASE,SUMDTT,S1,C1,ISTAGE,
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
11490      1  DTT,IDUR,SIND,TEMPM
11500       COMMON /GROTH/ GPSM,GPP,GRORT,PTF,LAI,DM,BIOMAS,PLA,SENLA,
11510      1  LFWT,SEEDRV,REGM,XPLANT,WIDTL,EMAT,SLW,PLAY,PLAMX,
11520      1  RTWT,STMWT,GRNWT,SWMIN,LN,EARWT,TLNO,SWMAX,FACLI,
11530      1RWID,SUMP,IDURP,PLAG,EGFT,GROSTM,CARBO,BLAMX(35),GBLA(35),
11540      1 SLA(35),NL1,NLMAX,EARS
11550       COMMON /WATER/ SUMES1,SUMES2,T,TLL,PESW,TSW,CUMDEP,ESW(10),
11560      1    CSD1,CSD2,SI1(6),SI2(6),ICSDUR,ES,EP,ET,EO,CES,CEP,CET,
11570      1    RLV(10),PRECIP,CRAIN,DRAIN,IDRSW,RTDEP,SWDF1,SWDF2,
11580      1    SWDF3,TRWU,RWUMX
11590       COMMON /PARAM/ ISOIL,IIRR,IWETH,ISOW,PLANTS,KOUTGR,KOUTWA,SDEPTH,
11600      1  LAT,KVARTY,KIRR,KSOIL,IQUIT,NEWSOL,NEWWET,MULTYR,ISWSWB
11610      2 ,PHINT,KNIT,IODATE,XYIELD,XGRWT,XGPSM,XGPE,XLAI,XBIOM,ISLKJD,
11620      3 MATJD,INSOIL
11630       COMMON /WRITS/ AES,AEP,AET,AEO,ASOLR,ATEMX,ATEMN,ARUNOF,
11640      1  ADRAIN,APRECP,ASWDF1,ASWDF2,IOUTGR,IOUTWA,JHEAD,KHEAD,
11650      2  TPRECP,RUNOFF
11660       COMMON /CLIMT/ TEMPMN,TEMPMX,RAIN,SOLRAD,TMFAC(8)
11670       CRAIN=CRAIN+PRECIP
11680       IF (KOUTWA.EQ.0) GO TO 10
11690       IOUTWA=IOUTWA+1
11700       AES=AES+ES
11710       AEP=AEP+EP
11720       AET=AET+ET
11730       AEO=AEO+EO
11740       ASOLR=ASOLR+SOLRAD
11750       ATEMX=ATEMX+TEMPMX
11760       ATEMN=ATEMN+TEMPMN
11770       ARUNOF=ARUNOF+RUNOFF
11780       ADRAIN=ADRAIN+DRAIN
11790       APRECP=APRECP+TPRECP
11800       IF (IOUTWA.EQ.KOUTWA) CALL OUTWA
11810 10    IF (KOUTGR.EQ.0) RETURN
11820       IF (ISTAGE.GT.6) RETURN
11830       IOUTGR=IOUTGR+1
11840       ASWDF1=ASWDF1+SWDF1
11850       ASWDF2=ASWDF2+SWDF2
11860       IF (IOUTGR.EQ.KOUTGR) CALL OUTGR
11870       RETURN
11880       END
11890 C
11900 C     ********************* LEAF SUBROUTINE ************************
11910 C
11920       SUBROUTINE LEAF
11930       REAL LAT,LL,LAI,LFWT,MAXLAI,LAWR
11940       REAL NDEM,NDEF1,NDEF2,NDEF3,NDEF4,INSOIL,SWMAX,FACLI
11950       COMMON /CLIMT/ TEMPMN,TEMPMX,RAIN,SOLRAD,TMFAC(8)
11960       COMMON /DATEC/ MO,ND,IYR,JDATE,JDATEX,IDIM(12),NYRS
11970       COMMON /PARAM/ ISOIL,IIRR,IWETH,ISOW,PLANTS,KOUTGR,KOUTWA,SDEPTH,
11980      1  LAT,KVARTY,KIRR,KSOIL,IQUIT,NEWSOL,NEWWET,MULTYR,ISWSWB
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
11990       2  ,PHINT,KNIT,IODATE,XYIELD,XGRWT,XGPSM,XGPE,XLAI,XBIOM,ISLKJD,
12000       3 MATJD,INSOIL
12010        COMMON /GENET/ P1,P2,P3,P5,G2,G3
12020        COMMON /PHENL/ P9,CUMDTT,TBASE,SUMDTT,S1,C1,ISTAGE,
12030       1  DTT,IDUR,SIND,TEMPM
12040        COMMON /GROTH/ GPSM,GPP,GRORT,PTF,LAI,DM,BIOMAS,PLA,SENLA,
12050       1  LFWT,SEEDRV,REGM,XPLANT,WIDTL,EMAT,SLW,PLAY,PLAMX,
12060       1  RTWT,STMWT,GRNWT,SWMIN,LN,EARWT,TLNO,SWMAX,FACLI,
12070       1RWID,SUMP,IDURP,PLAG,EGFT,GROSTM,CARBO,BLAMX(35),GBLA(35),
12080       1 SLA(35),NL1,NLMAX,EARS
12090        COMMON /WATER/ SUMES1,SUMES2,T,TLL,PESW,TSW,CUMDEP,ESW(10),
12100       1    CSD1,CSD2,SI1(6),SI2(6),ICSDUR,ES,EP,ET,EO,CES,CEP,CET,
12110       1    RLV(10),PRECIP,CRAIN,DRAIN,IDRSW,RTDEP,SWDF1,SWDF2,
12120       1    SWDF3,TRWU,RWUMX
12130        COMMON /NDFPG/ NDEF1,NDEF2,NDEF3,NDEF4,GNP,CNSD1,CNSD2
12140        SLAWR=1.0
12150        LAWR=PLA/LFWT
12157        IF(LAWR.GT.130..AND.LAI.GT.1.0) SLAWR=(170.-LAWR)/20.
12168        IF (NDEF4.GT.0.40) GO TO 11
12170        IF(LAWR.GT.130..AND.LAI.GT.1.0) SLAWR=(190.-LAWR)/20.
12171  11       IF(SLAWR.LT.0)SLAWR=0.0
12172          IF (SLAWR.GT.1.0) SLAWR=1.0
12180        M1=NL1
12190        EXTRA=0.0
12200        M2=M1+2
12210        TGROLF=0.
12220        DO 501 L = M1,M2
12230        IF (L.GT.TLNO) GO TO 501
12240        LN=L
12250        LN1=LN + 1
12260        LN2=LN + 2
12270        LN3=LN + 3
12280        IF(CARBO.EQ.0.)GO TO 30
12290        PHINT=96.
12300        IF(LN.GT.1)PHINT=114.
12320        TTAP=(LN-2)*38.+20.
12350        IF(TTAP.LT.0.) TTAP=0.
12360        IF(CUMDTT.LT.TTAP)GO TO 51
12370        TTCOL=96.+(LN-1)*38.
12380        SUMTTY=CUMDTT-DTT
12390        IF(CUMDTT.LT.TTCOL.OR.LN.NE.M1)GO TO 21
12400 C**********ONLY FOR FIRST LEAF AND WHEN IT COLLARS********
12410        NL1=NL1+1
12420        EXTRA=CUMDTT-TTCOL
12430        IF(LN3.GT.NLMAX) GO TO 661
12440        IF(GBLA(LN2).LT.4.)GBLA(LN2)=4.
12450        FRAC=(SUMTTY-TTAP-76.)/114.
12460        BLAMX(LN3)=((GBLA(LN2)+(1.-FRAC)*BLAMX(LN2))**0.75)*
12470       1  6.127-16.7
12480        GO TO 662
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
12490 661   CONTINUE
12500       BLX=0.0
12510       FRAC=(SUMTTY-TTAP-76.)/114.
12520       IF(LN.GE.NLMAX)FRAC=1.0
12530       IF(LN1.EQ.NLMAX)FRAC=(SUMTTY-TTAP-38.)/114.
12540       IF(LN2.GE.NLMAX)BLX=GBLA(NLMAX)+(1-FRAC)*BLAMX(NLMAX)
12550       IF(LN.GE.NLMAX.AND.BLX.LT.4.)BLX=4.0
12560       IF (LN3.GT.NLMAX) BLAMX(LN3)=BLX*(1.0148-0.06048*(LN3-NLMAX)
12570      2 -0.0020122*(LN3-NLMAX)**2)
12580 662   GROLF=(DTT-EXTRA)/PHINT*BLAMX(LN)*AMIN1(SWDF2,SLAWR)
12590       GO TO 9
12600 21    IF(LN.GT.1)GO TO 22
12610 C**********ONLY FOR THE FIRST LEAF AND BEFORE IT COLLARS***
12620       IF(CUMDTT.GE.20.AND.SUMTTY.LT.20.)BLAMX(2)=
12630      1  (((96./SUMTTY)*GBLA(1))**0.75)*6.327-16.7
12640       IF(CUMDTT.GE.58..AND.SUMTTY.LT.58.)BLAMX(3)=((114./
12650      1  (SUMTTY-20.)*GBLA(2))**0.75)*5.927-16.7
12660 C=================================
12670 C     NOTE; GROLF SHOULD BE FIGURED WITH
12680 C           1. DTT-EXTRA FOR THE LOWEST LEAF ON THE DAY IT
12690 C              COLLARS
12700 C           2. DTT FOR THE FIRST LEAF ALL OTHER TIMES
12710 C              AND FOR THE SECOND AND THIRD LEAF WHEN THE THIRD
12720 C              LEAF COLLARS.
12730 22    IF(CARBO .EQ.0.)GO TO 30
12740       DTT2=DTT
12750 24    GROLF=DTT2/PHINT*BLAMX(LN)*AMIN1(SWDF2,SLAWR)
12762 9     GBLA(LN)=GBLA(LN)+GROLF
12770       SLA(LN)=SLA(LN)+GROLF
12780 30    SENLA=0.
