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

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I dedicate this work to my parents.
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-specific. 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 Eutrudeptox 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.
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
AERIAL ENVIRONMENT

CONTROL INPUTS

fertilizers
herbicides
pesticides
irrigation etc

transpiration
respiration
cO₂ fixation
daylight etc

MANAGEMENT

genotype
tillage

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 nonexistent.

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 random 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 (Tschesche 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 et al., 1974;
Coligado and Brown, 1975b) or the sensitivity to photoperiod remain
unaltered by temperature (Warrington and Kanemasu, 1983b; Stevenson and
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.

\[ Y = \frac{MT}{E_0} \]  

(2.1)

where \( Y \) = crop yield, \( T \) = transpiration, \( E_0 \) = 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:
\[ ET = K_c \cdot ET_m \]  \hspace{1cm} (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):

\[ ET_m = a \frac{s}{s+g} R_n \]  \hspace{1cm} (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 (Center and Camper, 1973). Therefore, the yield of individual plants is reduced resulting in a lower harvest index with increasing population density (Center 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 efficiency (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 NH3 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 NO₃⁻ and NH₄⁺-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 \( P_{\text{soil}} \), rate \( k_1/k_2 \), intensity \( P_{\text{solution}} \), 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 (Dalai 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 CaCl₂ 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):

\[
\begin{align*}
\text{rapid} & \quad \text{soil solution P} & \quad \text{labile P} & \quad \text{nonlabile P} & \quad \text{fixed P} \\
\text{slow} & \quad \text{solution P} & \quad \text{labile P} & \quad \text{nonlabile P} & \quad \text{fixed P}
\end{align*}
\]

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 concentrations (<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 CaCO₃.

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 ³²P 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, ³²P, 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.

\[ \text{3}^{1}\text{P}_{\text{surface}} + \text{3}^{2}\text{P}_{\text{solution}} \rightleftharpoons \text{3}^{2}\text{P}_{\text{surface}} + \text{3}^{1}\text{P}_{\text{solution}} \]  \hspace{1cm} (2.4)

Thus:

\[ \frac{\text{3}^{2}\text{P}_{\text{surface}}}{\text{3}^{1}\text{P}_{\text{surface}}} = \frac{\text{3}^{2}\text{P}_{\text{solution}}}{\text{3}^{1}\text{P}_{\text{solution}}} \]  \hspace{1cm} (2.5)

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

\[ \text{3}^{1}\text{P}_{\text{surface}} = \text{3}^{2}\text{P}_{\text{surface}} \times \frac{\text{3}^{1}\text{P}_{\text{solution}}}{\text{3}^{2}\text{P}_{\text{solution}}} \]  \hspace{1cm} (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 \(^{32}\text{P}\) - labelled orthophosphate, assuming that the phosphate ions in solution exchange with the solid phase phosphate and \(^{32}\text{P}\) becomes diluted throughout the total exchangeable pool in the soil. The fundamental equation for isotopic dilution is:

\[ \frac{y}{(E+x)} = \frac{y_{t}}{x_{t}} \]  \hspace{1cm} (2.7)

Here \(y\) = amount of \(^{32}\text{P}\) added per g of soil; \(x\) = amount of carrier \(^{32}\text{P}\) added with the \(^{32}\text{P}\) (per g soil); \(y_{t}\), \(x_{t}\) = amount of \(^{32}\text{P}\) and \(^{31}\text{P}\) 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:

\[ E = \frac{y_{t}x_{t}}{y_{t}} - x \]  \hspace{1cm} (2.8)
Identical expression:

\[ E = x \left( \frac{S_i}{S_t} - 1 \right) \]  \hspace{1cm} (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 \(^{32}\text{P}\) is used for measurement of labile \( P \), then Equation (2.8) reduces to:

\[ E = \frac{x_t}{y_t} = \frac{y}{S_t} = \frac{x_t}{f} \]  \hspace{1cm} (2.10)

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

However, the radioactive \(^{32}\text{P}\) cannot clearly distinguish between labile and nonlabile \( P \) and if the \(^{32}\text{P}\) 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 \(^{32}\text{P}\) 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 $^{31}\text{P}$, 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 $^{32}\text{P}$ 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:

$$ (E + x)S_t = ES \quad (2.11) $$

or

$$ E = x \frac{S_t}{S - S_t} \quad (2.12) $$

where S and $S_t$ are specific activities before and after equilibration with inactive P. The very small quantity of $^{32}\text{P}$ 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 $^{32}\text{P}$ 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
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 CaCO₃ 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 CaF₂ and therefore P present in soils as CaHPO₄ is extracted (Thomas and Peasley, 1973). F ions cannot extract P from basic Ca-P and Fe-P unless F solution is acidified. NaHCO₃ 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 -H₂O 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 negligibly small 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 hysteresis 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 the residual 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, erosion 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:

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

(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:

$$X_{opt} = \ln \left[ \frac{ABCy}{P_x(1+R-V)} \right] / C$$

(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 given 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:

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

(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):

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

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

$$\text{Y} = A[1 - \exp(-C(X+N+bT))]$$  
(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 Jones 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 concentrations 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).

\section*{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:

\begin{equation}
Y_p = b_0 + b_1N + b_2N^2 + b_3P + b_4P^2 + b_5PN
\end{equation}  \hspace{1cm} (2.18)

\begin{itemize}
\item $Y_p =$ predicted maize yield
\item $b_0 =$ intercept (estimated yield when $P$ and $N$ are both zero in coded values)
\item $b_1, b_2, \ldots, b_n =$ partial regression coefficients
\item $N =$ coded value of nitrogen differential
\item $P =$ coded value of phosphorus differential
\end{itemize}

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.

\section*{Non-site specific equation}

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

\begin{equation}
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
\end{equation}  \hspace{1cm} (2.19)
where, $N\text{ext} =$ KCl extractable soil nitrogen,

$P\text{ext} =$ 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-specificity. 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 objective 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 MgSO₄, 15 kg Zn/ha as ZnSO₄, 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.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Date</th>
<th>Implement</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tillage</td>
<td>11/10/83</td>
<td>Rake</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>11/16-17/83</td>
<td>Roto-till</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>11/28/83</td>
<td>Rake</td>
<td>-</td>
</tr>
<tr>
<td>Fertilizer</td>
<td>11/29/83</td>
<td>Roto-till</td>
<td>Urea, blanket treatment broadcast.</td>
</tr>
<tr>
<td></td>
<td>01/06/84</td>
<td>-</td>
<td>Urea-banded</td>
</tr>
<tr>
<td></td>
<td>01/31/84</td>
<td>-</td>
<td>Urea-banded</td>
</tr>
<tr>
<td>Insecticides</td>
<td>As necessary</td>
<td>Sevin, diazinon</td>
<td></td>
</tr>
<tr>
<td>Fungicides</td>
<td>-do-</td>
<td>Diathine Z7A</td>
<td></td>
</tr>
<tr>
<td>Herbicides</td>
<td>-do-</td>
<td>Lasso-attrex</td>
<td></td>
</tr>
</tbody>
</table>
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 \( \text{NH}_4^+ \) and \( \text{NO}_3^- \) 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 (°C)
Daily minimum temperature (°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, (°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, (°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, PRINT, (°C day)
Table 3.2  (continued) Input data needed for maize growth and development using CERES maize N version.

<table>
<thead>
<tr>
<th>SOIL DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of layers</td>
</tr>
<tr>
<td>Depth of layers (cm)</td>
</tr>
<tr>
<td>Soil albedo</td>
</tr>
<tr>
<td>Soil water by layer: initial soil water content (cm³ cm⁻³)</td>
</tr>
<tr>
<td>: saturated soil water content (cm³ cm⁻³)</td>
</tr>
<tr>
<td>: drained upper limit of soil water (cm³ cm⁻³)</td>
</tr>
<tr>
<td>: lower limit of extractable soil water (cm³ cm⁻³)</td>
</tr>
<tr>
<td>: root preference factor (Unit less 0-1)</td>
</tr>
<tr>
<td>Runoff curve number</td>
</tr>
<tr>
<td>Upper limit of stage 1 soil evaporation (mm)</td>
</tr>
<tr>
<td>Profile drainage rate constant (1 day⁻¹)</td>
</tr>
<tr>
<td>Soil Nitrogen by layer: initial NO₃⁻ and NH₄⁺ content (mg kg⁻¹)</td>
</tr>
<tr>
<td>: Organic carbon (%)</td>
</tr>
<tr>
<td>: bulk density (g cm⁻³)</td>
</tr>
<tr>
<td>: pH</td>
</tr>
<tr>
<td>C:N in roots and in straw</td>
</tr>
<tr>
<td>Amount of straw incorporated (kg/ha) and depth of incorporation (cm)</td>
</tr>
<tr>
<td>Temperature amplitude for the growing period (°C)</td>
</tr>
<tr>
<td>Mean temperature for the growing period (°C)</td>
</tr>
<tr>
<td>N mineralization factor, DMOD</td>
</tr>
</tbody>
</table>
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.