12790       PHFRA=DTT/PHINT
12800       IF(LN.NE.5) GO TO 31
12810       SENLA=PHFRA*GBLA(1)
12820       LNS=1
12830 31    IF(LN.NE.7)GO TO 32
12840       SENLA=PHFRA*GBLA(2)
12850       LNS=2
12860 32    IF(LN.LT.15)GO TO 33
12870       SENLA=PHFRA*GBLA(LN-12)
12880       LNS=LN-12
12890 33    IF(SENLA.LE.0)GO TO 41
12900       SLA(LNS)=SLA(LNS)-SENLA
12910       IF(SLA(LNS).GE.0.)GO TO 41
12920       SENLA=SLA(LNS)+SENLA
12930       SLA(LNS)=0.
12940 41    PLA=PLA+GROLF-SENLA
12950       LFWT=LFWT-SENLA/200.
12960       IF(CARBO.EQ.0.0)GO TO 51
12970       IF(LN.NE.M2.OR.EXTRA.LE.0.)GO TO 50
12980       LN=LN+1
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
12990       DTT2=EXTRA
13000       GO TO 24
13010 50    CONTINUE
13020       TGROLF=TGROLF+GROLF
13030 501   CONTINUE
13040       LFWT=LFWT+CARBO
13050       CARBO=0.0
13060 51    CONTINUE
13070       RETURN
13080       END
13090 C
13100 C     ********** PHASE INITIALIZATION SUBROUTINE **********************
13110 C
13120       SUBROUTINE PHASEI
13130       REAL LAT,LAI,LL,LFWT,NDEM,NDEF1,NDEF2,NDEF3,NDEF4,SWMAX,
13140      1   FACLI
13150       COMMON /PARAM/ ISOIL,IIRR,IWETH,ISOW,PLANTS,KOUTGR,KOUTWA,SDEPTH,
13160      1  LAT,KVARTY,KIRR,KSOIL,IQUIT,NEWSOL,NEWWET,MULTYR,ISWSWB
13170      2  ,PHINT,KNIT,IODATE,XYIELD,XGRWT,XGPSM,XGPE,XLAI,XBIOM,ISLKJD,
13180      3 MATJD,INSOIL
13190       COMMON /SOILI/ SALB,U,SWCON,DLAYR(10),DUL(10),LL(10),SW(10),
13200      1 SAT(10),DEPMAX,TDUL,NLAYR,SMX,WF(10),WR(10),RWU(10),SWEF,CN2
13210       COMMON /WATER/ SUMES1,SUMES2,T,TLL,PESW,TSW,CUMDEP,ESW(10),
13220      1    CSD1,CSD2,SI1(6),SI2(6),ICSDUR,ES,EP,ET,EO,CES,CEP,CET,
13230      1    RLV(10),PRECIP,CRAIN,DRAIN,IDRSW,RTDEP,SWDF1,SWDF2,
13240      1    SWDF3,TRWU,RWUMX
13250       COMMON /PHENL/ P9,CUMDTT,TBASE,SUMDTT,S1,C1,ISTAGE,
13260      1  DTT,IDUR,SIND,TEMPM
13270       COMMON /GROTH/ GPSM,GPP,GRORT,PTF,LAI,DM,BIOMAS,PLA,SENLA,
13280      1  LFWT,SEEDRV,REGM,XPLANT,WIDTL,EMAT,SLW,PLAY,PLAMX,
13290      1  RTWT,STMWT,GRNWT,SWMIN,LN,EARWT,TLNO,SWMAX,FACLI,
13300      1RWID,SUMP,IDURP,PLAG,EGFT,GROSTM,CARBO,BLAMX(35),GBLA(35),
13310      1 SLA(35),NL1,NLMAX,EARS
13320       COMMON /GENET/ P1,P2,P3,P5,G2,G3
13330       COMMON /NCTRL/ KOUTMN,IOUTMN,KOUTNU,IOUTNU,MINCK,NHDMN,NHDUP,
13340      1  IFERT,KFERT,ISWNIT,DMOD,XSTRAW,GRPCTN,GRPTN,XTOTNP,XAPTNP
13350      2,XGNUP
13360       COMMON /NCONC/ TANC,TCNP,RCNP,RANC,TMNC,VANC,VMNC,XSTAGE
13370       COMMON /NPLANT/ GRAINN,ROOTN,STOVN,PDWI,STOVWT,PGRORT,NDEM
13380       COMMON /NDFPG/ NDEF1,NDEF2,NDEF3,NDEF4,GNP,CNSD1,CNSD2
13390       IF (ISTAGE.GT.5) GO TO 10
13400       SI1(ISTAGE)=CSD1
13410       SI2(ISTAGE)=CSD2
13420       CNSD1=0.0
13430       CNSD2=0.0
13440       CSD1=0.
13450       CSD2=0.
13460       ICSDUR=0
13470 10     GO TO(1,2,3,4,5,6,7,8,9),ISTAGE
13480 1     ISTAGE=2
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
13490       SIND=0.
13500       RETURN
13510 2     ISTAGE=3
13520       TLNO=IFIX(CUMDTT/21.+6.0)
13530       NLMAX=TLNO-6.
13540       P3=(TLNO - 2.)*38.9+96.-SUMDTT
13550       SUMDTT=0.
13560       RETURN
13570 3     ISTAGE=4
13580       PTF=1.0
13590        SWMAX = STMWT * 2.20
13610       SUMP=0.
13620       IDURP=0
13630       SUMDTT=SUMDTT-P3
13640       PLAMX=PLA
13650       RETURN
13660 4     ISTAGE=5
13680       SWMIN=0.85*SWMAX
13690       VANC=TANC
13700       VMNC=TMNC
13710       EMAT=0.0
13720       RETURN
13730 5     ISTAGE=6
13740       RETURN
13750 6     ISTAGE=7
13760       CUMDTT=0.
13770       CRAIN=0.
13780       CES=0.
13790       CEP=0.
13800       CET=0.
13810       DTT=0.
13820       RETURN
13830 7     ISTAGE=8
13840       RTDEP=SDEPTH
13850       SUMDTT = 0.
13860       RETURN
13870 8     ISTAGE=9
13880       CET=0.
13890       P9=15.+6.*SDEPTH
13900       CES=0.
13910       CEP=0.
13920       CUMDTT=0.
13930        NDEF1=1.0
13940        NDEF2=1.0
13950        NDEF3=1.0
13960        NDEF4=1.0
13970       CRAIN=0.
13980       SUMDTT=0.
13990       TBASE=10.
14000       RETURN
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
14010 9      ISTAGE=1
14020        P3=400.
14030        SUMDTT=SUMDTT-P9
14040        CUMDTT = CUMDTT-P9
14050        PLA = 1.0
14060        PLAY=1.0
14070        PLAG=0.0
14080         FACLI=1.0
14090        LAI=PLANTS*PLA*0.0001
14100        SEEDRV=0.20
14110        LFWT=0.20
14120        RTWT=0.20
14130        STMWT=0.20
14140        STOVWT=0.40
14150        BIOMAS=STOVWT
14160        NLMAX=18.
14170        NL1=1
14180        DO 90 I=1,35
14190        SLA(I)=0.0
14200        GBLA(I)=0.0
14210   90   CONTINUE
14220        BLAMX(1)=7.65
14230        WIDTL=3.0
14240        GROSTM=0.
14250        GRNWT=0.
14260        SENLA=0.
14270        GRORT=0.
14280        REGM=1.
14290        IDUR=0
14300        TLNO = 30.
14310        LN = 1
14320        CSD1=0.
14330        CSD2=0.
14340        CNSD1=0.0
14350        CNSD2=0.0
14360        TBASE=8.0
14370        CUMDEP=0.
14380        RWID=0.023
14390        IF(ISWSWB.EQ.0) RETURN
14400        DO 100 L=1,NLAYR
14410           CUMDEP=CUMDEP+DLAYR(L)
14420           RLV(L)=0.20*PLANTS/DLAYR(L)
14430           IF (CUMDEP.GT.RTDEP) GO TO 110
14440 100    CONTINUE
14450 110    RLV(L)=RLV(L)*(1.-(CUMDEP-RTDEP)/DLAYR(L))
14460        L1=L+1
14470        IF (L1.GE.NLAYR) GO TO 121
14480        DO 120 L=L1,NLAYR
14490           RLV(L)=0.
14500 120    CONTINUE
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
14510   121 DO 130 L=1,NLAYR
14520   130    RWU(L)=0.
14530 140   CONTINUE
14540       IF (ISWNIT.EQ.0) GO TO 150
14550       RANC=0.022
14560       TANC=0.044
14570       GRAINN=0.0
14580       ROOTN=RANC*RTWT
14590       STOVN=STOVWT*TANC
14600 150   RETURN
14610       END
14620 C
14630 C*****************SOIL NITROGEN INITIALIZATION SUBROUTINE***********
14640 C
14650       SUBROUTINE SOILNI
14660       REAL NH4,NO3,NHUM,IFOM,IFON,LL,NOUT,NUP,NNOM,MF
14670       DIMENSION  LOC(4),FTYPE(6,6)
14680       COMMON /SOILI/ SALB,U,SWCON,DLAYR(10),DUL(10),LL(10),SW(10),
14690      1 SAT(10),DEPMAX,TDUL,NLAYR,SMX,WF(10),WR(10),RWU(10),SWEF,CN2
14700       COMMON /NMINR/ RDLIGN,RDCELL,RDCARB,FOM(10),IFOM(10),FON(10),
14710      1  IFON(10),DMINR,NHUM(10),HUM(10),TIFOM,TIFON
14720       COMMON /NSPOOL/ SNH4(10),SNO3(10),NH4(10),NO3(10),FAC(10),
14730      1   BD(10),PH(10)
14740       COMMON /NCTRL/ KOUTMN,IOUTMN,KOUTNU,IOUTNU,MINCR,NHDMN,NHDUP,
14750      1  IFERT,KFERT,ISWNIT,DMOD,XSTRAW,GRPCTN,GRPTN,XTOTNP,XAPTNP
14760      2,XGNUP
14770       COMMON /NFERTB/ JFDAY(10),AFERT(10),DFERT(10),NFERT,IFTYPE(10)
14780       COMMON /NWRITP/ ATANC,ATCNP,ARANC,ARCNP,ANDEM2,ATNUP,ARTN,ASTOVN,
14790      1  AGRN,CTNUP,TNUP,APTNUP
14800       COMMON /NBALT/ PNUP(10),NNOM(10),DTNOX(10)
14810       COMMON /NMOVE/ FLUX(10),SWX(10),FLOW(10),MU,NOUT(10),NUP(10)
14820       COMMON /NSTEMP/ ST(10),ANG,TMN,AMP
14830       COMMON /NITRF/ CNI(10),WFY(10),TFY(10),RNTRF(10)
14840        COMMON /NTINIT/ TLCH(10),TUPFLX(10),TPNUP(10),TNOM(10),
14850      1 TTNOX(10),TST(10),TRNTRF(10)
14860       COMMON /NROOT/ RNFAC(10),RNLOSS(10),JJ
14870        COMMON /NGEN2/ STRAW,SDEP,SCN,ROOT,RCN,OC(10)
14880       COMMON /DATEC/ MO,ND,IYR,JDATE,JDATEX,IDIM(12),NYRS
14890       COMMON /PARAM/ ISOIL,IIRR,IWETH,ISOW,PLANTS,KOUTGR,KOUTWA,SDEPTH,
14900      1  LAT,KVARTY,KIRR,KSOIL,IQUIT,NEWSOL,NEWWET,MULTYR,ISWSWB
14910      2  ,PHINT,KNIT,IODATE,XYIELD,XGRWT,XGPSM,XGPE,XLAI,XBIOM,ISLKJD,
14920      3 MATJD,INSOIL
14930         DIMENSION WRN(10)
14940       CHARACTER  FTYPE*36
14950       DATA FTYPE/'UREA','    ','    ','    ','    ','    ',
14960      *           'AMMO','NIUM',' NIT','RATE','    ','    ',
14970      *           'ANHY','DROU','S AM','MONI','A   ','    ',
14980      *           'CALC','IUM ','AMMO','NIUM',' NIT','RATE',
14990      *           'M NI','TRAT','E   ','    ','    ','    ',
15000      *           '    ','    ','    ','    ','    ','    '/
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
15010 C*****SUBROUTINE INITIALIZES SOIL NITROGEN PARAMETERS
15020 C*****AND INPUTS RESIDUE PARAMETERS
15030         IF(DMOD.EQ.0.)DMOD=1.
15040        CTNUP=0.0
15050  9     READ (1,175,END=148) LNIT
15060        IF (LNIT.NE.KNIT) GO TO 9
15070        READ (1,190) LOC
15080        DO 10 I=1,NLAYR
15090           READ (1,200) NH4(I),NO3(I),BD(I),PH(I)
15100 10     CONTINUE
15110 C*****INPUT RESIDUE PARAMETERS
15120        READ (1,210) STRAW,SDEP,SCN
15130        READ (1,210) ROOT,RCN
15140        DO 11 I=1,NLAYR
15150           IF (BD(I).EQ.0.) BD(I)=1.2
15160           IF (PH(I).EQ.0.0) PH(I)=7.0
15170           RNLOSS(I)=0.0
15180 11     CONTINUE
15190 C************INPUT ORGANIC CARBON DATA
15200        DO 90 I=1,NLAYR
15210           READ (1,220) OC(I)
15220 90     CONTINUE
15230        READ (1,180) TAV,AMP,JDATE
15240 C************INPUT FERTILIZER DATA
15250 148    REWIND 1
15260        WRITE (6,290)
15270 149    READ(IFERT,175,END=160) LFERT
15280        IF (LFERT.NE.KFERT) GO TO 149
15290        J=1
15300        NFERT=0
15310 150    READ (IFERT,300) JFDAY(J),AFERT(J),DFERT(J),IFTYPE(J)
15320        IF (JFDAY(J).EQ.0.OR.JFDAY(J).EQ.99) GO TO 160
15330        M=IFTYPE(J)
15340        IF (M.EQ.0) M=1
15350        IF (AFERT(J).EQ.0.) M=6
15360        WRITE (6,310) JFDAY(J),AFERT(J),DFERT(J),(FTYPE(JZ,M),JZ=1,6)
15370        J=J+1
15380        NFERT=NFERT+1
15390        GO TO 150
15400  160   REWIND IFERT
15410           JDATE=JJ
15420 C*****CALCULATE N CONTRIBUTIONS
15430        SNKG=STRAW*0.40/SCN
15440        RNKG=ROOT*0.40/RCN
15450 C******DISTRIBUTE ROOT MASS
15460        WSUM=0.0
15470        DEPTH=0.0
15480        DO 20 I=1,NLAYR
15490           DEPTH=DEPTH+DLAYR(I)
15500           WRN(I)=EXP(-3.0*DEPTH/DEPMAX)
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
15510           WSUM=WSUM+WRN(I)
15520           NOUT(I)=0.0
15530           NUP(I)=0.0
15540           PNUP(I)=0.0
15550           NNOM(I)=0.0
15560 20     CONTINUE
15570        DO 30 I=1,NLAYR
15580           FACTOR=WRN(I)/WSUM
15590           FOM(I)=ROOT*FACTOR
15600           FON(I)=RNKG*FACTOR
15610 30     CONTINUE
15620        DEPTH=0.0
15630        IOUT=1
15640        DO 70 I=1,NLAYR
15650           DEPTH=DEPTH+DLAYR(I)
15660           FR=DLAYR(I)/SDEP
15670           IF (I.EQ.1.AND.SDEP.LE.DEPTH) GO TO 40
15680           GO TO 50
15690 40        FR=1
15700           IOUT=2
15710 50        IF (SDEP.LE.DEPTH) GO TO 60
15720           FR=(SDEP-DEPTH-DLAYR(I))/SDEP
15730           IOUT=2
15740 60        ADD=STRAW*FR
15750           FOM(I)=FOM(I)+ADD
15760           FON(I)=FON(I)+ADD*0.40/SCN
15770           GO TO (70,80), IOUT
15780 70     CONTINUE
15790 80     TIFOM=0.0
15800        TIFON=0.0
15810        DO 95 I=1,NLAYR
15820                RNLOSS(I)=0.0
15830           HUM(I)=OC(I)*1.E03*BD(I)*DLAYR(I)/0.4
15840           IFOM(I)=FOM(I)
15850           IFON(I)=FON(I)
15860           TIFOM=TIFOM+IFOM(I)
15870           TIFON=TIFON+IFON(I)
15880 95     CONTINUE
15890        RDCARB=0.8
15900        RDCELL=0.05
15910        RDLIGN=0.0095
15920        DMINR=8.3E-05*DMOD
15930        IF (MINCK.EQ.0) GO TO 100
15940        WRITE (2,230) LOG
15950        WRITE (2,240)
15960 100    DL1=0.0
15970        DO 110 L=1,NLAYR
15980           DL2=DL1+DLAYR(L)
15990           SNO3(L)=NO3(L)*BD(L)*DLAYR(L)*1.E-01
16000           SNH4(L)=NH4(L)*BD(L)*DLAYR(L)*1.E-01
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
16010           NHUM(L)=OC(L)*DLAYR(L)*BD(L)*1.E02-(SNO3(L)+SNH4(L))
16020           IF (MINCK.NE.0) WRITE (2,250) L,DL1,DL2,NH4(L),SNH4(L),NO3(L),
16030         1   SNO3(L),BD(L),PH(L)
16040           DL1=DL2
16050 110     CONTINUE
16060         IF (MINCK.NE.0) WRITE (2,260)
16070         DL1=0.0
16080         DO 120 L=1,NLAYR
16090           DL2=DL1+DLAYR(L)
16100           IF (MINCK.NE.0) WRITE (2,250) L,DL1,DL2,OC(L),HUM(L),NHUM(L)
16110           DL1=DL2
16120 120     CONTINUE
16130         IF (MINCK.EQ.0) GO TO 130
16140         WRITE (2,270) STRAW,SDEP,SCN,SNKG,ROOT,RCN,RNKG
16150         WRITE (2,280) RDCARB,RDCELL,RDLIGN,DMINR
16160 C********** INITIALIZE SOIL TEMPERATURE ROUTINE
16170 130     ANG=0.01724
16180         ALX=ANG*FLOAT(JDATE)
16190         ZY1=0.
16200         XX=0.
16210         DD=DEPMAX*10.0
16220         DO 140 L=1,NLAYR
16230           ZY=(DLAYR(L)*10.0+XX)/2.0
16240           ZZ=ZY-ZY1
16250           ZD=-ZY/DD
16260           YY=ZD+ALX
16270           SY=SIN(YY)
16280           AE=AMP*EXP(ZD)
16290           DTDT=AE*SY*ANG
16300           DTDZ=AE*(COS(YY)-SY)/DD
16310           ST(L)=TAV+DTDT+DTDZ*ZZ
16320           XX=DLAYR(L)*10.0+XX
16330           ZY1=ZY
16340 140     CONTINUE
16350 C********** INITIALIZE NITRIFICATION ROUTINE
16360         DO 170 L=1,NLAYR
16370           CNI(L)=0.1
16380           WFY(L)=(SW(L)-LL(L))/DUL(L)
16390           IF (SW(L).GT.DUL(L)) WFY(L)=1.0-((SW(L)-DUL(L))
16400         1                   /(SAT(L)-DUL(L)))
16410           IF (WFY(L).LT.0.0) WFY(L)=0.0
16420           TFY(L)=0.0009766*ST(L)*ST(L)
16430           IF (ST(L).LT.5.0) TFY(L)=0.0
16440           TLCH(L)=0.0
16450           TUPFLX(L)=0.0
16460           TPNUP(L)=0.0
16470           TNOM(L)=0.0
16480           TTNOX(L)=0.0
16490           TST(L)=0.0
16500           TRNTRF(L)=0.0
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
16510           DTNOX(L)=0.0
16520 170     CONTINUE
16530         RETURN
16540 C
16550 175     FORMAT(I3)
16560 180     FORMAT(3X,2F6.1,I4)
16570 190     FORMAT (4A4)
16580 200     FORMAT(3X,2F6.1,2F6.2)
16590 210     FORMAT(3X,3F6.0)
16600 220     FORMAT(3X,F6.2)
16610 230     FORMAT (5(/),5X,'LOCATION : ',4A4,/,5X,10('-'),/)
16620 240     FORMAT (//,1X,'INITIAL MINERAL N IN LAYERS',/,1X,27('-'),//,5X,
16630        1  'LAYER',10X,'DEPTH',16X,'AMMONIUM',12X,'NITRATE',/,37X,'PPM',5X,
16640        2  'KG/HA',7X,'PPM',5X,'KG./HA',/)
16650 250     FORMAT (I10,4X,F4.0,1X,'-',1X,F4.0,4X,6F10.1)
16660 260     FORMAT (///,1X,'INITIAL ORGANIC MATTER IN LAYERS',/,1X,32('-'),//,
16670        1  5X,'LAYER',10X,'DEPTH',6X,'% ORGANIC',5X,'HUMUS',3X,'HUMIC N',/,
16680        2  34X,'CARBON',5X,'KG/HA',5X,'KG/HA',/)
16690 270     FORMAT (////,1X,'FRESH ORGANIC MATTER',1X,/,20('-'),//,1X,
16700        1  'TOTAL SURFACE RESIDUE(STRAW)',T35,'=',F7.1,2X,'KG/HA',/,1X,
16710        2  'DEPTH OF INCORPORATION',T35,'=',F7.1,2X,'CM',/,1X,
16720        3  'C:N RATIO OF STRAW',T35,'=',F7.1,/,1X,'N IN STRAW',T35,'=',
16730        4  F7.1,2X,'KG N/HA',//,1X,'TOTAL ROOT RESIDUE',T35,'=',F7.1,2X,
16740        5  'KG/HA',/,1X,'DISTRIBUTED ACCORDING TO F=EXP(-3*DEPTH/DEPMAX)',
16750        6  /,1X,'C:N RATIO OF ROOT RESIDUE',T35,'=',F7.1,/,1X,
16760        7  'N IN ROOT RESIDUE',T35,'=',F7.1,2X,'KG N/HA')
16770 280     FORMAT (////,1X,'MAXIMUM DECAY RATES OF OM FRACTIONS:',/,1X,
16780        1  36('-'),/,T37,'CARBOHYDRATE',T50,':',F10.6,/,T37,'CELLULOSE',
16790        2  T50,':',F10.6,/,T37,'LIGNIN',T50,':',F10.6,/,T37,'HUMUS',T50,
16800        3  ':',E7.1,/)
16810 290     FORMAT (/,' FERTILIZER INPUTS',/,' JULIAN DAY',5X,'KG/HA',5X,
16820        1  'DEPTH','   SOURCE',/)
16830 300     FORMAT (5X,I3,2F6.1,I2)
16840 310     FORMAT (I10,2F10.2,3X,6A4)
16850         END
16860 C
16870 C
16880 C******************MINERALIZATION AND IMMOBILIZATION ROUTINE*******
16890 C
16900         SUBROUTINE MINIMO
16910         REAL IFOM,IFON,MF,NHUM,LL,NO3,NH4,NNOM
16920         COMMON /SOILI/ SALB,U,SWCON,DLAYR(10),DUL(10),LL(10),SW(10),
16930        1 SAT(10),DEPMAX,TDUL,NLAYR,SMX,WF(10),WR(10),RWU(10),SWEF,CN2
16940         COMMON /CLIMT/ TEMPMN,TEMPMX,RAIN,SOLRAD,TMFAC(8)
16950         COMMON /NMINR/ RDLIGN,RDCELL,RDCARB,FOM(10),IFOM(10),FON(10),
16960        1  IFON(10),DMINR,NHUM(10),HUM(10),TIFOM,TIFON
16970         COMMON /NOMT/ TIMOB,TMINF,TMINH,DECR(10),CNR(10),TNNOM,POMR,PONR,
16980        1  FOCNR(10),SCNR(10)
16990         COMMON /NSPOOL/ SNH4(10),SNO3(10),NH4(10),NO3(10),FAC(10),
17000        1   BD(10),PH(10)
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
17010       COMMON /NSTEMP/ ST(10),ANG,TMN,AMP
17020       COMMON /NFERTB/ JFDAY(10),AFERT(10),DFERT(10),NFERT,IFTYPE(10)
17030       COMMON /NCTRL/ KOUTMN,IOUTMN,KOUTNU,IOUTNU,MINCK,NHDMN,NHDUP,
17040      1  IFERT,KFERT,ISWNIT,DMOD,XSTRAW,GRPCTN,GRPTN,XTOTNP,XAPTNP
17050      2,XGNUP
17060       COMMON /DATEC/ MO,ND,IYR,JDATE,JDATEX,IDIM(12),NYRS
17070       COMMON /NBALT/ PNUP(10),NNOM(10),DTNOX(10)
17080       IF (IFERT.EQ.0) GO TO 70
17090       DEPTH=0.0
17100       DO 10 K=1,NFERT
17110          J=K
17120          IF (JDATE.EQ.JFDAY(J)) GO TO 20
17130 10    CONTINUE
17140       GO TO 70
17150 20    DO 60 L=1,NLAYR
17160          DEPTH=DEPTH+DLAYR(L)
17170          IF (DFERT(J).GT.DEPTH) GO TO 60
17180            M=IFTYPE(J)
17190          GO TO (30,40,30,40,50), M
17200 C        FERTILIZER TYPES
17210 C        0,1 =UREA (HYDROLYSIS TO BE ADDED LATER)
17220 C        2   =AMMONIUM NITRATE
17230 C        3   =ANHYDROUS AMMONIA
17240 C        4   =CALCIUM AMMONIUM NITRATE
17250 C        5   =M NITRATE
17260 30       SNH4(L)=SNH4(L)+AFERT(J)
17270          GO TO 70
17280 40       SNH4(L)=SNH4(L)+0.5*AFERT(J)
17290          SNO3(L)=SNO3(L)+0.5*AFERT(J)
17300          GO TO 70
17310 50       SNO3(L)=SNO3(L)+AFERT(J)
17320          GO TO 70
17330 60    CONTINUE
17340 70    CONTINUE
17350       TMN=(TEMPMX+TEMPMN)*0.5
17360       CALL SOLT
17370       TIMOB=0.0
17380       TMINF=0.0
17390       TMINH=0.0
17400       TNNOM=0.0
17410       TOM=0.0
17420       TON=0.0
17430       DO 100 I=1,NLAYR
17440          MF=(SW(I)-LL(I)*0.50)/(DUL(I)-LL(I)*0.50)
17450          IF (MF.LE.0.) MF=0.
17460          FAC(I)=1.0/(BD(I)*1.E-01*DLAYR(I))
17470          NO3(I)=SNO3(I)*FAC(I)
17480          NH4(I)=SNH4(I)*FAC(I)
17490          TFAC=1
17500          IF (ST(I).LE.0.) TFAC=0.0
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
17510           TFAC=0.00097666*ST(I)*ST(I)
17520           RATIO=FOM(I)/IFOM(I)
17530           RDECR=RDLIGN
17540           IF (RATIO.GT.0.8) RDECR=RDCARB
17550           IF (RATIO.LE.0.8.AND.RATIO.GT.0.1) RDECR=RDCELL
17560           TOTN=SNO3(I)+SNH4(I)-2.0/FAC(I)
17570           IF (TOTN.LT.0.0) TOTN=0.0
17580           CNR(I)=(0.4*FOM(I))/(FON(I)+TOTN)
17590           CNRF=EXP(-0.693*(CNR(I)-25)/25.0)
17600           IF (CNRF.GT.1.0) CNRF=1.0
17610           DECR(I)=RDECR*TFAC*MF*CNRF
17620           GRNOM=DECR(I)*FON(I)
17630           RHMIN=NHUM(I)*DMINR*TFAC*MF
17640           HUM(I)=HUM(I)-RHMIN*10.0+0.2*GRNOM/0.04
17650           NHUM(I)=NHUM(I)-RHMIN+0.2*GRNOM
17660           RNAC=AMIN1(TOTN,DECR(I)*FOM(I)*(0.02-FON(I)/FOM(I)))
17670           FOM(I)=FOM(I)-DECR(I)*FOM(I)
17680           FON(I)=FON(I)+RNAC-GRNOM
17690           NNOM(I)=0.8*GRNOM+RHMIN-RNAC
17700           TNNOM=TNNOM+NNOM(I)
17710           TON=TON+FON(I)
17720           TOM=TOM+FOM(I)
17730           SNH4(I)=SNH4(I)+NNOM(I)
17740           IF (SNH4(I).GT.1.0) GO TO 90
17741         IF (SNO3(I).LE.0.) GO TO 85
17750           DEF=1.0-SNH4(I)
17760           SNO3(I)=SNO3(I)-DEF
17761           IF (SNO3(I).LE.0.0) SNO3(I)=0.0
17770           SNH4(I)=1.0
17771         GO TO 90
17772    85   SNO3(I)=0.0
17773         IF (SNH4(I).LE.0.0) SNH4(I)=0.0
17780 90          SCNR(I)=0.4*(FOM(I)+HUM(I))/(FON(I)+NHUM(I)+SNO3(I)+SNH4(I))
17790         FOCNR(I)=0.4*FOM(I)/FON(I)
17800           TIMOB=TIMOB+RNAC
17810           TMINF=TMINF+GRNOM*0.8
17820           TMINH=TMINH+RHMIN
17830 100    CONTINUE
17840        POMR=TOM/TIFOM
17850        PONR=TON/TIFON
17860        CALL NITRIF
17870        RETURN
17880        END
17890 C
17900 C***************DETAILED NITROGEN BALANCE OUTPUT ROUTINE**********
17910 C
17920        SUBROUTINE NBAL
17930        REAL MF,IFOM,IFON,NHUM,LL,NOUT,NUP,NNOM
17940        COMMON /CLIMT/ TEMPMN,TEMPMX,RAIN,SOLRAD,TMFAC(8)
17950        COMMON /DATEC/ MO,ND,IYR,JDATE,JDATEX,IDIM(12),NYRS
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
17960       COMMON /NMINR/ RDLIGN,RDCELL,RDCARB,FOM(10),IFOM(10),FON(10),
17970      1  IFON(10),DMINR,NHUM(10),HUM(10),TIFOM,TIFON
17980       COMMON /NOMT/ TIMOB,TMINF,TMINH,DECR(10),CNR(10),TNNOM,POMR,PONR,
17990      1  FOCNR(10),SCNR(10)
18000       COMMON /NSPOOL/ SNH4(10),SNO3(10),NH4(10),NO3(10),FAC(10),
18010      1   BD(10),PH(10)
18020       COMMON /SOILI/ SALB,U,SWCON,DLAYR(10),DUL(10),LL(10),SW(10),
18030      1 SAT(10),DEPMAX,TDUL,NLAYR,SMX,WF(10),WR(10),RWU(10),SWEF,CN2
18040       COMMON /NCTRL/ KOUTMN,IOUTMN,KOUTNU,IOUTNU,MINCK,NHDMN,NHDUP,
18050      1  IFERT,KFERT,ISWNIT,DMOD,XSTRAW,GRPCTN,GRPTN,XTOTNP,XAPTNP
18060      2,XGNUP
18070       COMMON /NBALT/ PNUP(10),NNOM(10),DTNOX(10)
18080       COMMON /NMOVE/ FLUX(10),SWX(10),FLOW(10),MU,NOUT(10),NUP(10)
18090       COMMON /NITRF/ CNI(10),WFY(10),TFY(10),RNTRF(10)
18100       COMMON /NSTEMP/ ST(10),ANG,TMN,AMP
18110        COMMON /NTINIT/ TLCH(10),TUPFLX(10),TPNUP(10),TNOM(10),