\(^1\) 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., 1983a). 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 \( \text{cm}^3 \text{ cm}^{-1} \text{ day}^{-1} \), 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):

\[
RWU = \frac{4\pi \times K(0) \times (U_r - U_s)}{\ln(c^2/r^2)}
\]

Using the assumptions: \( r=0.02 \text{ mm} \), difference between water potential at root surface and water potential at bulk soil = 21 cm water, \( c=(\pi \times RLV)^{-1/2} \) 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):

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

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):

\[
HUM(I) = OC(I) \times 1000 \times BD(I) \times DLAYR(I)/0.4
\]
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 $OC(I) \times BD(I) \times DLAYR(I)$ 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):

$$NHUM(I) = \frac{OC(I)}{10} \times DLAYR(I) \times BD(I) \times 1000 - [NO3(I) + SNH4(I)]$$

where factor 10 converts organic C (kg/ha) to total soil N (kg/ha), assuming C:N of 10, and $SN03(I)$ 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):

$$DECR(I) = RDECR \times TFAC \times MF \times CNRF$$

$RDECR$ 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).

\[ ST_t = \frac{\left( ST_{t-1} + TP + DTDT + DTDZ \times ZZ \right)}{2.0} \]

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):

\[ GRNOM = DECR(I) \times FON(I) \]
The rate of mineralization of N from stable organic matter (RHMIN) is computed as (line 17630):

\[ RHMIN = NHUM(I) \times DMINR \times TFAC \times MF \]

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 variability. 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):

\[ NHUM(I) = NHUM(I) - RHMIN + 0.2 \times GRNOM \]

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):

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

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):

\[ NNOM(I) = 0.8 \times GRNOM + RHMIN - RNAC \]
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 SNH₄ 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):

\[ CNI(L) = CNI(L) \times \exp (2.302 \times ELNC) \]

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):

\[ RNTRF(L) = A \times 40.0 \times SNH4(L)/[SNH4(L) \times 90.0] \]
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):

\[ \text{CNI} = \text{CNI} \times \text{AMINL}(\text{XW}, \text{XT}, \text{SARNC}) \]

**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):

\[ \text{RNFAC}(L) = 1.0 - [1.17 \times \exp(-0.20 \times \text{TOTN})] \]

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):

\[ \text{TNDEM} = \text{STOVWT} \times (\text{TCNP} - \text{TANC}) + \text{DNG} \]
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 nitrogen 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):

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

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):

$$RNO3U(L) = (RWU(L)/[SW(L) \times DLAYR(L)]) \times SNO3(L)$$
where RWU(L) is root water uptake as calculated in WATBAL subroutine (line 7050). RWU(L) divided by total soil water in a layer \([SW(L) \times DLAYR(L)]\) 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 \((SN03(L))\) 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, \(UN03\), and ammonium, \(UNH4\), from a layer in the root zone are computed as (lines 19380 - 19390):

\[
UN03 = RNO3U(L) \times NUF \\
UNH4 = RNH4U(L) \times NUF
\]

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):

\[ NFAC = 1.0 - \frac{TCNP - TANC}{TCNP - TMNC} \]

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, SN03(L), is dissolved in all of the water in the layer before drainage occurs:

\[ [SW(L) \times DLAYR(L) + FLUX(L)] \]
Thus, the amount of nitrate leached is calculated as (line 19820):

\[ NOUT = \frac{SNO3(L) \times FLUX(L)}{[SW(L) \times DLAYR(L) + FLUX(L)]} \times 0.5 \times 0.8 \]

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 denitrification rate, DNRATE, is calculated as (line 22890):

\[ DNRATE = 6 \times 10^{-5} \times CW \times NO3(L) \times BD(L) \times FW \times FT \times DLAYR \]

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.

<table>
<thead>
<tr>
<th>Site/block</th>
<th>Planting date*</th>
<th>Variety</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tropeptic Eutrustox</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WAI-F83</td>
<td>11/30/83</td>
<td>H610,X304C</td>
<td>N x Variety</td>
</tr>
<tr>
<td>WAI-D82</td>
<td>07/02/82</td>
<td>X304C</td>
<td>N x Water</td>
</tr>
<tr>
<td>WAI-A10</td>
<td>07/10/78</td>
<td>X304C</td>
<td>N</td>
</tr>
<tr>
<td>WAI-B10</td>
<td>01/03/79</td>
<td>X304C</td>
<td>N</td>
</tr>
<tr>
<td>WAI-D10</td>
<td>06/07/79</td>
<td>X304C</td>
<td>N</td>
</tr>
<tr>
<td>WAI-G10</td>
<td>05/25/82</td>
<td>X304C</td>
<td>N</td>
</tr>
<tr>
<td>MOL-A10</td>
<td>07/06/78</td>
<td>X304C</td>
<td>N</td>
</tr>
<tr>
<td>MOL-B10</td>
<td>01/09/79</td>
<td>X304C</td>
<td>N</td>
</tr>
<tr>
<td>MOL-J10</td>
<td>01/10/81</td>
<td>X304C</td>
<td>N</td>
</tr>
</tbody>
</table>

| **Hydric Dystrandent** | | |
| 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

<table>
<thead>
<tr>
<th>Genetic Coefficients</th>
<th>X304C</th>
<th>H610</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1 (°C-day)</td>
<td>340</td>
<td>320</td>
</tr>
<tr>
<td>P2 (days delay/hour increase in photoperiod)</td>
<td>0.52</td>
<td>0.52</td>
</tr>
<tr>
<td>P5 (°C-day)</td>
<td>880</td>
<td>860</td>
</tr>
<tr>
<td>G2 (potential number of Kernels)</td>
<td>650</td>
<td>600</td>
</tr>
<tr>
<td>G3 (potential grain fill rate) mg kernel⁻¹</td>
<td>8.00</td>
<td>8.00</td>
</tr>
<tr>
<td>PHINT (°C-day)</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>
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 computation 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 withdrawal 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 been 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 initiation 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 varieties 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.

Photosynthesis 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 minimum 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 Eutruxtox sites

The performance of the maize model was tested on experiments from Tropeptic Eutruxtox 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).

<table>
<thead>
<tr>
<th>Treatment (kg N ha(^{-1}))</th>
<th>Layer (cm)</th>
<th>Julian date 2 Actual*</th>
<th>Julian date 2 Simulated</th>
<th>Julian date 38 Actual</th>
<th>Julian date 38 Simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>0-10</td>
<td>0.24 (.03)</td>
<td>0.26</td>
<td>0.27 (.03)</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>10-30</td>
<td>0.31 (.02)</td>
<td>0.33</td>
<td>0.30 (.03)</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>30-50</td>
<td>0.37 (.02)</td>
<td>0.36</td>
<td>0.32 (.02)</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>50-70</td>
<td>0.38 (.02)</td>
<td>0.38</td>
<td>0.36 (.01)</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>70-90</td>
<td>0.38 (.01)</td>
<td>0.38</td>
<td>0.35 (.02)</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>90-110</td>
<td>0.38 (.01)</td>
<td>0.39</td>
<td></td>
<td>0.37</td>
</tr>
<tr>
<td>50</td>
<td>0-10</td>
<td>0.27 (.03)</td>
<td>0.26</td>
<td>0.28 (.03)</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>10-30</td>
<td>0.34 (.02)</td>
<td>0.33</td>
<td>0.32 (.02)</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>30-50</td>
<td>0.35 (.02)</td>
<td>0.36</td>
<td>0.35 (.02)</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>50-70</td>
<td>0.39 (.02)</td>
<td>0.38</td>
<td>0.36 (.02)</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>70-90</td>
<td>0.39 (.02)</td>
<td>0.38</td>
<td>0.37 (.02)</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>90-110</td>
<td>0.39 (.01)</td>
<td>0.39</td>
<td></td>
<td>0.37</td>
</tr>
<tr>
<td>0</td>
<td>0-10</td>
<td>0.24 (.02)</td>
<td>0.26</td>
<td>0.27 (.03)</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>10-30</td>
<td>0.34 (.02)</td>
<td>0.33</td>
<td>0.32 (.02)</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>30-50</td>
<td>0.35 (.02)</td>
<td>0.36</td>
<td>0.34 (.02)</td>
<td>0.33</td>
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<tr>
<td></td>
<td>50-70</td>
<td>0.39 (.02)</td>
<td>0.38</td>
<td>0.36 (.02)</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>70-90</td>
<td>0.39 (.02)</td>
<td>0.38</td>
<td>0.37 (.02)</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>90-110</td>
<td>0.39 (.01)</td>
<td>0.39</td>
<td>0.37 (.02)</td>
<td>0.37</td>
</tr>
</tbody>
</table>

* Measured with one standard deviation.
Table 3.6 Comparison of observed and simulated phenological events for X304C variety and H610 variety.