18120      1 TTNOX(10),TST(10),TRNTRF(10)
18130       DO 10 L=1,NLAYR
18140          TLCH(L)=TLCH(L)+NOUT(L)
18150          TUPFLX(L)=TUPFLX(L)+NUP(L)
18160          TPNUP(L)=TPNUP(L)+PNUP(L)
18170          TNOM(L)=TNOM(L)+NNOM(L)
18180          TTNOX(L)=TTNOX(L)+DTNOX(L)
18190          TST(L)=TST(L)+ST(L)
18200          TRNTRF(L)=TRNTRF(L)+RNTRF(L)
18210          DTNOX(L)=0.0
18220          NUP(L)=0.0
18230 10    CONTINUE
18240       X=JDATE/MINCK
18250       IF (X*MINCK.NE.JDATE) GO TO 30
18260       WRITE (2,40) JDATE,TIMOB,TMINF,TMINH
18270       WRITE (2,50)
18280       TNO3=0.0
18290       TNH4=0.0
18300       TSW=0.0
18310       DO 20 L=1,NLAYR
18320          TST(L)=TST(L)/FLOAT(MINCK)
18330          WRITE (2,60) L,FOM(L),FON(L),TST(L),SNO3(L),SNH4(L),TRNTRF(L),
18340      1     CNR(L),FOCNR(L),SCNR(L),TLCH(L),TUPFLX(L),TPNUP(L),TNOM(L),
18350      2     TTNOX(L)
18360          TLCH(L)=0.0
18370          TUPFLX(L)=0.0
18380          TPNUP(L)=0.0
18390          TNOM(L)=0.0
18400          TTNOX(L)=0.0
18410          TST(L)=0.0
18420          TRNTRF(L)=0.0
18430 20    CONTINUE
18440 30    RETURN
18450 C
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
18460 40    FORMAT (5(/),25X,'JDATE =',I4,//,20X,'GROSS N IMMOBILIZATION IN PR
18470      1OFILE =',T70,F7.2,'KG N/HA',/,20X,'GROSS N RELEASE FROM FRESH OM M
18480      2INERALIZATION =',T70,F7.2,'KG N/HA',/,20X,'N RELEASED FROM HUMUS =
18490      3',T70,F7.2,'KG N/HA')
18500 50    FORMAT (1X,'LAYER',6X,'FOM',5X,'FON',6X,'TEMP',4X,'SNO3',4X,
18510      1  'SNH4',2X,'NITRIF',5X,'C:N*',2X,'FOM C:N',1X,'SOIL C:N',4X,
18520      2  'LEACH',4X,'UPFLX',5X,'UPTK',5X,'MINN',4X,'DENIT')
18530 60    FORMAT (I7,F9.0,F8.1,F8.0,2F8.1,F9.3,3F9.2,5F9.3)
18540       END
18550 C
18560 C*****************NITROGEN UPTAKE ROUTINE*********************
18570 C
18580       SUBROUTINE NUPTAK
18590       REAL NO3,NNOM,NH4,NDEM,NUF,LL,LAT,LFWT,NOUT,NUP,LAI
18600       COMMON /PARAM/ ISOIL,IIRR,IWETH,ISOW,PLANTS,KOUTGR,KOUTWA,SDEPTH,
18610      1  LAT,KVARTY,KIRR,KSOIL,IQUIT,NEWSOL,NEWWET,MULTYR,ISWSWB
18620      2  ,PHINT,KNIT,IODATE,XYIELD,XGRWT,XGPSM,XGPE,XLAI,XBIOM,ISLKJD,
18630      3 MATJD,INSOIL
18640       COMMON /SOILI/ SALB,U,SWCON,DLAYR(10),DUL(10),LL(10),SW(10),
18650      1 SAT(10),DEPMAX,TDUL,NLAYR,SMX,WF(10),WR(10),RWU(10),SWEF,CN2
18660       COMMON /GROTH/ GPSM,GPP,GRORT,PTF,LAI,DM,BIOMAS,PLA,SENLA,
18670      1  LFWT,SEEDRV,REGM,XPLANT,WIDTL,EMAT,SLW,PLAY,PLAMX,
18680      1  RTWT,STMWT,GRNWT,SWMIN,LN,EARWT,TLNO,SWMAX,FACLI,
18690      1RWID,SUMP,IDURP,PLAG,EGFT,GROSTM,CARBO,BLAMX(35),GBLA(35),
18700      1 SLA(35),NL1,NLMAX,EARS
18710       COMMON /WATER/ SUMES1,SUMES2,T,TLL,PESW,TSW,CUMDEP,ESW(10),
18720      1    CSD1,CSD2,SI1(6),SI2(6),ICSDUR,ES,EP,ET,EO,CES,CEP,CET,
18730      1    RLV(10),PRECIP,CRAIN,DRAIN,IDRSW,RTDEP,SWDF1,SWDF2,
18740      1    SWDF3,TRWU,RWUMX
18750       COMMON /NSPOOL/ SNH4(10),SNO3(10),NH4(10),NO3(10),FAC(10),
18760      1   BD(10),PH(10)
18770       COMMON /NCONC/ TANC,TCNP,RCNP,RANC,TMNC,VANC,VMNC,XSTAGE
18780       COMMON /PHENL/ P9,CUMDTT,TBASE,SUMDTT,S1,C1,ISTAGE,
18790      1  DTT,IDUR,SIND,TEMPM
18800       COMMON /NPLANT/ GRAINN,ROOTN,STOVN,PDWI,STOVWT,PGRORT,NDEM
18810       COMMON /NROOT/ RNFAC(10),RNLOSS(10),JJ
18820       COMMON /DATEC/ MO,ND,IYR,JDATE,JDATEX,IDIM(12),NYRS
18830       COMMON /NWRITP/ ATANC,ATCNP,ARANC,ARCNP,ANDEM2,ATNUP,ARTN,ASTOVN,
18840      1  AGRN,CTNUP,TNUP,APTNUP
18850       COMMON /NBALT/ PNUP(10),NNOM(10),DTNOX(10)
18860       COMMON /NMOVE/ FLUX(10),SWX(10),FLOW(10),MU,NOUT(10),NUP(10)
18870       COMMON /NNN/ NFAC,DSTOVN
18880       DIMENSION RNO3U(10), RNH4U(10)
18890       TNUP=0.0
18900           TRNLOS=0.0
18910       DO 10 L=1,NLAYR
18920          NO3(L)=SNO3(L)*FAC(L)*BD(L)
18930          NH4(L)=SNH4(L)*FAC(L)*BD(L)
18940          TOTN=NO3(L)+NH4(L)
18950          RNFAC(L)=1.0-(1.17*EXP(-0.20*TOTN))
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
18960           IF (RNFAC(L).LE.0.01) RNFAC(L)=0.01
18970           PNUP(L)=0.0
18980 10     CONTINUE
18990             DNG=PDWI*TCNP
19000          IF(XSTAGE.LE.1.2)DNG=0.0
19010         IF (PDWI.EQ.0.) PDWI=1.
19020         TNDEM=STOVWT*(TCNP-TANC)+DNG
19030         RNDEM=RTWT*(RCNP-RANC)+PGRORT*RCNP
19040         NDEM=TNDEM+RNDEM
19050         ANDEM=NDEM*PLANTS*10.0
19060         DROOTN=0.0
19070         DSTOVN=0.0
19080         TRNU=0.0
19090         TNUP=0.0
19100         IF (ANDEM.LE.0.0) GO TO 50
19110         DO 20 L=1,NLAYR
19120            IF (RLV(L).EQ.0.0) GO TO 30
19130            L1=L
19140            FNH4=1.0-EXP(-0.030*NH4(L))
19150            FNO3=1.0-EXP(-0.025*NO3(L))
19160            IF (FNO3.LT.0.03) FNO3=0.0
19170            IF (FNO3.GT.1.0) FNO3=1.0
19180            IF (FNH4.LT.0.03) FNH4=0.0
19190            IF (FNH4.GT.1.0) FNH4=1.0
19200            SMDFR=(SW(L)-LL(L))/ESW(L)
19210            IF(SMDFR.LT.0.0) SMDFR=0.0
19213            RFAC=RLV(L)*SMDFR*SMDFR*DLAYR(L)*100
19220            RNO3U(L)=(RWU(L)/(SW(L)*DLAYR(L)))*SNO3(L)
19230            IF (SMDFR.LT.1.00) RNO3U(L)=RFAC*FNO3*0.008
19240            IF (SMDFR.LT.0.50.AND.NFAC.LT.0.70) RNO3U(L)=
19241       1 RFAC*FNO3*0.008*SMDFR
19242            UP1=SNO3(L)-RNO3U(L)
19250            SMIN=1.0/FAC(L)
19260            IF (UP1.LT.SMIN) RNO3U(L)=SNO3(L)-SMIN
19261            IF (RNO3U(L).LT.0.) RNO3U(L)=0.0
19271            RNH4U(L)=RFAC*FNH4*0.008
19281            IF (SMDFR.LT.0.50.AND.NFAC.LT.0.70) RNH4U(L)=
19291       1 RFAC*FNH4*0.008*SMDFR
19293         UP2=SNH4(L)-RNH4U(L)
19294         IF(UP2.LT.SMIN) RNH4U(L)=SNH4(L)-SMIN
19295            IF (RNH4U(L).LT.0.) RNH4U(L)=0.0
19300            TRNU=TRNU+RNO3U(L)+RNH4U(L)
19310 20     CONTINUE
19320 30     IF (ANDEM.GT.TRNU) ANDEM=TRNU
19330         IF (TRNU.EQ.0.0) GO TO 60
19340         NUF=ANDEM/TRNU
19350         TRNU=TRNU*NUF
19360         TRNS=0.0
19370         DO 40 L=1,L1
19380            UNO3=RNO3U(L)*NUF
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
19390           UNH4=RNH4U(L)*NUF
19400           SNO3(L)=SNO3(L)-UNO3
19410           SNH4(L)=SNH4(L)-UNH4
19420           PNUP(L)=UNO3+UNH4
19430           RNLOSS(L)=RANC*RLV(L)*0.006665
19440            TRNLOS=TRNLOS+RNLOSS(L)
19450           TNUP=TNUP+PNUP(L)
19460           TRNS=TRNS+SNO3(L)+SNH4(L)
19470 40      CONTINUE
19480         TRNU=TRNU/(PLANTS*10.0)
19490         DSTOVN=TNDEM/NDEM*TRNU
19500         DROOTN=RNDEM/NDEM*TRNU*0.985
19510         STOVN=STOVN+DSTOVN
19520 50      TANC=STOVN/STOVWT
19530          DROOTN=DROOTN-TRNLOS
19540         ROOTN=ROOTN+DROOTN
19550         RANC=ROOTN/(RTWT+0.5*GRORT-0.01*RTWT)
19562    60   RETURN
19570         END
19580 C
19590 C*****************DRAINAGE AND LEACHING ROUTINE*******************
19600 C
19610         SUBROUTINE NFLUX (ICODE)
19620         REAL NO3,LL,NH4,NOUT,NUP,NNOM
19630         COMMON /SOILI/ SALB,U,SWCON,DLAYR(10),DUL(10),LL(10),SW(10),
19640        1 SAT(10),DEPMAX,TDUL,NLAYR,SMX,WF(10),WR(10),RWU(10),SWEF,CN2
19650         COMMON /NSPOOL/ SNH4(10),SNO3(10),NH4(10),NO3(10),FAC(10),
19660        1   BD(10),PH(10)
19670         COMMON /NMOVE/ FLUX(10),SWX(10),FLOW(10),MU,NOUT(10),NUP(10)
19680         COMMON /NBALT/ PNUP(10),NNOM(10),DTNOX(10)
19690         COMMON /NROOT/ RNFAC(10),RNLOSS(10),JJ
19700         COMMON /DATEC/ MO,ND,IYR,JDATE,JDATEX,IDIM(12),NYRS
19710         IF(ICODE.EQ.1) GO TO 38
19720         DO 10 L=1,NLAYR
19730            NOUT(L)=0.0
19740 10      CONTINUE
19750         OUTN=0.0
19760         DO 35 L=1,NLAYR
19770            SNO3(L)=SNO3(L)+OUTN
19780            NO3(L)=SNO3(L)*FAC(L)
19790            IF (NO3(L).GT.1.0) GO TO 20
19800            OUTN=0.0
19810            GO TO 35
19820 20         NOUT(L)=SNO3(L)*FLUX(L)/(SW(L)*DLAYR(L)+FLUX(L))
19830          SMIN=1.0/FAC(L)
19840          IF(SNO3(L)-NOUT(L).LT.SMIN)NOUT(L)=SNO3(L)-SMIN
19850            OUTN=NOUT(L)
19860            SNO3(L)=SNO3(L)-OUTN
19870          NO3(L)=SNO3(L)*FAC(L)
19880    35    CONTINUE
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
      RETURN
   38 DO 40 L=1,NLAYR
         NUP(L)=0.0
40    CONTINUE
      OUTN=0.0
      DO 50 J=1,MU
         K=MU+1-J
         SNO3(K)=SNO3(K)+OUTN
        IF(FLOW(K).LT.0.)GO TO 50
        NUP(K)=SNO3(K)*FLOW(K)/(SW(K)*DLAYR(K)+FLOW(K))*0.5
        OUTN=NUP(K)
        IF(K.EQ.1)GO TO 50
        SNO3(K)=SNO3(K)-OUTN
50    CONTINUE
          OUTN=0.0
          DO 60 J=1,MU
          SNO3(J)=SNO3(J)-OUTN
          IF(FLOW(J).GT.0.)GO TO 60
          NUP(J)=SNO3(J)*FLOW(J)/(SW(J)*DLAYR(J)+FLOW(J))*0.5
          OUTN=NUP(J)
          SNO3(J)=SNO3(J)+OUTN
60        CONTINUE
      RETURN
      END
C
C*********************NITROGEN DEFICIENCY FACTOR ROUTINE************
C
      SUBROUTINE NFACTO
      COMMON /NNN/ NFAC,DSTOVN
      COMMON /GENET/ P1,P2,P3,P5,G2,G3
      COMMON /PHENL/ P9,CUMDTT,TBASE,SUMDTT,S1,C1,ISTAGE,
     1  DTT,IDUR,SIND,TEMPM
      COMMON /NDFPG/ NDEF1,NDEF2,NDEF3,NDEF4,GNP,CNSD1,CNSD2
      COMMON /NCONC/ TANC,TCNP,RCNP,RANC,TMNC,VANC,VMNC,XSTAGE
      COMMON /DATEC/ MO,ND,IYR,JDATE,JDATEX,IDIM(12),NYRS
      REAL NFAC,NDEF1,NDEF2,NDEF3,NDEF4
      TCNP=EXP(1.52-.221*XSTAGE)/100.0
      TMNC=0.0025
      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) NFAC=1.0
      IF (NFAC.LT.0.) NFAC=0.
      NDEF1=1.0
      NDEF2=1.0
      NDEF3=1.0
      IF(NFAC.LT.0.80)NDEF1=0.90*NFAC+0.3
      IF(NFAC.LT.0.4)NDEF2=1.00*NFAC+0.60
      IF(NFAC.LT.0.5)NDEF3=0.35+1.30*NFAC
      NDEF4=NFAC
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
20380        IF(NDEF1.GT.1.)NDEF1=1.
20390        IF(NDEF2.GT.1.)NDEF2=1.
20391        IF(NDEF3.GT.1.)NDEF3=1.
20400        CNSD1=CNSD1+1.0-NFAC
20410        CNSD2=CNSD2+1.0-NDEF2
20420        RETURN
20430        END
20440 C
20450 C*****************NITROGEN OUTPUT CONTROLLING ROUTINE****************
20460 C
20470        SUBROUTINE NWRITE
20480        REAL NDEM
20490        COMMON /NCTRL/ KOUTMN,IOUTMN,KOUTNU,IOUTNU,MINCK,NHDMN,NHDUP,
20500       1  IFERT,KFERT,ISWNIT,DMOD,XSTRAW,GRPCTN,GRPTN,XTOTNP,XAPTNP
20510       2,XGNUP
20520        COMMON /NWRITP/ ATANC,ATCNP,ARANC,ARCNP,ANDEM2,ATNUP,ARTN,ASTOVN,
20530       1  AGRN,CTNUP,TNUP,APTNUP
20540        COMMON /NAMIN/ APOMR,APONR,ACNR,ADECR,AIMOB,AMINF,AMINH,ANOM
20550        COMMON /NPLANT/ GRAINN,ROOTN,STOVN,PDWI,STOVWT,PGRORT,NDEM
20560        COMMON /NCONC/ TANC,TCNP,RCNP,RANC,TMNC,VANC,VMNC,XSTAGE
20570        COMMON /NOMT/ TIMOB,TMINF,TMINH,DECR(10),CNR(10),TNNOM,POMR,PONR,
20580       1  FOCNR(10),SCNR(10)
20590        COMMON /PHENL/ P9,CUMDTT,TBASE,SUMDTT,S1,C1,ISTAGE,
20600       1  DTT,IDUR,SIND,TEMPM
20610        COMMON /DATEC/ MO,ND,IYR,JDATE,JDATEX,IDIM(12),NYRS
20620        COMMON /PARAM/ ISOIL,IIRR,IWETH,ISOW,PLANTS,KOUTGR,KOUTWA,SDEPTH,
20630       1  LAT,KVARTY,KIRR,KSOIL,IQUIT,NEWSOL,NEWWET,MULTYR,ISWSWB
20640       2  ,PHINT,KNIT,IODATE,XYIELD,XGRWT,XGPSM,XGPE,XLAI,XBIOM,ISLKJD,
20650       3 MATJD,INSOIL
20660        IF (MINCK.GE.1) CALL NBAL
20670        CTNUP=CTNUP+TNUP
20680        IF (KOUTMN.EQ.0) GO TO 10
20690        IOUTMN=IOUTMN+1
20700        APOMR=APOMR+POMR
20710        APONR=APONR+PONR
20720        ACNR=ACNR+(FOCNR(1)+FOCNR(2))/2.0
20730        ADECR=ADECR+(DECR(1)+DECR(2))/2.0
20740        AIMOB=AIMOB+TIMOB
20750        AMINF=AMINF+TMINF
20760        AMINH=AMINH+TMINH
20770        ANOM=ANOM+TNNOM
20780        IF (IOUTMN.EQ.KOUTMN) CALL OUTMN
20790 10     APTNUP=STOVN*10*PLANTS
20800        IF (KOUTNU.EQ.0) RETURN
20810        IF (ISTAGE.GT.6) RETURN
20820        IOUTNU=IOUTNU+1
20830        ATANC=ATANC+TANC
20840        ATCNP=ATCNP+TCNP
20850        ARANC=ARANC+RANC
20860        ARCNP=ARCNP+RCNP
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
20870       ANDEM2=ANDEM2+NDEM*PLANTS*10.0
20880       ATNUP=ATNUP+TNUP
20890       ARTN=ARTN+ROOTN
20900       ASTOVN=ASTOVN+STOVN
20910       AGRN=AGRN+GRAINN
20920       IF (IOUTNU.EQ.KOUTNU) CALL OUTNU
20930       RETURN
20940       END
20950 C
20960 C***********UPTAKE AND PLANT N OUTPUT ROUTINE*****************
20970 C
20980       SUBROUTINE OUTNU
20990       REAL NDEF1,NDEF2,NDEF3,NDEF4,NO3,NH4
21000       COMMON /DATEC/ MO,ND,IYR,JDATE,JDATEX,IDIM(12),NYRS
21010       COMMON /SOILI/ SALB,U,SWCON,DLAYR(10),DUL(10),LL(10),SW(10),
21020      1 SAT(10),DEPMAX,TDUL,NLAYR,SMX,WF(10),WR(10),RWU(10),SWEF,CN2
21030       COMMON /PHENL/ P9,CUMDTT,TBASE,SUMDTT,S1,C1,ISTAGE,
21040      1  DTT,IDUR,SIND,TEMPM
21050       COMMON /GROTH/ GPSM,GPP,GRORT,PTF,LAI,DM,BIOMAS,PLA,SENLA,
21060      1  LFWT,SEEDRV,REGM,XPLANT,WIDTL,EMAT,SLW,PLAY,PLAMX,
21070      1  RTWT,STMWT,GRNWT,SWMIN,LN,EARWT,TLNO,SWMAX,FACLI,
21080      1RWID,SUMP,IDURP,PLAG,EGFT,GROSTM,CARBO,BLAMX(35),GBLA(35),
21090      1 SLA(35),NL1,NLMAX,EARS
21100       COMMON /WATER/ SUMES1,SUMES2,T,TLL,PESW,TSW,CUMDEP,ESW(10),
21110      1    CSD1,CSD2,SI1(6),SI2(6),ICSDUR,ES,EP,ET,EO,CES,CEP,CET,
21120      1    RLV(10),PRECIP,CRAIN,DRAIN,IDRSW,RTDEP,SWDF1,SWDF2,
21130      1    SWDF3,TRWU,RWUMX
21140       COMMON /NCTRL/ KOUTMN,IOUTMN,KOUTNU,IOUTNU,MINCK,NHDMN,NHDUP,
21150      1  IFERT,KFERT,ISWNIT,DMOD,XSTRAW,GRPCTN,GRPTN,XTOTNP,XAPTNP
21160      2,XGNUP
21170       COMMON /NWRITP/ ATANC,ATCNP,ARANC,ARCNP,ANDEM2,ATNUP,ARTN,ASTOVN,
21180      1  AGRN,CTNUP,TNUP,APTNUP
21190       COMMON /NDFPG/ NDEF1,NDEF2,NDEF3,NDEF4,GNP,CNSD1,CNSD2
21200       COMMON /NPLANT/ GRAINN,ROOTN,STOVN,PDWI,STOVWT,PGRORT,NDEM
21210       COMMON /NSPOOL/ SNH4(10),SNO3(10),NO3(10),NH4(10),FAC(10),
21220      1   BD(10),PH(10)
21230       COMMON /TITL/ TITLE(20)
21240       IF (NHDUP.EQ.1) GO TO 10
21250       IF (KOUTNU.NE.0) WRITE (4,60) TITLE
21260       IF (KOUTNU.NE.0) WRITE (4,50)
21270       NHDUP=1
21280       GO TO 40
21290 10    DAUP=FLOAT(IOUTNU)
21300       ATANC=(ATANC/DAUP)*100.0
21310       ATCNP=(ATCNP/DAUP)*100.0
21320       ARANC=(ARANC/DAUP)*100.0
21330       ARCNP=(ARCNP/DAUP)*100.0
21340       ANDEM2=ANDEM2/DAUP
21350       ATNUP=ATNUP/DAUP
21360       ARTN=(ARTN/DAUP)*1000.0
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
21370       ASTOVN=(ASTOVN/DAUP)*1000.0
21380       AGRN=1000.0*AGRN/DAUP
21390       XGNP=0.0
21400       IF (GRNWT.GT.0.) XGNP=GRAINN*100.0/GRNWT
21410       TNH4=0.0
21420       TNO3=0.0
21430       DEPTH=0.0
21440       DO 20 L=1,NLAYR
21450          DEPTH=DEPTH+DLAYR(L)
21460          IF (DEPTH.GT.RTDEP) GO TO 30
21470          TNO3=TNO3+SNO3(L)
21480          TNH4=TNH4+SNH4(L)
21490 20    CONTINUE
21500 30    CALL CALDAT
21510       WRITE (4,70) MO,ND,IYR,JDATE,ATANC,ATCNP,ARANC,ARCNP,ANDEM2,ATNUP,
21520      1  ARTN,ASTOVN,AGRN,XGNP,CTNUP,APTNUP,TNO3,TNH4
21530 40    ATANC=0.0
21540       ATCNP=0.0
21550       ARANC=0.0
21560       ARCNP=0.0
21570       ANDEM2=0.0
21580       ATNUP=0.0
21590       ARTN=0.0
21600       ASTOVN=0.0
21610       AGRN=0.0
21620       IOUTNU=0
21630       RETURN
21640 C
21650 50    FORMAT (/,10X,'JUL',1X,'----TOPS N%---',2X,'----ROOT N%---',2X,
21660      1  '---N (KG/HA)--',2X,'------MG N/PLANT------',4X,'GRAIN',1X,
21670      2  'N UPTAKE KG/HA',2X,'-PLANT EXTR N-',/,3X,'DAY',4X,'DAY',2(5X,
21680      3  'ACT',4X,'CRIT'),2X,'DEMAND',2X,'UPTAKE',3X,'ROOTS',4X,'TOPS',
21690      4  3X,'GRAIN',6X,'N%',3X,'TOTAL',1X,'VEG TOP',5X,'NO3',5X,'NH4')
21700 60    FORMAT (/,20X,20A4,/)
21710 70    FORMAT (1X,I2,'/',I2,'/',I2,I4,14F8.2)
21720       END
21730 C
21740 C*****************SOIL NITROGEN OUTPUT ROUTINE***************
21750 C
21760       SUBROUTINE OUTMN
21770       REAL NH4,NO3
21780       COMMON /NAMIN/ APOMR,APONR,ACNR,ADECR,AIMOB,AMINF,AMINH,ANOM
21790       COMMON /NSPOOL/ SNH4(10),SNO3(10),NH4(10),NO3(10),FAC(10),
21800      1   BD(10),PH(10)
21810       COMMON /DATEC/ MO,ND,IYR,JDATE,JDATEX,IDIM(12),NYRS
21820       COMMON /NCTRL/ KOUTMN,IOUTMN,KOUTNU,IOUTNU,MINCK,NHDMN,NHDUP,
21830      1  IFERT,KFERT,ISWNIT,DMOD,XSTRAW,GRPCTN,GRPTN,XTOTNP,XAPTNP
21840      2,XGNUP
21850       COMMON /TITL/ TITLE(20)
21860       IF (NHDMN.EQ.1) GO TO 10
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
21870         IF (KOUTMN.NE.0) WRITE (3,50) TITLE
21880         IF (KOUTMN.NE.0) WRITE (3,40) (L,L=1,6),(L,L=1,6)
21890        NHDMN=1
21900        GO TO 20
21910 10     DAMN=FLOAT(IOUTMN)
21920        APOMR=APOMR/DAMN
21930        APONR=APONR/DAMN
21940        ACNR=ACNR/DAMN
21950        ADECR=ADECR/DAMN
21960        AIMOB=AIMOB/DAMN
21970        AMINF=AMINF/DAMN
21980        AMINH=AMINH/DAMN
21990        ANDEM=ANOM/DAMN
22000        CALL CALDAT
22010         WRITE (3,30) MO,ND,IYR,JDATE,APOMR,APONR,ACNR,ADECR,AIMOB,AMINF,
22020       1  AMINH,ANOM,(NO3(L),L=1,6),(NH4(L),L=1,6)
22030 20     APOMR=0.0
22040        APONR=0.0
22050        ACNR=0.0
22060        ADECR=0.0
22070        AIMOB=0.0
22080        AMINF=0.0
22090        AMINH=0.0
22100        ANOM=0.0
22110        IOUTMN=0
22120        RETURN
22130 C
22140 30     FORMAT (1X,I2,'/',I2,'/',I2,I4,3F6.1,E8.1,10F6.1,6F5.1)
22150 40     FORMAT (/,9X,'JUL',9X,'FRESH OM',17X,'ORGANIC N',19X,
22160       1  'NITRATE (PPM)',19X,'AMMONIUM (PPM)',/,2(3X,'DAY'),2X,'% OMR',
22170       2  2X,'%ONR',3X,'C:N',4X,'DECR',2X,'IMOB',3X,'MIN',2X,'MINH',2X,
22180       3  'TMIN',6(4X,'L',I1),6(3X,'L',I1))
22190 50     FORMAT (/,40X,20A4,/)
22200        END
22210 C
22220 C**********SOIL TEMPERATURE ROUTINE
22230 C
22240        SUBROUTINE SOLT
22250        REAL LL
22260        COMMON /SOILI/ SALB,U,SWCON,DLAYR(10),DUL(10),LL(10),SW(10),
22270       1 SAT(10),DEPMAX,TDUL,NLAYR,SMX,WF(10),WR(10),RWU(10),SWEF,CN2
22280        COMMON /DATEC/ MO,ND,IYR,JDATE,JDATEX,IDIM(12),NYRS
22290        COMMON /NSTEMP/ ST(10),ANG,TMN,AMP
22300        COMMON /NSPOOL/ SNH4(10),SNO3(10),NH4(10),NO3(10),FAC(10),
22310       1   BD(10),PH(10)