<table>
<thead>
<tr>
<th>N Applied (kg ha(^{-1}))</th>
<th>Days After Planting</th>
<th>Variety X304C</th>
<th>Variety H610</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Emergence</td>
<td>Tassel</td>
<td>Silking</td>
</tr>
<tr>
<td>200 Observed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simulated</td>
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<td></td>
</tr>
<tr>
<td>50 Observed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simulated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 Observed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simulated</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>200 Observed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simulated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 Observed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simulated</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>0 Observed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simulated</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* 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.

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

* 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 anomalous 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).

<table>
<thead>
<tr>
<th>N Applied (kg N ha(^{-1}))</th>
<th>Leaf Area Index</th>
<th>Days</th>
<th>After</th>
<th>Planting</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>38</td>
<td>66</td>
<td>87</td>
</tr>
<tr>
<td>0</td>
<td>Measured</td>
<td>1.3</td>
<td>3.9</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>2.0</td>
<td>4.6</td>
<td>4.2</td>
</tr>
<tr>
<td>29</td>
<td>Measured</td>
<td>1.7</td>
<td>5.0</td>
<td>3.9</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>2.0</td>
<td>5.6</td>
<td>5.0</td>
</tr>
<tr>
<td>186</td>
<td>Measured</td>
<td>2.1</td>
<td>6.8</td>
<td>5.4</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>2.2</td>
<td>6.3</td>
<td>5.6</td>
</tr>
</tbody>
</table>
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 cultivars, X304C and H610 at three rates of N application.

<table>
<thead>
<tr>
<th>Day After Planting</th>
<th>Leaf Weight (g plant⁻¹)</th>
<th>N Applied (kg N ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>X304C Variety</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>Measured</td>
<td>3.6 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>3.9</td>
</tr>
<tr>
<td>71</td>
<td>Measured</td>
<td>39.9 ± 4.7</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>32.4</td>
</tr>
<tr>
<td>98</td>
<td>Measured</td>
<td>44.2 ± 1.7</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>33.3</td>
</tr>
<tr>
<td>105</td>
<td>Measured</td>
<td>50.4 ± 5.0</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>32.9</td>
</tr>
<tr>
<td>118</td>
<td>Measured</td>
<td>36.4 ± 3.0</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>32.1</td>
</tr>
<tr>
<td></td>
<td>H610 Variety</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>Measured</td>
<td>4.2 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>4.3</td>
</tr>
<tr>
<td>71</td>
<td>Measured</td>
<td>37.6 ± 6.0</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>30.4</td>
</tr>
<tr>
<td>98</td>
<td>Measured</td>
<td>46.5 ± 6.5</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>30.4</td>
</tr>
<tr>
<td>105</td>
<td>Measured</td>
<td>43.8 ± 3.0</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>30.1</td>
</tr>
<tr>
<td>118</td>
<td>Measured</td>
<td>31.5 ± 6.5</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>29.2</td>
</tr>
</tbody>
</table>

*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 Eutrulstox 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.

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

*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-GI0).
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 Dystrandept 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.

<table>
<thead>
<tr>
<th>Experiment/site</th>
<th>Planting date</th>
<th>Days After Planting</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Silking*</td>
</tr>
<tr>
<td>HAL-B21</td>
<td>7/13/78</td>
<td>Observed 71</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated 81</td>
</tr>
<tr>
<td>KUK-A21</td>
<td>6/29/78</td>
<td>Observed 66</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated 74</td>
</tr>
<tr>
<td>KUK-C11</td>
<td>2/16/78</td>
<td>Observed 77</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated 79</td>
</tr>
<tr>
<td>KUK-C12</td>
<td>5/23/79</td>
<td>Observed 69</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated 73</td>
</tr>
</tbody>
</table>

* 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.

<table>
<thead>
<tr>
<th>SITE</th>
<th>Coded N level (P, N)</th>
<th>Measured</th>
<th>Simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+.85, -.85</td>
<td>+.40, -.40</td>
<td>+.85, Opt</td>
</tr>
<tr>
<td>HAL-B21</td>
<td>Measured</td>
<td>4971 + 695</td>
<td>6441 + 273</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>4738*</td>
<td>6735</td>
</tr>
<tr>
<td>KUK-A21</td>
<td>Measured</td>
<td>6982 + 954</td>
<td>6955 + 1537</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>6404*</td>
<td>7893*</td>
</tr>
<tr>
<td>KUK-C11</td>
<td>Measured</td>
<td>7358 + 840</td>
<td>7257 + 418</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>8035*</td>
<td>9348</td>
</tr>
<tr>
<td>KUK-C12</td>
<td>Measured</td>
<td>7249 + 1529</td>
<td>8221 + 691</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>7310*</td>
<td>8817*</td>
</tr>
</tbody>
</table>

* 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 accommodate 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 predicting 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).
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.

<table>
<thead>
<tr>
<th>Site/Block</th>
<th>Location</th>
<th>Planting Date</th>
<th>Season</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tropeptic Eutrustox</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WAI-J84</td>
<td>Oahu, Hawaii</td>
<td>6/28/84</td>
<td>Dry</td>
</tr>
<tr>
<td>WAI-F10</td>
<td></td>
<td>11/17/82</td>
<td>Wet</td>
</tr>
<tr>
<td>MOL-L10</td>
<td>Molokai, Hawaii</td>
<td>6/08/82</td>
<td>Dry</td>
</tr>
<tr>
<td>MOL-M10</td>
<td></td>
<td>6/24/80</td>
<td>Dry</td>
</tr>
<tr>
<td>MOL-N10</td>
<td></td>
<td>5/20/81</td>
<td>Dry</td>
</tr>
<tr>
<td>MOL-N20</td>
<td></td>
<td>12/02/82</td>
<td>Wet</td>
</tr>
<tr>
<td><strong>Typic Palendult</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NAK-L10</td>
<td>South Sumatra, Indonesia</td>
<td>12/11/80</td>
<td>Wet</td>
</tr>
<tr>
<td>NAK-L20</td>
<td></td>
<td>11/25/81</td>
<td>Wet</td>
</tr>
<tr>
<td>NAK-A30</td>
<td></td>
<td>6/01/81</td>
<td>Dry</td>
</tr>
<tr>
<td>NAK-D30</td>
<td></td>
<td>6/12/81</td>
<td>Dry</td>
</tr>
<tr>
<td>NAK-O10</td>
<td></td>
<td>12/09/82</td>
<td>Wet</td>
</tr>
<tr>
<td>NAK-P10</td>
<td></td>
<td>12/16/82</td>
<td>Wet</td>
</tr>
<tr>
<td>BPMD-A30</td>
<td>South Sumatra, Indonesia</td>
<td>6/11/81</td>
<td>Dry</td>
</tr>
<tr>
<td>BPMD-C20</td>
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<td>12/13/80</td>
<td>Wet</td>
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<tr>
<td>BPMD-C30</td>
<td></td>
<td>11/27/81</td>
<td>Wet</td>
</tr>
<tr>
<td>BPMD-C40</td>
<td></td>
<td>12/18/82</td>
<td>Wet</td>
</tr>
<tr>
<td>BPMD-D40</td>
<td></td>
<td>12/09/82</td>
<td>Wet</td>
</tr>
</tbody>
</table>
Table 4.1 (continued) Experiments used for validation of the CERES maize model.