22320        ZY1=0.
22330        TP=TMN
22340        XI=JDATE
22350        ZZ=DLAYR(1)*5.0
22360        ALX=ANG*XI
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
22370       XX=0.
22380       Z=0.
22390       DO 10 L=1,NLAYR
22400          Z1=DLAYR(L)*10.0
22410          Z=Z+Z1
22420          F=BD(L)/(BD(L)+686.*EXP(-5.63*BD(L)))
22430          DP=1000.0+2500.*F
22440          WW=0.356-0.144*BD(L)
22450          B=ALOG(500./DP)
22460          DW=SW(L)-LL(L)
22470          IF (DW.LT.0.0) DW=0.0
22480          AW=DW*Z1
22490          WC=AW/(WW*(Z-XX))
22500          F=EXP(B*((1.-WC)/(1.+WC))**2)
22510          DD=F*DP
22520          ZY=(Z+XX)/2.0
22530          ZZ=ZY-ZY1
22540          ZD=-ZY/DD
22550          YY=ZD+ALX
22560          SY=SIN(YY)
22570          AE=AMP*EXP(ZD)
22580          DTDT=AE*SY*ANG
22590          DTDZ=AE*(COS(YY)-SY)/DD
22600          TP=(ST(L)+TP+DTDT+DTDZ*ZZ)/2.0
22610          ST(L)=TP
22620          ZY1=ZY
22630          XX=Z
22640 10    CONTINUE
22650       RETURN
22660       END
22670 C
22680 C******* DENITRIFICATION SUBROUTINE *********REPLACED 4-84
22690 C
22700       SUBROUTINE DNIT
22710       REAL LL,IFOM,MF,NNOM,NO3,NH4
22720       COMMON /SOILI/ SALB,U,SWCON,DLAYR(10),DUL(10),LL(10),SW(10),
22730      1  SAT(10),DEPMAX,TDUL,NLAYR,SMX,WF(10),WR(10),RWU(10),SWEF,CN2
22740       COMMON /NMINR/ RDLIGN,RDCELL,RDCARB,FOM(10),IFOM(10),FON(10),
22750      1  IFON(10),DMINR,NHUM(10),HUM(10),TIFOM,TIFON
22760       COMMON /NSPOOL/ SNH4(10),SNO3(10),NH4(10),NO3(10),FAC(10),
22770      1   BD(10),PH(10)
22780       COMMON /NSTEMP/ ST(10),ANG,TMN,AMP
22790       COMMON /NBALT/ PNUP(10),NNOM(10),DTNOX(10)
22800       DO 10 L=1,NLAYR
22810        IF(NO3(L).LT.1.0)GO TO 10
22820          FW=0.0
22830          IF (SW(L).LE.DUL(L)) GO TO 10
22840          SOILC=0.40*FOM(L)+0.40*HUM(L)
22850          CW=(SOILC*FAC(L))*0.0031+24.5
22860          FW=(SAT(L)-SW(L))/(SAT(L)-DUL(L))
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```
22870           FT=0.1*EXP(0.046*ST(L))
22880 C          DNRATE=6.0*1.E-04*CW*NO3(L)*SW(L)*FW*FT
22890           DNRATE=6.0*1.E-05*CW*NO3(L)*BD(L)*FW*FT*DLAYR(L)
22900           SMIN=1.0/FAC(L)
22910         SNO3(L)=SNO3(L)-DNRATE
22920         X=0
22930         IF(SNO3(L).LT.SMIN)X=SMIN-SNO3(L)
22940         SNO3(L)=SNO3(L)+X
22950         DNRATE=DNRATE-X
22960         DTNOX(L)=DNRATE
22970           NO3(L)=SNO3(L)*FAC(L)
22980 10     CONTINUE
22990        RETURN
23000        END
23010 C
23020 C************* NITRIFICATION SUBROUTINE ************************
23030 C
23040        SUBROUTINE NITRIF
23050        COMMON /NITRF/ CNI(10),WFY(10),TFY(10),RNTRF(10)
23060        COMMON /SOILI/ SALB,U,SWCON,DLAYR(10),DUL(10),LL(10),SW(10),
23070       1  SAT(10),DEPMAX,TDUL,NLAYR,SMX,WF(10),WR(10),RWU(10),SWEF,CN2
23080        COMMON /NSTEMP/ ST(10),ANG,TMN,AMP
23090        COMMON /NSPOOL/ SNH4(10),SNO3(10),NH4(10),NO3(10),FAC(10),
23100       1   BD(10),PH(10)
23110        COMMON /NCTRL/ KOUTMN,IOUTMN,KOUTNU,IOUTNU,MINCK,NHDMN,NHDUP,
23120       1  IFERT,KFERT,ISWNIT,DMOD,XSTRAW,GRPCTN,GRPTN,XTOTNP,XAPTNP
23130       2,XGNUP
23140        REAL LL,NO3,NH4
23150        DO 10 L=1,NLAYR
23160           SANC=1.0-EXP(-0.01363*SNH4(L))
23170           XL=(DUL(L)-LL(L))*0.25
23180           WFD=(SW(L)-LL(L))/XL
23190           IF(SW(L).GT.XL)WFD=1.0
23200           IF (SW(L).GT.DUL(L)) WFD=1.0-((SW(L)-DUL(L))/(SAT(L)-DUL(L)))
23210           IF (WFD.LT.0.0) WFD=0.0
23220           TF=(ST(L)-5.0)/30.0
23230           IF (ST(L).LT.5.0) TF=0.0
23240           ELNC=AMIN1(TF,WFD,SANC)
23250           RP2=CNI(L)*EXP(2.302*ELNC)
23260           IF (RP2.LT.0.01) RP2=0.01
23270           IF (RP2.GT.1.0) RP2=1.0
23280           CNI(L)=RP2
23290           A=AMIN1(RP2,WFD,TF)
23300           RNTRF(L)=A*40.0*SNH4(L)/(SNH4(L)+90.0)
23310           SNH4(L)=SNH4(L)-RNTRF(L)
23320           SNO3(L)=SNO3(L)+RNTRF(L)
23330           SARNC=1.0-EXP(-0.1363*SNH4(L))
23340           XW=AMAX1(WFD,WFY(L))
23350           XT=AMAX1(TF,TFY(L))
23360           CNI(L)=CNI(L)*AMIN1(XW,XT,SARNC)
```

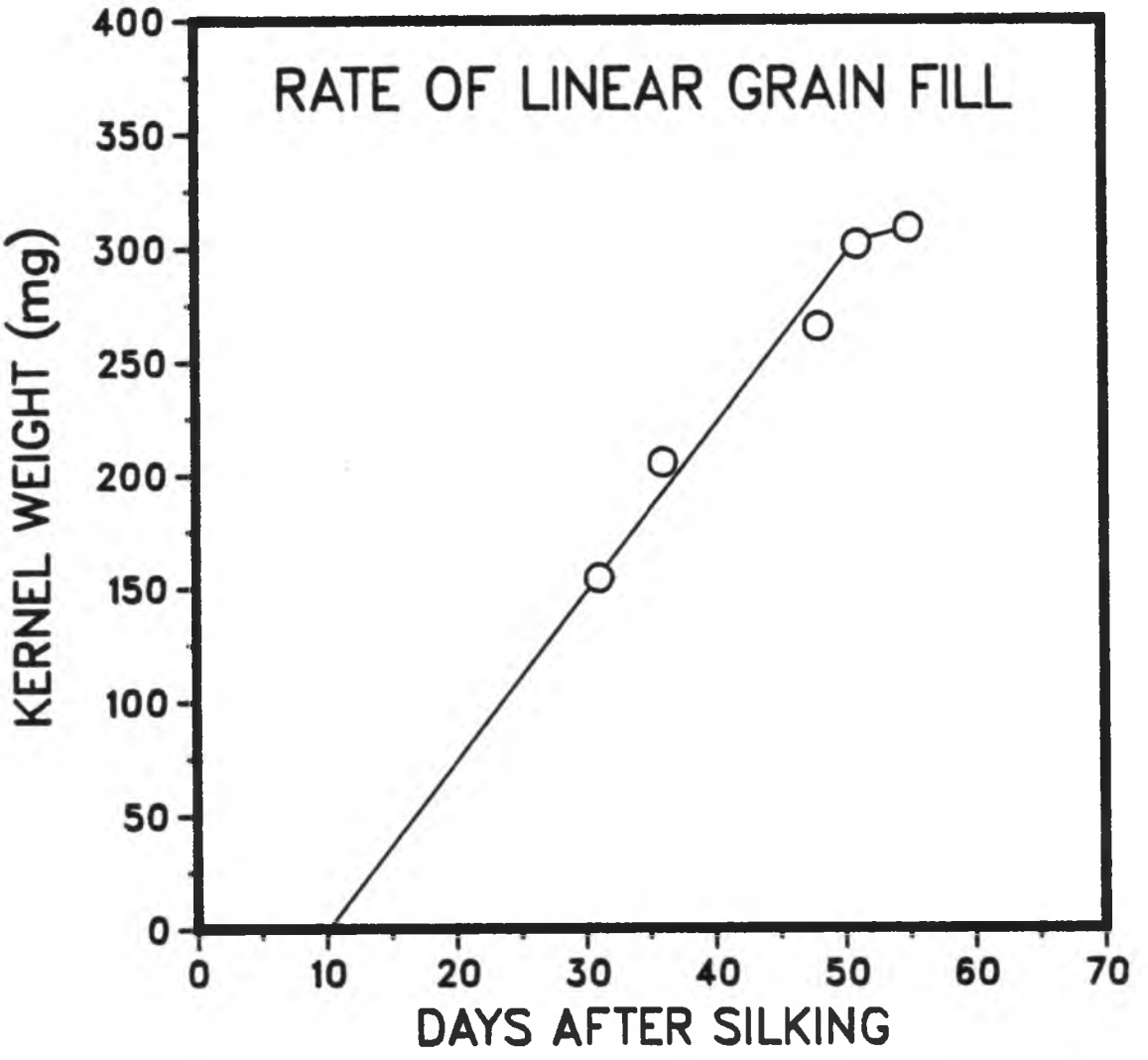
Appendix 3.1 (continued) Program listing of CERES maize model.

```
23370           IF (CNI(L).LE.0.01) CNI(L)=0.01
23380           WFY(L)=WFD
23390           TFY(L)=TF
23400 10      CONTINUE
23410         RETURN
23420         END
```

Appendix 3.2 Actual rates of nitrogen treatments in transfer experiments of the Benchmark Soils Project

Coded level	*Actual level (kg ha^{-1})
-.85	30
-.40	70
Opt.	108
+.40	144
+.85	190

*In some experiments the actual rate differed.



Appendix 3.3 Linear grain fill for the summer planting.

Appendix 4.1 Validation of simulated grain weights with observed weights on Tropeptic Eutrustox sites in Hawaii.

SITE		Coded N level (P, N)					
		Opt, 0	+.85, -.85	+.40, -.40	+.85, Opt	-.40, +.40	+.85, +.85
WAI-J84	Measured						0.284
	Simulated						0.284
WAI-F10	Measured		0.244	0.252	0.266	0.289	0.303
	Simulated		0.284	0.284	0.279	0.284	0.284
MOL-L10	Measured	0.251	0.251	0.267	0.251	0.267	0.267
	Simulated	0.289	0.261	0.244	0.255	0.264	0.264
MOL-M10	Measured	0.327	0.304	0.320	0.320	0.320	0.327
	Simulated	0.301	0.294	0.302	0.302	0.302	0.302
MOL-N10	Measured	0.246	0.244	0.268	0.268	0.268	0.268
	Simulated	0.301	0.301	0.301	0.301	0.301	0.301
MOL-N20	Measured	0.161	0.187	0.228	0.263	0.235	0.294
	Simulated	0.308	0.308	0.308	0.308	0.308	0.308

Appendix 4.2 Validation of simulated kernel numbers with observed kernel numbers on Tropeptic Eutrustox sites in Hawaii.

SITE		Coded N level (P, N)					
		Opt, 0	+.85, -.85	+.40, -.40	+.85, Opt	-.40, +.40	+.85, +.85
WAI-J84	Measured						570
	Simulated						564
WAI-F10	Measured		306	343	434	470	446
	Simulated		243	355	460	501	504
MOL-L10	Measured	290	382	400	429	460	482
	Simulated	274	365	467	497	498	498
MOL-M10	Measured	440	450	447	489	452	500
	Simulated	487	541	581	588	588	588
MOL-N10	Measured	380	410	410	460	440	516
	Simulated	294	357	436	472	481	481
MOL-N20	Measured	127	180	282	288	292	372
	Simulated	214	287	374	387	387	387

Appendix 4.3 Validation of simulated grain weights with observed weights on Typic Paleudults in Indonesia and Philippines.

SITE		Coded N level (P, N)					
		Opt, 0	+.85, -.85	+.40, -.40	+.85, Opt	-.40, +.40	+.85, +.85
NAK-L20	Measured	0.234	0.236	0.244	0.244	0.266	0.253
	Simulated	0.261	0.245	0.262	0.281	0.281	0.281
NAK-A30	Measured	0.215	0.215	0.224	0.235	0.260	0.250
	Simulated	0.225	0.199	0.215	0.240	0.248	0.248
NAK-D30	Measured	0.172	0.215	0.227	0.240	0.219	0.253
	Simulated	0.249	0.223	0.203	0.229	0.242	0.243
NAK-010	Measured	0.260	0.285	0.274	0.278	0.297	0.300
	Simulated	0.221	0.233	0.252	0.255	0.255	0.255
NAK-P10	Measured	0.266	0.242	0.264	0.264	0.274	0.267
	Simulated	0.221	0.233	0.252	0.255	0.255	0.255
BPMD-A30	Measured	0.238	0.245	0.229	0.244	0.244	0.247
	Simulated	0.262	0.255	0.245	0.255	0.264	0.270
BPMD-C20	Measured	0.239	0.270	0.286	0.286	0.300	0.293
	Simulated	0.262	0.255	0.245	0.255	0.264	0.270
BPMD-C30	Measured	0.231	0.229	0.251	0.237	0.264	0.292
	Simulated	0.266	0.245	0.229	0.264	0.269	0.269

Appendix 4.3 (continued) Validation of simulated grain weights with observed weights on Typic Paleudults in Indonesia and Philippines.