<table>
<thead>
<tr>
<th>Site/Block</th>
<th>Location</th>
<th>Planting Date</th>
<th>Season</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUK-A30</td>
<td>South Sumatra, Indonesia</td>
<td>6/04/81</td>
<td>Dry</td>
</tr>
<tr>
<td>BUK-D20</td>
<td></td>
<td>6/04/81</td>
<td>Dry</td>
</tr>
<tr>
<td>BUK-A40</td>
<td></td>
<td>6/02/82</td>
<td>Dry</td>
</tr>
<tr>
<td>BUK-F10</td>
<td></td>
<td>5/19/82</td>
<td>Dry</td>
</tr>
<tr>
<td>BUK-C30</td>
<td></td>
<td>11/26/81</td>
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</tr>
<tr>
<td>BUK-E20</td>
<td></td>
<td>12/02/81</td>
<td>Wet</td>
</tr>
<tr>
<td>BUK-E10</td>
<td></td>
<td>12/12/80</td>
<td>Wet</td>
</tr>
<tr>
<td>BUK-H10</td>
<td>South Sumatra, Indonesia</td>
<td>12/17/80</td>
<td>Wet</td>
</tr>
<tr>
<td>BUK-G10</td>
<td></td>
<td>12/11/82</td>
<td>Wet</td>
</tr>
<tr>
<td>SOR-A20</td>
<td>Luzon, Philippines</td>
<td>2/12/81</td>
<td>Wet</td>
</tr>
<tr>
<td>SOR-A30</td>
<td></td>
<td>2/13/82</td>
<td>Wet</td>
</tr>
<tr>
<td>SOR-B10</td>
<td></td>
<td>2/12/81</td>
<td>Wet</td>
</tr>
<tr>
<td>SOR-B20</td>
<td></td>
<td>2/09/82</td>
<td>Wet</td>
</tr>
<tr>
<td>SOR-E20</td>
<td></td>
<td>6/24/82</td>
<td>Dry</td>
</tr>
<tr>
<td>SOR-F10</td>
<td></td>
<td>6/24/82</td>
<td>Dry</td>
</tr>
<tr>
<td>DAV-L10</td>
<td></td>
<td>8/29/81</td>
<td>Dry</td>
</tr>
</tbody>
</table>

**Typic Paleudult**

**Hydric Dystrandept**

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>LPHS-D30</td>
<td>Java, Indonesia</td>
<td>6/21/82</td>
<td>Dry</td>
</tr>
<tr>
<td>LPHS-G20</td>
<td></td>
<td>12/02/82</td>
<td>Wet</td>
</tr>
</tbody>
</table>
Table 4.1 (continued) Experiments used for validation of the CERES maize model.

<table>
<thead>
<tr>
<th>Site/Block</th>
<th>Location</th>
<th>Planting Date</th>
<th>Season</th>
</tr>
</thead>
<tbody>
<tr>
<td>PUC-K20</td>
<td>Naga City, Philippines</td>
<td>6/22/81</td>
<td>Dry</td>
</tr>
<tr>
<td>PUC-Q40</td>
<td></td>
<td>1/29/82</td>
<td>Wet</td>
</tr>
<tr>
<td>PUC-Q50</td>
<td></td>
<td>1/05/83</td>
<td>Wet</td>
</tr>
<tr>
<td>PUC-R40</td>
<td></td>
<td>6/04/82</td>
<td>Dry</td>
</tr>
<tr>
<td>PUC-S20</td>
<td></td>
<td>2/06/81</td>
<td>Wet</td>
</tr>
<tr>
<td>PUC-S30</td>
<td></td>
<td>2/08/82</td>
<td>Wet</td>
</tr>
<tr>
<td>PUC-T10</td>
<td></td>
<td>1/18/83</td>
<td>Wet</td>
</tr>
<tr>
<td>PAL-D40</td>
<td>Camarines Sur, Philippines</td>
<td>6/05/82</td>
<td>Dry</td>
</tr>
<tr>
<td>PAL-F20</td>
<td></td>
<td>1/16/81</td>
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</tr>
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<td>1/30/82</td>
<td>Wet</td>
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<td>Wet</td>
</tr>
<tr>
<td>BUR-E20</td>
<td></td>
<td>2/04/81</td>
<td>Wet</td>
</tr>
<tr>
<td>BUR-E30</td>
<td></td>
<td>2/22/82</td>
<td>Wet</td>
</tr>
<tr>
<td>IOLE-E10*</td>
<td>Hawaii</td>
<td>6/08/78</td>
<td>Dry</td>
</tr>
<tr>
<td>IOLE-I10*</td>
<td></td>
<td>2/12/79</td>
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</tr>
<tr>
<td>IOLE-L10*</td>
<td></td>
<td>3/18/82</td>
<td>Dry</td>
</tr>
<tr>
<td>KUK-D11*</td>
<td></td>
<td>1/06/78</td>
<td>Wet</td>
</tr>
<tr>
<td>KUK-D20*</td>
<td></td>
<td>2/02/79</td>
<td>Wet</td>
</tr>
</tbody>
</table>
Table 4.1 (continued) Experiments used for validation of the CERES maize model.

<table>
<thead>
<tr>
<th>Site/Block</th>
<th>Location</th>
<th>Planting Date</th>
<th>Season</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waimanalo Experimental Station</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Soil Climate, Maui

<table>
<thead>
<tr>
<th>Site/Block</th>
<th>Location</th>
<th>Planting Date</th>
<th>Season</th>
</tr>
</thead>
<tbody>
<tr>
<td>Niftal (77 MSL)</td>
<td>Maui, Hawaii</td>
<td>4/24/84</td>
<td>Dry</td>
</tr>
<tr>
<td>Hailemaile (340 MSL)</td>
<td></td>
<td>4/24/84</td>
<td>Dry</td>
</tr>
<tr>
<td>Kekoa (800 MSL)</td>
<td></td>
<td>4/24/84</td>
<td>Dry</td>
</tr>
</tbody>
</table>

* 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):

$$R_1 = \frac{\sum_{i=1}^{t} \sum_{j=1}^{r} (Y_{ij} - \bar{X}_i)^2}{\sum_{i=1}^{t} \sum_{j=1}^{r} (Y_{ij} - \bar{Y}_i)^2}$$  \hspace{1cm} (4.1)
where $Y_{ij} =$ observed yield from treatment $i$ and replicate $j$ ($i = 1, \ldots, t$ and $j = 1, \ldots, r$)

$X_i =$ 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 $\sigma^2$ 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:

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

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

$$P(|D_i| \leq e) \geq 1 - a$$  \hspace{1cm} (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 $D^2/\text{Var}(D)$ has a chi-squared distribution with one degree of freedom (1) then

$$P[D^2/\text{Var}(D) \leq \chi^2_{1-a}(1)] = 1 - a$$  \hspace{1cm} (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 $D$, $\text{Var}(D)$. Since $\chi^2_{1-a}(1) = z_{1-a/2}$, where $z_{1-a/2}$ is the $(1-a/2)$ quantile of the standard normal distribution, Equation (4.4) can be written as:
\[ e^2 \geq \text{Var}(D)z^2_{1-a/2} \]

or as

\[ \text{Var}(D) \leq e^2/z^2_{1-a/2} \]  \hspace{1cm} (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 \( \text{Var}(D) \) 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 \( \text{Var}(D) \) must satisfy Eq. 4.5, Freese (1960) proposed to test the null hypotheses:

\[ H_0: E(D) = 0 \text{ and } \text{Var}(D) \geq e^2/\chi^2_{1-a}(1) \] \hspace{1cm} (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).

\[ H'_0: \text{Var}(D) \geq e^2/\chi^2_{1-a}(1) \]

This hypothesis would be rejected at significance level \( a' \) if

\[ \sum_{i=1}^{n} D_i^2 2_{1-a}(1)/e^2 \leq \chi^2_{a'}(n) \] \hspace{1cm} (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 \(100\frac{D}{Y}\) 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

\[
P(\frac{D}{Y} \leq p) \geq 1 - a \tag{4.8}
\]

If the unconditional distribution of \(D/Y\) \((\frac{D}{Y})\) 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 \(\text{Var}(D) \geq e^2/\chi^2_{1-a/2}\). The value of \(e^*\) is given by:

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

The critical error \(e^*\) thus gives a more conservative picture of the capabilities of the model. The critical percentage, \(p^*\), is similarly given as:
\[ p^* = \left[ \sum_{i=1}^{n} \left( D_i \chi^2_{1-a}(1)/Y_i \chi^2_{a'}(n) \right) \right]^{1/2} \] (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:

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

where \( Z_i = D_i^2 - nb^2 \)

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

Similarly, bias corrected critical error, \( e^{**} \) would be:

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

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

*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 Eutrope sites in Hawaii.

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

^ Unreplicated experiment with 300 kg N ha^-1.
* Simulated yields are within one standard deviation of mean yields.
^ 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
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.

<table>
<thead>
<tr>
<th>Site/Block</th>
<th>Planting Date</th>
<th>Days After Planting</th>
<th>Silking</th>
<th>Physiological Maturity</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAK-L10</td>
<td>12/11/80</td>
<td>Observed</td>
<td>53</td>
<td>111</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated</td>
<td>59</td>
<td>104</td>
</tr>
<tr>
<td>NAK-L20</td>
<td>11/25/81</td>
<td>Observed</td>
<td>54</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated</td>
<td>67</td>
<td>119</td>
</tr>
<tr>
<td>NAK-A30</td>
<td>06/01/81</td>
<td>Observed</td>
<td>57</td>
<td>103</td>
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<tr>
<td></td>
<td></td>
<td>Simulated</td>
<td>61</td>
<td>106</td>
</tr>
<tr>
<td>NAK-D30</td>
<td>06/12/81</td>
<td>Observed</td>
<td>52</td>
<td>102</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated</td>
<td>63</td>
<td>108</td>
</tr>
<tr>
<td>NAK-010</td>
<td>12/09/82</td>
<td>Observed</td>
<td>52</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated</td>
<td>57</td>
<td>99</td>
</tr>
<tr>
<td>NAK-P10</td>
<td>12/16/82</td>
<td>Observed</td>
<td>47</td>
<td>97</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated</td>
<td>55</td>
<td>97</td>
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<td>BPMD-A30a</td>
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<td>Observed</td>
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<td>95</td>
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<tr>
<td></td>
<td></td>
<td>Simulated</td>
<td>63</td>
<td>110</td>
</tr>
<tr>
<td>BPMD-C20</td>
<td>12/13/80</td>
<td>Observed</td>
<td>55</td>
<td>104</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated</td>
<td>72</td>
<td>121</td>
</tr>
<tr>
<td>BPMD-C30</td>
<td>11/27/81</td>
<td>Observed</td>
<td>52</td>
<td>107</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated</td>
<td>62</td>
<td>106</td>
</tr>
<tr>
<td>BPMD-C40</td>
<td>12/18/82</td>
<td>Observed</td>
<td>54</td>
<td>100</td>
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<tr>
<td></td>
<td></td>
<td>Simulated</td>
<td>60</td>
<td>107</td>
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</tbody>
</table>
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.

<table>
<thead>
<tr>
<th>Site/Block</th>
<th>Planting Date</th>
<th>Days After Planting</th>
<th>Silking</th>
<th>Physiological Maturity</th>
</tr>
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<tbody>
<tr>
<td>BPMD-D40</td>
<td>12/09/82</td>
<td>Observed</td>
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<td>98</td>
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<tr>
<td></td>
<td></td>
<td>Simulated</td>
<td>61</td>
<td>107</td>
</tr>
<tr>
<td>BUK-A30</td>
<td>06/04/81</td>
<td>Observed</td>
<td>57</td>
<td>109</td>
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<tr>
<td></td>
<td></td>
<td>Simulated</td>
<td>59</td>
<td>104</td>
</tr>
<tr>
<td>BUK-D20</td>
<td>06/04/81</td>
<td>Observed</td>
<td>57</td>
<td>105</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated</td>
<td>59</td>
<td>104</td>
</tr>
<tr>
<td>BUK-A40a</td>
<td>06/02/82</td>
<td>Observed</td>
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<td>110</td>
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<tr>
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<td></td>
<td>Simulated</td>
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<td>114</td>
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<tr>
<td>BUK-F10a</td>
<td>05/19/82</td>
<td>Observed</td>
<td>59</td>
<td>104</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated</td>
<td>64</td>
<td>116</td>
</tr>
<tr>
<td>BUK-C30</td>
<td>11/26/81</td>
<td>Observed</td>
<td>58</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated</td>
<td>68</td>
<td>122</td>
</tr>
<tr>
<td>BUK-E20</td>
<td>12/02/81</td>
<td>Observed</td>
<td>61</td>
<td>116</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated</td>
<td>69</td>
<td>122</td>
</tr>
<tr>
<td>BUK-E10</td>
<td>12/12/80</td>
<td>Observed</td>
<td>55</td>
<td>106</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated</td>
<td>62</td>
<td>108</td>
</tr>
<tr>
<td>BUK-H10</td>
<td>12/17/80</td>
<td>Observed</td>
<td>59</td>
<td>114</td>
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<td></td>
<td></td>
<td>Simulated</td>
<td>69</td>
<td>116</td>
</tr>
<tr>
<td>BUK-G10</td>
<td>12/11/82</td>
<td>Observed</td>
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<tr>
<td></td>
<td></td>
<td>Simulated</td>
<td>65</td>
<td>112</td>
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</table>
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.

<table>
<thead>
<tr>
<th>Site/Block</th>
<th>Planting Date</th>
<th>Silking*</th>
<th>Days After Planting</th>
<th>Physiological Maturity</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOR-A20</td>
<td>02/12/81</td>
<td>Observed</td>
<td>58</td>
<td>103</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated</td>
<td>62</td>
<td>105</td>
</tr>
<tr>
<td>SOR-A30&lt;sup&gt;b,c&lt;/sup&gt;</td>
<td>02/13/82</td>
<td>Observed</td>
<td>64</td>
<td>112</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated</td>
<td>73</td>
<td>122</td>
</tr>
<tr>
<td>SOR-B10</td>
<td>02/12/81</td>
<td>Observed</td>
<td>60</td>
<td>103</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated</td>
<td>62</td>
<td>105</td>
</tr>
<tr>
<td>SOR-B10&lt;sup&gt;b,c&lt;/sup&gt;</td>
<td>02/09/82</td>
<td>Observed</td>
<td>65</td>
<td>113</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated</td>
<td>73</td>
<td>123</td>
</tr>
<tr>
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<td>Observed</td>
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<td>108</td>
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<tr>
<td></td>
<td></td>
<td>Simulated</td>
<td>66</td>
<td>117</td>
</tr>
<tr>
<td>SOR-F10&lt;sup&gt;b&lt;/sup&gt;</td>
<td>06/24/82</td>
<td>Observed</td>
<td>58</td>
<td>105</td>
</tr>
<tr>
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<td></td>
<td>Simulated</td>
<td>66</td>
<td>117</td>
</tr>
<tr>
<td>DAV-L10</td>
<td>08/29/81</td>
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<td>50</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Simulated</td>
<td>58</td>
<td>106</td>
</tr>
</tbody>
</table>

<sup>a</sup> Water stress.

<sup>b</sup> Moderate to severe lodging.

<sup>c</sup> 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.

<table>
<thead>
<tr>
<th>SITE</th>
<th>Measured</th>
<th>Simulated</th>
<th>Coded N level (P, N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAK-L10*a</td>
<td>Measured</td>
<td>Simulated</td>
<td>Opt, 0 +.85, -.85 +.40, -.40 +.85, Opt +.40, +.40 +.85, +.85</td>
</tr>
<tr>
<td></td>
<td>5710 + 793</td>
<td>6343 + 1002</td>
<td>7341 + 362</td>
</tr>
<tr>
<td>NAK-L20</td>
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<td>7209*</td>
<td>8318</td>
</tr>
<tr>
<td>NAK-A30</td>
<td>3705 + 700</td>
<td>4620 + 32</td>
<td>4977 + 263</td>
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<td>NAK-D30</td>
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<td>4975*</td>
<td>6675</td>
</tr>
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<td>2473 + 204</td>
<td>4322 + 486</td>
<td>5926 + 566</td>
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<td>3723 + 600</td>
<td>3864 + 112</td>
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<td>BPMD-C20</td>
<td>5671 + 647</td>
<td>7058 + 842</td>
<td>7457 + 715</td>
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<tr>
<td>BUK-E10*a</td>
<td>5561*</td>
<td>6463*</td>
<td>7647*</td>
</tr>
<tr>
<td>BUK-H10*a</td>
<td>9238 + 480</td>
<td>8991*</td>
<td>9283 + 456</td>
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<tr>
<td>BUK-G10*a</td>
<td>9238 + 456</td>
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</tbody>
</table>
Table 4.5 (continued) Validation of simulated grain yields with observed yields on Typic Paleudult sites in Indonesia and Philippines.