SITE		Coded N level (P, N)					
		Opt, 0	+.85, -.85	+.40, -.40	+.85, Opt	-.40, +.40	+.85, +.85
BPMD-C40	Measured	0.245	0.250	0.230	0.273	0.273	0.270
	Simulated	0.260	0.235	0.240	0.262	0.268	0.268
BPMD-D40	Measured	0.219	0.220	0.260	0.290	0.250	0.270
	Simulated	0.233	0.214	0.228	0.240	0.240	0.240
BUK-C30	Measured						0.310
	Simulated						0.289
BUK-H10	Measured						0.316
	Simulated						0.268
BUK-G10	Measured						0.302
	Simulated						0.264
BUK-E20	Measured						0.288
	Simulated						0.278
BUK-E10	Measured						0.293
	Simulated						0.210
BUK-D20	Measured						0.253
	Simulated						0.263
BUK-A30	Measured						0.242
	Simulated						0.263

Appendix 4.3 (continued) Validation of simulated grain weights with observed weights on Typic Paleudults in Indonesia and Philippines.

SITE		Coded N level (P, N)					
		Opt, 0	+.85, -.85	+.40, -.40	+.85, Opt	-.40, +.40	+.85, +.85
SOR-A20	Measured	0.230	0.236	0.236	0.252	0.265	0.272
	Simulated	0.261	0.237	0.229	0.255	0.263	0.263
SOR-A30	Measured	0.211	0.234	0.231	0.231	0.256	0.246
	Simulated	0.282	0.2696	0.245	0.226	0.245	0.265
SOR-B10	Measured	0.257	0.220	0.235	0.263	0.248	0.271
	Simulated	0.263	0.248	0.229	0.247	0.263	0.263
SOR-B20	Measured	0.235	0.237	0.240	0.270	0.272	0.277
	Simulated	0.263	0.237	0.218	0.234	0.256	0.271
SOR-E20	Measured	0.246	0.204	0.213	0.250	0.245	0.231
	Simulated	0.2867	0.286	0.286	0.286	0.286	0.286
SOR-F10	Measured	0.211	0.197	0.220	0.214	0.222	0.249
	Simulated	0.286	0.286	0.286	0.286	0.286	0.286
DAV-L10	Measured		0.204	0.214	0.261	0.248	0.260
	Simulated		0.239	0.246	0.269	0.280	0.284

Appendix 4.4 Validation of simulated kernels per ear with observed kernels per ear on Typic Paleudults in Indonesia and Philippines.

SITE		Coded N level (P, N)					
		Opt, 0	+.85, -.85	+.40, -.40	+.85, Opt	+.40, +.40	+.85, +.85
NAK-L20	Measured	356	392	439	471	451	480
	Simulated	340	429	464	465	465	465
NAK-A30	Measured	251	314	324	311	300	365
	Simulated	224	365	453	457	457	457
NAK-D30	Measured	210	293	382	380	400	370
	Simulated	192	307	452	468	469	468
NAK-010	Measured	330	411	380	434	405	480
	Simulated	511	547	547	548	548	548
NAK-P10	Measured	440	436	435	480	480	510
	Simulated	498	521	521	521	521	521
BPMD-A30	Measured	210	222	270	230	270	265
	Simulated	476	535	540	540	540	540
BPMD-C20	Measured	346	381	380	445	400	440
	Simulated	309	370	455	481	484	484
BPMD-C30	Measured	138	245	309	399	400	375
	Simulated	173	290	420	433	434	434

Appendix 4.4 (continued) Validation of simulated kernels per ear with observed kernels per ear on Typic Paleudults in Indonesia and Philippines.

SITE		Coded N level (P, N)					
		Opt, 0	+.85, -.85	+.40, -.40	+.85, Opt	+.40, +.40	+.85, +.85
BPMD-C40	Simulated	268	368	442	448	448	448
BPMD-D40	Measured	380	412	468	460	490	463
	Simulated	356	456	497	497	497	496
BUK-C30	Measured						401
	Simulated						416
BUK-H10	Measured						428
	Simulated						490
BUK-G10	Measured						450
	Simulated						454
BUK-E20	Measured						410
	Simulated						446
BUK-E10	Measured						430
	Simulated						616
BUK-D20	Measured						370
	Simulated						415
BUK-A30	Measured						368
	Simulated						415

Appendix 4.4 (continued) Validation of simulated kernels per ear with observed kernels per ear on Typic Paleudults in Indonesia and Philippines.

SITE		Coded N level (P, N)					
		Opt, 0	+.85, -.85	+.40, -.40	+.85, Opt	+.40, +.40	+.85, +.85
SOR-A20							
	Simulated	221	332	439	459	460	460
SOR-B10	Measured	187	233	326	370	381	420
	Simulated	193	292	421	458	460	460
SOR-E20	Measured	150	268	275	291	282	315
	Simulated	170	238	310	314	314	314
SOR-F10	Measured	174	328	317	360	345	375
	Simulated	170	238	310	314	314	314
DAV-L10	Measured		433	420	459	484	474
	Simulated		388	456	461	461	461

Appendix 4.5 Validation of simulated kernel weights with observed weights on Hydric Dystrandept sites in Indonesia, Philippines, and Hawaii.

SITE		Coded N level (P, N)					
		Opt, 0	+.85, -.85	+.40, -.40	+.85, Opt	+.40, +.40	+.85, +.85
LPHS-D30	Measured		0.250	0.241	0.266	0.249	0.259
	Simulated		0.277	0.277	0.277	0.277	0.277
LPHS-G20	Measured	0.235	0.243	0.247	0.256	0.244	0.2553
	Simulated	0.292	0.292	0.292	0.292	0.292	0.293
PUC-K20	Measured		0.251	0.272	0.272	0.239	0.258
	Simulated		0.244	0.255	0.292	0.308	0.305
PUC-Q40	Measured	0.255	0.261	0.243	0.260	0.270	0.301
	Simulated	0.273	0.249	0.232	0.250	0.273	0.280
PUC-Q50	Measured	0.238	0.238	0.248	0.244	0.250	0.253
	Simulated	0.292	0.284	0.258	0.267	0.292	0.292
PUC-R40	Measured	0.226	0.240	0.240	0.267	0.252	0.233
	Simulated	0.274	0.246	0.243	0.276	0.292	0.297
PUC-S20	Measured	0.262	0.242	0.249	0.287	0.284	0.297
	Simulated	0.279	0.275	0.249	0.268	0.288	0.290
PUC-S30	Measured	0.218	0.221	0.250	0.260	0.257	0.269
	Simulated	0.292	0.246	0.221	0.234	0.256	0.270
PUC-T10	Measured	0.248	0.246	0.280	0.270	0.300	0.280
	Simulated	0.241	0.225	0.245	0.259	0.263	0.263

Appendix 4.5 (continued) Validation of simulated kernel weights with observed weights on Hydric Dystrandept sites in Indonesia, Philippines, and Hawaii.

		Coded level (P, N)					
SITE		Opt, 0	+.85, −.85	+.40, −.40	+.85, Opt	+.40, +.40	+.85, +.85
PAL-D40	Measured	0.220	0.240	0.243	0.259	0.236	0.270
	Simulated	0.208	0.217	0.241	0.255	0.259	0.259
PAL-F20	Measured	0.248	0.275	0.276	0.300	0.300	0.300
	Simulated	0.252	0.235	0.252	0.267	0.267	0.267
PAL-F30	Measured	0.249	0.240	0.261	0.276	0.264	0.281
	Simulated	0.249	0.228	0.258	0.270	0.280	0.280
PAL-F40	Measured	0.250	0.242	0.262	0.260	0.300	0.300
	Simulated	0.249	0.236	0.252	0.258	0.258	0.258
PAL-G30	Measured	0.218	0.240	0.260	0.270	0.280	0.280
	Simulated	0.218	0.198	0.226	0.246	0.254	0.254
BUR-E20	Measured	0.261	0.267	0.280	0.270	0.310	0.292
	Simulated	0.254	0.242	0.262	0.277	0.280	0.280
IOLE-E10	Measured		0.287	0.287	0.283	0.272	0.305
	Simulated		0.314	0.303	0.311	0.314	0.314
IOLE-I10	Measured		0.251	0.247	0.246	0.253	0.280
	Simulated		0.329	0.329	0.294	0.318	0.329
KUK-D11	Measured		0.284	0.305	0.300	0.297	0.293
	Simulated		0.309	0.300	0.309	0.309	0.309
KUK-D20	Measured		0.273	0.269	0.268	0.306	0.292
	Simulated		0.310	0.320	0.314	0.314	0.314

Appendix 4.6 Validation of simulated kernels per ear with observed numbers on Hydric Dystrandept sites in Indonesia, Philippines, and Hawaii.

SITE		Coded N level(P, N)					
		Opt, 0	+.85, -.85	+.40, -.40	+.85, Opt	+.40, +.40	+.85, +.85
LPHS-G20	Measured	210	250	322	334	305	361
	Simulated	167	231	312	391	403	403
PUC-K20	Measured	-	304	306	340	385	367
	Simulated	-	334	374	374	374	386
PUC-Q40	Measured	183	298	375	390	408	367
	Simulated	207	302	425	461	462	462
PUC-S20	Measured	211	220	391	406	372	428
	Simulated	200	278	396	430	431	428
PUC-S30	Measured	200	300	380	415	402	440
	Simulated	217	315	458	502	502	502
PUC-T10	Measured	455	512	487	506	478	550
	Simulated	447	544	573	573	573	573
PAL-D40	Measured	307	344	336	373	391	354
	Simulated	356	390	395	395	395	395
PAL-F20	Measured	353	356	340	361	350	369
	Simulated	367	450	477	477	477	477

Appendix 4.6 (continued) Validation of simulated kernels per ear with observed numbers on Hydric Dystrandept sites in Indonesia, Philippines, and Hawaii.

SITE		Coded N level (P, N)					
		Opt, 0	+.85, -.85	+.40, -.40	+.85, Opt	+.40, +.40	+.85, +.85
PAL-F30							
	Simulated	275	371	393	393	393	393
PAL-F40	Measured	313	378	390	449	358	405
	Simulated	350	438	465	465	465	465
PAL-G30	Measured	275	347	342	362	372	364
	Simulated	309	424	452	452	452	452
BUR-E20	Measured	302	370	382	445	360	400
	Simulated	389	469	487	487	487	487
IOLE-E10	Measured		318	355	367	348	372
	Simulated		256	362	400	404	404
IOLE-I10	Measured		190	241	356	370	344
	Simulated		156	269	389	415	415
KUK-D11	Measured		323	367	405	413	422
	Simulated		329	447	454	454	454
KUK-D20	Measured		296	374	423	376	440
	Simulated		250	349	406	408	408

Appendix 4.7 Comparison of simulated and observed grain yields (kg ha^{-1}) under different population densities over nine bimonthly plantings.

MONTH		Population Density (1,000 plants ha^{-1})					
		50	75	100	125	150	200
JAN 1980	Measured[a]	7940	8680	8840	9330	9750	8840
	Simulated	9561	10081	10595	11016	11028	6885
MAR 1980	Measured	10010	11150	12960	14100	15090	14200
	Simulated	10496	11209	11663	11969	12217	12337
MAY 1980	Measured	8470	9510	9890	12370	10370	8620
	Simulated	10545	11199	11610	11775	11926	12162
JULY 1980	Measured	9260	10070	10100	11220	11060	9390
	Simulated	9219	9767	9831	9904	9959	10040
SEPT 1980*	Measured	4330	4080	4520	3420	2870	2820
	Simulated	5918	6404	6764	6944	3876	3625
NOV 1980*	Measured	2310	2620	2370	2430	2340	2090
	Simulated	6128	6581	7031	7276	4211	3915
JAN 1981	Measured	6110	6150	6410	6300	6590	5590
	Simulated	8072	8437	8620	8766	8891	9120
MAR 1981	Measured	7500	8440	8270	10910	12490	11820
	Simulated	9036	9224	9379	9483	9568	9630
MAY 1981	Measured	10220	10340	11410	12570	12320	10320
	Simulated	10379	11030	11168	11261	11320	11390

* Severe lodging encountered.
[a] Source: Lee (1983).

Appendix 5.1 Sample Calculation.

Carrier Method

$$E = x(S_i/S_t - 1) \qquad (2.9)$$

Initial activity of the sample: 1000 m Ci/m mol = 30.3 m Ci/mg P

$$= 30.3 \frac{mCi}{mgP} * 10^3 \frac{mCi}{mCi} * 2.22 \times 10^6 \frac{cpm}{mCi}$$

$$= 6.6 \times 10^{10} \text{ cpm/mg P}$$

And x = 30 mg P/kg soil

For 5 mCi ^{33}P and 150 mg P (amount P added to 3g soil):

$$S_i = \frac{(5 * 2.22 * 10^6) \text{ cpm/mg}}{(150 \text{ mg P} * 10^{-3}) \text{ mg/mg}}$$

$$= 7.4 \times 10^7 \text{ cpm/mg P}$$

Note: Amount of P contributed by radioisotope is less than 1 mg P, therefore is insignificant.

Date of experiment: 2 days after assay date.