<table>
<thead>
<tr>
<th>SITE</th>
<th>Coded N level (P, N)</th>
<th>Opt, 0</th>
<th>+.85, -.85</th>
<th>+.40, -.40</th>
<th>+.85, Opt</th>
<th>+.40, +.40</th>
<th>+.85, +.85</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOR-A20</td>
<td>Measured</td>
<td>3693 + 1119</td>
<td>5144 + 1746</td>
<td>6216 + 681</td>
<td>6766 + 826</td>
<td>6609 + 455</td>
<td>7798 + 1104</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>3958*</td>
<td>5375*</td>
<td>6890*</td>
<td>8031</td>
<td>8295</td>
<td>8295*</td>
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<td>SOR-A30d,e</td>
<td>Measured</td>
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<td>5079 + 1236</td>
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<td>6146 + 706</td>
<td>6763 + 148</td>
<td>6715 + 816</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>3365*</td>
<td>4916*</td>
<td>6546</td>
<td>7713</td>
<td>8713</td>
<td>9451</td>
</tr>
<tr>
<td>SOR-B10</td>
<td>Measured</td>
<td>3297 + 1175</td>
<td>3518 + 335</td>
<td>5254 + 447</td>
<td>6532 + 552</td>
<td>6479 + 158</td>
<td>77245 + 759</td>
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<tr>
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<td>Simulated</td>
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<td>4972</td>
<td>6607</td>
<td>7757</td>
<td>8295</td>
<td>8295*</td>
</tr>
<tr>
<td>SOR-B20d,e</td>
<td>Measured</td>
<td>3900 + 756</td>
<td>4949 + 582</td>
<td>5738 + 318</td>
<td>7101 + 526</td>
<td>6697 + 5990</td>
<td>7651 + 816</td>
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<tr>
<td></td>
<td>Simulated</td>
<td>4025*</td>
<td>5392*</td>
<td>7051</td>
<td>8254</td>
<td>9144</td>
<td>9650</td>
</tr>
<tr>
<td>SOR-E20d</td>
<td>Measured</td>
<td>2411 + 372</td>
<td>3753 + 381</td>
<td>3756 + 208</td>
<td>4989 + 662</td>
<td>40735 + 272</td>
<td>5000 + 249</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
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<td>4658</td>
<td>6059</td>
<td>6145</td>
<td>6145</td>
<td>6145</td>
</tr>
<tr>
<td>SOR-F10d</td>
<td>Measured</td>
<td>2527 + 143</td>
<td>4435 + 658</td>
<td>4786 + 910</td>
<td>5299 + 571</td>
<td>5304 + 292</td>
<td>6415 + 499</td>
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<tr>
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<td>Simulated</td>
<td>3322</td>
<td>4658*</td>
<td>6059</td>
<td>6145</td>
<td>6145</td>
<td>6145*</td>
</tr>
<tr>
<td>BPMD-C30</td>
<td>Measured</td>
<td>2181 + 867</td>
<td>3830 + 813</td>
<td>5320 + 624</td>
<td>6314 +283</td>
<td>7147 + 631</td>
<td>7402 + 837</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>3176</td>
<td>4824</td>
<td>6592</td>
<td>7836</td>
<td>8002</td>
<td>8008*</td>
</tr>
<tr>
<td>BPMD-C40</td>
<td>Measured</td>
<td>5392 + 535</td>
<td>5936 + 167</td>
<td>6631 + 820</td>
<td>7889 + 664</td>
<td>7756 + 1050</td>
<td>7867 + 1040</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>4743*</td>
<td>5907*</td>
<td>7284*</td>
<td>8033*</td>
<td>8219</td>
<td>8219*</td>
</tr>
<tr>
<td>BPMD-D40</td>
<td>Measured</td>
<td>5785 + 698</td>
<td>6212 + 556</td>
<td>8317 + 1998</td>
<td>8502 + 514</td>
<td>8399 + 407</td>
<td>8599 + 1279</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>5686*</td>
<td>6693*</td>
<td>7750*</td>
<td>8160*</td>
<td>8162*</td>
<td>8162*</td>
</tr>
<tr>
<td>BUK-A30a</td>
<td>Measured</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6114 + 281</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7476</td>
</tr>
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Table 4.5 (continued) Validation of simulated grain yields with observed yields on Typic Paleudult sites in Indonesia and Philippines.

<table>
<thead>
<tr>
<th>SITE</th>
<th>Coded N level (P, N)</th>
<th>Measured</th>
<th>Simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Opt, 0</td>
<td>+.85, -.85</td>
<td>+.40, -.40</td>
</tr>
<tr>
<td>BUK-A40c</td>
<td>Measured</td>
<td>5938 + 339</td>
<td>7476</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>7476</td>
<td></td>
</tr>
<tr>
<td>BUK-F10c</td>
<td>Measured</td>
<td>2415 + 230</td>
<td>8407</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>8407</td>
<td></td>
</tr>
<tr>
<td>BUK-C30a</td>
<td>Measured</td>
<td>8519 + 456</td>
<td>8249*</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>8249*</td>
<td></td>
</tr>
<tr>
<td>BUK-E20a</td>
<td>Measured</td>
<td>8089 + 848</td>
<td>8500*</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>8500*</td>
<td></td>
</tr>
<tr>
<td>DAV-L10</td>
<td>Measured</td>
<td>6055 + 249</td>
<td>7676 + 418</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>6351</td>
<td>7680*</td>
</tr>
</tbody>
</table>

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.
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.

<table>
<thead>
<tr>
<th>Site/Block</th>
<th>Planting Date</th>
<th>Days After Planting</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Silking* Physiological Maturity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LPHS-D30</td>
<td>06/21/82</td>
<td>Observed 80</td>
<td>147</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated 86</td>
<td>158</td>
<td></td>
</tr>
<tr>
<td>LPHS-G20</td>
<td>12/02/82</td>
<td>Observed 75</td>
<td>139</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated 81</td>
<td>143</td>
<td></td>
</tr>
<tr>
<td>PUC-K20b</td>
<td>06/22/81</td>
<td>Observed 64</td>
<td>115</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated 76</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>PUC-Q40</td>
<td>01/29/82</td>
<td>Observed 68</td>
<td>117</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated 72</td>
<td>122</td>
<td></td>
</tr>
<tr>
<td>PUC-Q50c</td>
<td>01/05/83</td>
<td>Observed 66</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated 66</td>
<td>122</td>
<td></td>
</tr>
<tr>
<td>PUC-R40b</td>
<td>06/04/82</td>
<td>Observed 62</td>
<td>105</td>
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<tr>
<td></td>
<td></td>
<td>Simulated 66</td>
<td>120</td>
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</tr>
<tr>
<td>PUC-S20</td>
<td>02/06/81</td>
<td>Observed 68</td>
<td>115</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Simulated 70</td>
<td>122</td>
<td></td>
</tr>
<tr>
<td>PUC-S30</td>
<td>02/08/82</td>
<td>Observed 70</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated 73</td>
<td>126</td>
<td></td>
</tr>
<tr>
<td>PUC-T10</td>
<td>01/18/83</td>
<td>Observed 73</td>
<td>132</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated 68</td>
<td>122</td>
<td></td>
</tr>
<tr>
<td>PAL-D40b</td>
<td>06/05/82</td>
<td>Observed 60</td>
<td>112</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Simulated 64</td>
<td>119</td>
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</tr>
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</table>
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.

<table>
<thead>
<tr>
<th>Site/Block</th>
<th>Planting Date</th>
<th>Days After Planting</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
<td>Silking*</td>
<td>Physiological Maturity</td>
</tr>
<tr>
<td>PAL-F20</td>
<td>01/16/81</td>
<td>Observed 69</td>
<td>120</td>
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<tr>
<td></td>
<td></td>
<td>Simulated 72</td>
<td>122</td>
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<tr>
<td>PAL-F30</td>
<td>01/30/82</td>
<td>Observed 68</td>
<td>123</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated 68</td>
<td>118</td>
</tr>
<tr>
<td>PAL-F40</td>
<td>01/06/83</td>
<td>Observed 65</td>
<td>118</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated 68</td>
<td>118</td>
</tr>
<tr>
<td>PAL-G30</td>
<td>02/06/82</td>
<td>Observed 69</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated 69</td>
<td>118</td>
</tr>
<tr>
<td>BUR-E20b</td>
<td>02/04/81</td>
<td>Observed 71</td>
<td>124</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated 72</td>
<td>122</td>
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<td>02/22/82</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Simulated 71</td>
<td>121</td>
</tr>
<tr>
<td>IOLE-E10</td>
<td>06/08/78</td>
<td>Observed 72</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated 78</td>
<td>140</td>
</tr>
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</table>
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.

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

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.

<table>
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<th>SITE</th>
<th>Measured</th>
<th>Simulated</th>
</tr>
</thead>
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</tr>
<tr>
<td>Measured</td>
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</tr>
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<td>6491 + 1489</td>
<td>9164</td>
</tr>
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<td>6575 + 558</td>
<td>9210</td>
</tr>
<tr>
<td></td>
<td>6758 + 562</td>
<td>9210</td>
</tr>
<tr>
<td>LPHS-G20</td>
<td></td>
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</tr>
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<td>Measured</td>
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</tr>
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<td>4630*</td>
</tr>
<tr>
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<td>6247 + 607</td>
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</tr>
<tr>
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<td>5234</td>
</tr>
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<td>6677 + 311</td>
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<td>7902*</td>
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<tr>
<td></td>
<td>7274 + 410</td>
<td>8512</td>
</tr>
<tr>
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<td>8512</td>
</tr>
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<td>6510 + 486</td>
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<td>8030*</td>
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<td>8619 + 160</td>
<td>8376</td>
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<td>9286 + 288</td>
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<td>9329 + 160</td>
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<td>9790 + 564</td>
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<tr>
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<td>10365 + 229</td>
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</tr>
</tbody>
</table>
Table 4.7 (continued) Validation of simulated grain yields with observed yields on Hydric Dystrandept sites in Indonesia, Philippines and Hawaii.

<table>
<thead>
<tr>
<th>SITE</th>
<th>Coded N level (P, N)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Opt, 0</td>
<td>+.85, -.85</td>
<td>+.40, -.40</td>
<td>+.85, Opt</td>
<td>+.40, +.40</td>
<td>+.85, +.85</td>
</tr>
<tr>
<td>PAL-D40</td>
<td>Measured</td>
<td>4628 ± 166</td>
<td>5664 ± 186</td>
<td>5609 ± 464</td>
<td>6613 ± 346</td>
<td>6324 ± 867</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>5067</td>
<td>1861*</td>
<td>65222</td>
<td>6897</td>
<td>7001</td>
</tr>
<tr>
<td>PAL-F20</td>
<td>Measured</td>
<td>6002 ± 115</td>
<td>6701 ± 376</td>
<td>6409 ± 364</td>
<td>7426 ± 362</td>
<td>7205 ± 362</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>6364</td>
<td>7250</td>
<td>8204</td>
<td>8732</td>
<td>8732</td>
</tr>
<tr>
<td>PAL-F30</td>
<td>Measured</td>
<td>4701 ± 399</td>
<td>6009 ± 139</td>
<td>5763 ± 791</td>
<td>6745 ± 317</td>
<td>6025 ± 619</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>4679*</td>
<td>5811</td>
<td>6956</td>
<td>7536</td>
<td>7536</td>
</tr>
<tr>
<td>PAL-F40</td>
<td>Measured</td>
<td>5346 ± 522</td>
<td>6259 ± 543</td>
<td>7000 ± 96</td>
<td>8002 ± 368</td>
<td>7309 ± 65</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>5990</td>
<td>7093</td>
<td>8000</td>
<td>8201*</td>
<td>8201</td>
</tr>
<tr>
<td>PAL-G30</td>
<td>Measured</td>
<td>4114 ± 517</td>
<td>5701 ± 625</td>
<td>6088 ± 292</td>
<td>6652 ± 365</td>
<td>7129 ± 783</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>4625*</td>
<td>5745*</td>
<td>6989</td>
<td>7612</td>
<td>7876*</td>
</tr>
<tr>
<td>BUR-E20</td>
<td>Measured</td>
<td>5409 ± 393</td>
<td>6739 ± 941</td>
<td>7319 ± 929</td>
<td>8205 ± 291</td>
<td>7594 ± 459</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>6782</td>
<td>7772</td>
<td>8755</td>
<td>9229</td>
<td>9350</td>
</tr>
<tr>
<td>BUR-E30</td>
<td>Measured</td>
<td>2074 ± 494</td>
<td>5128 ± 462</td>
<td>4211 ± 598</td>
<td>4889 ± 547</td>
<td>3831 ± 906</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>5407</td>
<td>6378</td>
<td>7548</td>
<td>8170</td>
<td>8296</td>
</tr>
<tr>
<td>IOLE-E10</td>
<td>Measured</td>
<td>6263</td>
<td>6980</td>
<td>7113</td>
<td>6478</td>
<td>7768</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>5510</td>
<td>7490</td>
<td>8618</td>
<td>8691</td>
<td>8691</td>
</tr>
</tbody>
</table>
Table 4.7 (continued) Validation of simulated grain yields with observed yields on Hydric Dystrandept sites in Indonesia, Philippines and Hawaii.

<table>
<thead>
<tr>
<th>SITE</th>
<th>Measured</th>
<th>Simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>IOLE-L10</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coded N level (P, N)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Opt, 0, +.85, -.85, +.40, -.40, +.85, Opt, +.40, -.40, +.85, -.40</td>
<td></td>
</tr>
<tr>
<td>IOLE-L10</td>
<td>4833 ± 335</td>
<td>5151 ± 293</td>
</tr>
<tr>
<td>KUK-D11</td>
<td>6293 ± 1637</td>
<td>7663 ± 718</td>
</tr>
<tr>
<td>KUK-D20</td>
<td>5546 ± 807</td>
<td>6889 ± 1049</td>
</tr>
<tr>
<td>* Mean yields ± one standard deviation of observations.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>* Simulated yields are within one standard deviation of observed mean yields.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>* Volcanic ash fall.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>* Water stress.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>* Lodging.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>* Pest damage.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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 NH$_4^+$ levels therefore, would be considerably higher than the field levels. This error in initial soil N determination therefore, explains some of the anomalies 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-Dll 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-Dll 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.
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.

<table>
<thead>
<tr>
<th>Elevation (m)</th>
<th>Days After Planting&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Emergence</td>
</tr>
<tr>
<td>77</td>
<td>Observed&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
</tr>
<tr>
<td>340</td>
<td>Observed</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
</tr>
<tr>
<td>800</td>
<td>Observed</td>
</tr>
<tr>
<td></td>
<td>Simulated</td>
</tr>
</tbody>
</table>

<sup>a</sup> Planted on April 24, 1984.

<sup>b</sup> 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.

<table>
<thead>
<tr>
<th>Elevation (m)</th>
<th>Grain yield $\text{kg ha}^{-1}$</th>
<th>Total Dry Matter $\text{kg ha}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>77</td>
<td>Observed $11533 \pm 860$</td>
<td>$25025 \pm 2145$</td>
</tr>
<tr>
<td></td>
<td>Simulated $12339^*$</td>
<td>$23699^*$</td>
</tr>
<tr>
<td>340</td>
<td>Observed $11600 \pm 994$</td>
<td>$21033 \pm 1898$</td>
</tr>
<tr>
<td></td>
<td>Simulated $12234^*$</td>
<td>$25182$</td>
</tr>
<tr>
<td>800</td>
<td>Observed $9178 \pm 1654$</td>
<td>$18731 \pm 4659$</td>
</tr>
<tr>
<td></td>
<td>Simulated $9009^*$</td>
<td>$22584^*$</td>
</tr>
</tbody>
</table>

$^a$ 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.

<table>
<thead>
<tr>
<th>Niftal Site</th>
<th>Solar radiation + 100 cal cm$^{-2}$ day$^{-1}$</th>
<th>Max. and min. temp. -2°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silking (DAP)</td>
<td>Observed 62</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Simulated 67</td>
<td>67</td>
</tr>
<tr>
<td>Physiological Maturity (DAP)</td>
<td>Observed 120</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Simulated 119</td>
<td>119</td>
</tr>
<tr>
<td>Grain Yield (kg ha$^{-1}$)</td>
<td>Observed 11533</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Simulated 12339</td>
<td>12765 (10900*)</td>
</tr>
<tr>
<td>Total Dry Matter (kg ha$^{-1}$)</td>
<td>Observed 25025</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Simulated 23699</td>
<td>25807</td>
</tr>
</tbody>
</table>

* 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 at least 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 non-site-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

<table>
<thead>
<tr>
<th>Site</th>
<th>Normalized$^a$</th>
<th>Tabulated F*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[A]</td>
<td>[B]</td>
</tr>
<tr>
<td>WAI-F10</td>
<td>2503744</td>
<td>2727924</td>
</tr>
<tr>
<td>MOL-L10</td>
<td>2468844</td>
<td>6631189</td>
</tr>
<tr>
<td>MOL-M10</td>
<td>17947468</td>
<td>2565763</td>
</tr>
<tr>
<td>MOL-N10</td>
<td>5628938</td>
<td>19693354</td>
</tr>
<tr>
<td>NAK-L20</td>
<td>3803363</td>
<td>6193029</td>
</tr>
<tr>
<td>NAK-A30</td>
<td>18404305</td>
<td>6721695</td>
</tr>
<tr>
<td>NAK-D30</td>
<td>7741024</td>
<td>3137472</td>
</tr>
<tr>
<td>NAK-O10</td>
<td>10584131</td>
<td>7096951</td>
</tr>
<tr>
<td>NAK-P10</td>
<td>4733048</td>
<td>7632881</td>
</tr>
</tbody>
</table>

* At 95% Significance level
$^a$ If Normalized R$_{1-1} \leq F$ then model prediction is not significantly different from observed yields.