Half-life of ^{33}P = 25.4 d

Therefore S_i on day 2 is:

$$= 7.40 \times 10^7 \text{ cpm/mg P } (\exp -[\frac{0.693 \times 2}{25.4}])$$

$$= 7.01 \times 10^7 \text{ cpm/mg P}$$

The specific activity of the equilibrium solution is determined from the actual counts at time and amount of P in solution by colorimetric method:

Actual count in 0.5 ml sample = 10214 cpm

Therefore the total count at t = (10214 x 30 ml/0.5ml) cpm

However the instrument efficiency = 85.26%

Appendix 5.1 (continued) Sample Calculation.

Therefore the total corrected total count = (10214 x 30/0.5)/0.8526

$= 7.188 \times 10^5$ cpm

Amount of P in solution (Ascorbic acid method) = 0.390 mg P/ml

Therefore $S_t = 7.188 \times 10^5$ cpm/(0.390 mg P/ml x 30 ml x 10^{-3})

$= 6.144 \times 10^7$ cpm

Substituting in Eq. (2.9):

$E = 300$ mg P/kg $(7.01 \times 10^7/6.144 \times 10^7 - 1)$

= 4.22 mg P/kg soil

Inverse Dilution Method

$$E = x[S_t/(S - S_t] \qquad (2.12)$$

Initial specific activity of the sample (stock) = 30.3 mCi/mg P

$= 6.6 \times 10^{10}$ cpm/mg P

S on day six of equilibration is determined from actual activity of ^{33}P and P in solution:

Total corrected count = (actual count x dilution factor)/efficiency

$= 2.524 \times (30/0.5)/0.8526$

$= 1.776 \times 10^5$ cpm

And P in solution = 0.04 mg P/l

$S = 1.776 \times 10^5/(0.04$ mg/ml x 30ml x 10^{-3}mg/mg)

$= 1.48 \times 10^8$ cpm

Amount of inactive carrier (x) added on day 6 = 50 mg P/kg soil. S_t, final specific activity determined after 24 hours of equilibration.

Appendix 5.1 (continued) Sample Calculation.

Total count = actual count x dilution factor x decay factor/efficiency

(The decay factor corrects for the decay that took place on day 7)

Decay factor = [exp - (0.693 x 6/25.4)]/[exp -(0.693 x 7/2555.4)]

= 1.0277

Total count = 450.2 x (30/0.5) x 1.0277/0.852

= 3.258×10^4 cpm

And P in solution = 0.10 mg P/l

$S_t = (3.258 \times 10^4)$ cpm/$(0.10 \times 31 \times 10^{-3})$ mg P

= 1.051 cpm/mg P

Substituting in Eq. (2.12):

$E = 50[1.051 \times 10^7/(1.48 \times 10^8 - 1.051 \times 10^7)]$ mg P/kg soil

= 3.82 mg P/kg soil.

Appendix 5.2 Number of observations, mean, range and standard deviation for soil test P and other soil properties in slightly weathered soils.

Soil property	Number of observations	Mean	Minimum	Maximum	Standard deviation
Soil P methods (mg/kg)					
Mod. Truog P	120	34.4	0.2	770.8	83.9
Bray I P	120	5.5	0.04	203.6	18.8
Olsen P	120	10.7	0.12	375.8	35.4
Double Acid P	120	3.4	0.01	81.5	9.6
Hydroxide-carb P	120	186.6	2.1	2129.3	335.2
Chloride-sulfate resin P	120	14.4	0.30	255.6	29.4
Chloride resin P	13	54.2	0.08	170.8	42.2
Isotope carrier P	69	15.0	0.06	324.9	40.9
Solution P	68	1.63	0.02	45.0	5.72
0.5 N H_2SO_4 P	120	219.1	12.4	4034.3	273.9
Organic P (mg kg^{-1})	120	242.1	3.8	1302.0	199.4
P Availability (kg/1)	76	0.0014	0.000039	0.022	0.0032
Buffering Capacity (1 kg^{-1})	76	4166	45	25210	4831
P sorption (mg kg^{-1}) at:					
0.02 mg P 1^{-1}	71	150	-150	715	153.6
0.10 mg P 1^{-1}	75	389.5	2.0	2000	385.7
Clay (%)	120	43.9[a]	3.3	76.9	28.1
pH	120	5.8	4.0	8.7	0.9
pH (KCl)	71	4.6	3.5	6.3	0.7
Organic C (%)	120	1.9	0.06	16.2	2.3

Appendix 5.2 (continued) Number of observations, mean, range and standard deviation for soil test P and other soil properties in slightly weathered soils.

Soil property	Number of observation	Mean	Min	Max	Standard deviation
Total N (%)	110	0.18	0.01	1.38	0.21
CEC ($cmol(+)kg^{-1}$)	117	25.9	2.4	99.7	21.1
CEC($cmol_{(+)}$ $kg\ clay^{-1}$)	117	72.2	12.0	585.0	78.6
Base Saturation (%)	117	61.8	2.0	100.0	27.8
Exchangeable bases ($cmol_{(+)}\ kg^{-1}$)					
Ca	120	11.1	0.06	47.8	12.3
Mg	120	6.8	0.08	45.2	9.7
K	120	0.53	0.0	5.8	0.8
Na	120	0.73	0.0	11.50	1.6
Ex. Al ($cmol\ (+)\ kg^{-1}$)	120	0.61	0.0	7.20	1.2
ECEC ($cmol\ (+)\ kg^{-1}$)	120	20.0	0.5	104.4	22.0
Al Saturation (%)	120	7.6	0	90.3	16.0
Dith. Cit. extr. Fe (%)	88	4.4	0.10	19.0	3.3
Oxalate extr. Fe (%)	39	0.63	0.0	2.30	2.3
Phosphate retention (%)	71	49.7	0.00	99.0	23.1
Lime required ($kg\ ha^{-1}$)	120	0.68	0	8.1	1.4

a. Log transformed mean re-expressed in terms of the original data using Equations (5.4 and 5.5) (Haan, 1977).

Appendix 5.3 Number of observations, mean, range and standard deviation for soil test P and other soil properties in highly weathered soils.

Soil property	Number of observations	Mean	Minimum	Maximum	Standard deviation
Soil P methods (mg/kg)					
Mod. Truog P	70	14.1	0.2	41.3	11.4
Modified Bray P	70	4.3	0.06	15.6	4.3
Olsen P	70	5.9	0.10	16.3	5.0
Double Acid P	70	2.3	0.01	7.3	2.2
Hydroxide-carb P	70	152.3	8.8	620.6	124.4
Chloride-sulfate resin P	70	11.3	0.10	41.6	13.1
Isotope carrier P	44	4.3	0.06	14.4	3.9
0.5 N H_2SO_4	70	107.8	7.09	278.2	71.6
Organic P (mg kg^{-1})	70	190.7	49.8	399.7	87.4
P Availability (kg l^{-1})	17	0.0004	0.00005	0.00086	0.00026
P Buffering Capacity (l kg^{-1})	17	5108	1163	20105	5033
P sorption (mg kg^{-1}) at:					
0.02 mg P l^{-1}	15	194	20	685	210
0.10 mg P l^{-1}	15	439.0	118.0	1300.0	349.0
Clay (%)	30	69.6[a]	27.0	88.7	23.6
pH	30	5.2	3.8	6.5	0.5
pH (KCl)	16	4.3	3.6	5.8	0.7
Organic C (%)	30	1.3	0.18	4.6	1.2
Total N (%)	30	0.11	0.02	0.24	0.08

Appendix 5.3 (continued) Number of observations, mean, range and variance for soil properties in highly weathered soils.

Soil property	Number of observation	Mean	Min	Max	Standard deviation
CEC ($cmol(+)kg^{-1}$)	30	9.8	3.7	20.7	4.1
CEC($cmol(+)_{-1}$ $kg\ clay^{-1}$)	30	14.9	5.1	30.4	6.9
Base Saturation (%)	30	33.7	1.0	87.0	30.0
Exchangeable bases ($cmol_{(+)}\ kg^{-1}$)					
Ca	30	1.6	0.0	5.0	1.7
Mg	30	0.91	0.0	3.4	1.2
K	30	0.19	0.0	1.62	0.31
Na	30	0.17	0.0	0.50	0.14
Ex. Al ($cmol\ (+)\ kg^{-1}$)	30	1.1	0.00	4.4	1.1
ECEC ($cmol(+)\ kg^{-1}$)	30	4.1	0.30	10.1	2.5
Al Saturation (%)	30	38.7	0.0	91.7	36.6
Dith. Cit. extr. Fe (%)	26	8.3	2.9	33.0	7.6
Lime required ($kg\ ha^{-1}$)	30	1.2	0	5.0	1.3

a. Log transformed mean re-expressed in terms of the original data using Equations (5.4 and 5.5) (Haan, 1977).

Appendix 5.4 Number of observations, mean, range and standard deviation for soil test P and other soil properties in Andisols.

Soil property	Number of observations	Mean	Minimum	Maximum	Standard deviation
Soil P methods (mg/kg)					
Mod. Truog P	21	47.6	4.8	279.7	62.8
Bray I P	21	4.9	0.18	23.0	5.3
Olsen P	21	10.4	1.1	50.7	12.2
Double Acid P	21	1.2	0.04	7.9	1.8
Hydroxide P	21	1325.1	245.3	3626.9	901.7
Chloride-sulfate resin P	21	12.1	0.10	74.3	17.2
Chloride resin P	8	14.4	0.29	61.1	19.7
Isotope carrier P	11	11.3	1.80	26.8	7.8
Solution P	7	0.73	0.10	1.96	0.68
0.5 N H_2SO_4 P	21	680.8	211.9	1524.8	394.1
Organic P (mg kg^{-1})	21	868.1	228.8	1983.2	440.9
P Availability ($kg\ l^{-1}$)	21	0.0001	0.00003	0.0004	0.00009
P Buffering Capacity ($l\ kg^{-1}$)	15	16528	2706	38340	10849
P sorption ($mg\ kg^{-1}$) at:					
0.02 mg P l^{-1}	15	464	20	1065	285
0.10 mg P l^{-1}	15	1111.0	250.0	2320.0	511
pH	21	5.8	5.1	6.9	0.6
pH (KCl)	13	5.2	4.3	6.0	0.5
Organic C	19	8.7	2.7	14.4	3.4

Appendix 5.4 (continued) Number of observations, mean, range and standard deviation for soil test P and other soil properties in Andisols.

Soil property	Number of observation	Mean	Min	Max	Standard deviation
Total N (%)	19	0.73	0.23	1.81	0.3
CEC (cmol(+)kg^{-1})	17	25.9	2.4	99.7	21.1
Base Saturation (%)	17	32.6	5.0	76.0	23.8
Exchangeable bases ($cmol_{(+)}$ kg^{-1})					
Ca	21	14.8	1.6	36.3	14.8
Mg	21	3.8	0.30	8.6	3.0
K	21	0.73	0.0	4.2	0.9
Na	21	0.39	0.10	1.51	0.7
Ex. Al ($cmol_{(+)}$ kg^{-1})	21	0.35	0.0	1.9	0.08
ECEC ($cmol_{(+)}$ kg^{-1})	21	25.1	2.4	44.8	17.3
Al Saturation (%)	21	6.7	0	34.5	12.0
Dith. Cit. extr. Fe (%)	17	9.6	89.0	100.0	5.1
Oxalate extr. Fe (%)	11	3.4	1.8	5.7	1.3
Phosphate retention (%)	12	96.2	89.0	100.0	4.5
Lime required (kg ha^{-1})	21	0.4	0	2.1	0.7

[a] Log transformed mean re-expressed in terms of the original data using Equations (5.4 and 5.5) (Haan, 1977).

Appendix 5.5 Number of observations, mean, range and standard deviation for soil test P and other soil properties in calcareous soils.

Soil property	Number of observations	Mean	Minimum	Maximum	Standard deviation
Soil P methods (mg/kg^{-1})					
Mod. Truog P	22	77.4	11.0	294.1	74.7
Bray I P	22	1.8	0.02	9.6	3.0
Olsen P	22	3.4	0.42	10.4	2.8
Double Acid P	22	1.3	0.05	5.84	1.4
Hydroxide Carbonate P	22	40.9	2.4	549.1	114
Chloride-sulfate resin P	22	5.1	0.20	29.2	7.3
Isotope carrier P	7	3.7	1.20	6.8	1.7
Solution P	10	0.92	0.21	4.7	1.4
0.5 N H_2SO_4 P					
Organic P($mg\ kg^{-1}$	22	110.4	1.4	239.7	76.0
P Availability ($kg/1^{-1}$)	9	0.0033	0.00089	0.0125	0.003
P Buffering Capacity ($1\ kg^{-1}$)	9	548	80	1123	334
P sorption ($mg\ kg^{-1}$) at:					
0.02 mg P 1^{-1}	9	17.8	5	45	12.5
0.10 mg P 1^{-1}	9	68.3	45.0	90.0	18
pH	22	8.1	7.4	9.3	0.57
Clay (%)	22	38.5	21.4	77.4	30.9
$CaCO_3$ (%)	22	25.0	0	61.0	23.2
Organic C (%)	22	0.64	0.16	1.99	0.40

Appendix 5.5 (continued) Number of observations, mean, range and standard deviation for soil test P and other soil properties in calcareous soils.

Soil Property	Number of Observation	Mean	Min	Max	Standard Deviation
Total N (%)	22	0.05	0.01	0.16	0.04
CEC (cmol(+) kg^{-1})	22	41.8	3.9	100.6	38.6
CEC(cmol (+) $kg\ clay^{-1}$)	22	84.6	13.2	196.1	62.1
Exchangeable bases (cmol(+) kg^{-1})					
Mg	22	16.1	2.9	38.0	12.4
K	22	1.02	0.10	2.8	1.00
Na	22	9.8	0.30	23.6	7.4
Dith. Cit. extr. Fe (%)	9	1.4	0.0	1.7	0.32

[a] Log transformed mean and standard deviation re-expressed in terms of the original data using Equations (5.4 and 5.5) (Haan, 1977).

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