R$_{1-1} = \frac{r[A]}{[B]}$ 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 $R_j^{-1}$ values for each of the experiments. The numerator, denominator, and $R_j^{-1}$ 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; Mekhail 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 NaHCO₃ (Olsen et al., 1954), NH₄F + HCl (Bray and Kurtz, 1945), HCl + H₂SO₄ (double acid P), or 0.02 N H₂SO₄ (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 $^{33}\text{P}$ 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 capacity, 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. Radiotope $^{33}$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 radiotope 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.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Alfisol</th>
<th>Andisol</th>
<th>Aridisol</th>
<th>Entisol</th>
<th>Histosol</th>
<th>Inceptisol</th>
<th>Mollisol</th>
<th>Oxisol</th>
<th>Ultisol</th>
<th>Vertisol</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topsoil</td>
<td>8</td>
<td>16</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>11</td>
<td>12</td>
<td>25</td>
<td>11</td>
<td>2</td>
<td>91</td>
</tr>
<tr>
<td>Subsoil</td>
<td>27</td>
<td>5</td>
<td>10</td>
<td>1</td>
<td>0</td>
<td>14</td>
<td>11</td>
<td>46</td>
<td>17</td>
<td>11</td>
<td>142</td>
</tr>
<tr>
<td>Total</td>
<td>35</td>
<td>21</td>
<td>13</td>
<td>2</td>
<td>2</td>
<td>25</td>
<td>23</td>
<td>71</td>
<td>28</td>
<td>13</td>
<td>233</td>
</tr>
</tbody>
</table>
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/umol) 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 polypropylene centrifuge tubes. To each of the samples 10ml of 0.03 M $\text{CaCl}_2$, 3 ml of 50 ppm $\text{Ca(H}_2\text{PO}_4)_2$ 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 $\text{CaCl}_2$ 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):

\[
E = x(S_i/S_t - 1)
\]

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

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 Mekhail et al. (1965) and Dalal and Hallsworth (1977). To four sets of 3 g soil samples in a 50 ml polypropylene 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 centrifuged 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):
\[ E = x \frac{S_t}{(S - S_t)} \]  

(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 sieved 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 bicarbonate form**

The bicarbonate form of resin was generated by leaching the chloride form of the resin with 10% NaHCO₃ 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- Na₂SO₄ 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 NH₄F 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:

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

$$V_x = \bar{x}_x[\exp(s_y^2) - 1]$$

where $X_y =$ mean of log transformed data values, $S^2_y =$ variance of the log transformed data values, and $\bar{x}_x =$ 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$_2$SO$_4$ for 5 minutes. The Olsen P method as described by Olsen and Sommer (1982) was followed, where 5 g 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$_2$CO$_3$. 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 equilibrated with 20 ml of H$_2$O for 24 hours. Then extracted with 100 ml of 0.02 N H$_2$SO$_4$ containing 3 g of (NH$_4$)$_2$SO$_4$. 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 ascorbic 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$_2$SO$_4$) 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

Phosphate sorption 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$_2$PO$_4$)$_2$ 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:
\[
\text{Al saturation} = \frac{(\text{KCl-extr Al})}{\text{ECEC}} \times 100 \tag{5.1}
\]

Lime requirement was calculated based on neutralization of Al (Kamprath, 1970):
\[
\text{CaCO}_3 \text{ cmol/kg} = 1.5 \times (\text{KCl-extr Al}) \text{ cmol/kg} \tag{5.2}
\]

Lime requirement values in tonnes lime/ha were obtained assuming a bulk density of 1.00 g/cm³ (0.80 g/cm³ 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:
\[
\text{CEC cmol/kg clay} = \frac{(\text{CEC cmol/kg soil})}{\%\text{clay}} \times 100 \tag{5.3}
\]

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 $S_f$ (final specific activity) value as used in Equation (2.12) was greater than S which indicates some violation of experimental assumptions.

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

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.

<table>
<thead>
<tr>
<th>Soil name</th>
<th>Chloride- sulfate resin</th>
<th>Chloride resin</th>
<th>Bicarbonate resin</th>
<th>Isotope carrier-P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torroxic Haplustoll</td>
<td>255.57</td>
<td>170.76</td>
<td>240.79</td>
<td>324.90</td>
</tr>
<tr>
<td>Torroxic Haplustoll</td>
<td>74.09</td>
<td>70.16</td>
<td>72.34</td>
<td>34.36</td>
</tr>
<tr>
<td>Torroxic Haplustoll</td>
<td>66.50</td>
<td>63.71</td>
<td>64.19</td>
<td>22.73</td>
</tr>
<tr>
<td>Ustoxic Humitropept</td>
<td>12.14</td>
<td>4.64</td>
<td>7.48</td>
<td>6.98</td>
</tr>
<tr>
<td>Oxic Dystrandept</td>
<td>14.78</td>
<td>12.50</td>
<td>15.90</td>
<td>16.74</td>
</tr>
<tr>
<td>Typic Dystrandept</td>
<td>2.73</td>
<td>0.29</td>
<td>1.02</td>
<td>3.07</td>
</tr>
<tr>
<td>Entic Dystrandept</td>
<td>6.58</td>
<td>2.22</td>
<td>4.59</td>
<td>1.80</td>
</tr>
<tr>
<td>Typic Eutrandept</td>
<td>9.21</td>
<td>5.04</td>
<td>9.42</td>
<td>11.37</td>
</tr>
<tr>
<td>Torroxic Haplustoll</td>
<td>102.22</td>
<td>73.39</td>
<td>82.30</td>
<td>75.1</td>
</tr>
<tr>
<td>Typic Paleudult</td>
<td>1.32</td>
<td>ND</td>
<td>0.54</td>
<td>2.05</td>
</tr>
<tr>
<td>Typic Paleudult</td>
<td>3.64</td>
<td>0.81</td>
<td>2.98</td>
<td>1.08</td>
</tr>
<tr>
<td>Tropeptic Eutrustox</td>
<td>30.06</td>
<td>14.92</td>
<td>33.41</td>
<td>11.48</td>
</tr>
<tr>
<td>Typic Torrox</td>
<td>67.20</td>
<td>55.24</td>
<td>69.00</td>
<td>28.10</td>
</tr>
<tr>
<td>Typic Eutrandept</td>
<td>4.66</td>
<td>5.04</td>
<td>5.01</td>
<td>9.80</td>
</tr>
<tr>
<td>Typic Hydrandept</td>
<td>0.30</td>
<td>ND</td>
<td>0.18</td>
<td>4.06</td>
</tr>
<tr>
<td>Hydric Dystrandept</td>
<td>0.10</td>
<td>ND</td>
<td>ND</td>
<td>19.78</td>
</tr>
<tr>
<td>Hydric Dystrandept</td>
<td>0.40</td>
<td>ND</td>
<td>0.22</td>
<td>4.50</td>
</tr>
<tr>
<td>Hydric Dystrandept</td>
<td>0.61</td>
<td>ND</td>
<td>0.50</td>
<td>11.34</td>
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<tr>
<td>Tropeptic Haplorthox</td>
<td>6.78</td>
<td>0.40</td>
<td>6.90</td>
<td>3.05</td>
</tr>
<tr>
<td>Typic Eutrandept</td>
<td>11.94</td>
<td>15.32</td>
<td>10.49</td>
<td>12.31</td>
</tr>
<tr>
<td>Typic Eutrandept</td>
<td>74.39</td>
<td>61.09</td>
<td>-</td>
<td>38.72</td>
</tr>
</tbody>
</table>
Table 5.2 (continued) Comparison of labile P (mg P kg soil$^{-1}$) as obtained from anion exchange resin and isotope P methods.

<table>
<thead>
<tr>
<th>Soil name</th>
<th>Chloride- sulfate resin</th>
<th>Chloride resin</th>
<th>Bicarbonate resin</th>
<th>Isotope carrier-P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typic Tropofolist</td>
<td>66.88</td>
<td>50.00</td>
<td>-</td>
<td>72.41</td>
</tr>
<tr>
<td>Typic Tropofolist</td>
<td>29.35</td>
<td>33.47</td>
<td>-</td>
<td>34.28</td>
</tr>
<tr>
<td>Ardic Haplustoll</td>
<td>78.54</td>
<td>73.59</td>
<td>-</td>
<td>38.49</td>
</tr>
<tr>
<td>Ardic Haplustoll</td>
<td>38.76</td>
<td>35.68</td>
<td>-</td>
<td>24.24</td>
</tr>
<tr>
<td>Typic Vitrandept</td>
<td>21.15</td>
<td>13.91</td>
<td>-</td>
<td>16.84</td>
</tr>
<tr>
<td>Humoxic Tropohumult</td>
<td>0.81</td>
<td>ND</td>
<td>0.42</td>
<td>$S_f &gt; S_i$</td>
</tr>
<tr>
<td>Cumulic Haplustoll</td>
<td>29.15</td>
<td>32.66</td>
<td>-</td>
<td>30.12</td>
</tr>
<tr>
<td>Typic Torrox</td>
<td>45.54</td>
<td>41.13</td>
<td>-</td>
<td>24.06</td>
</tr>
<tr>
<td>Typic Gibsihumox</td>
<td>2.53</td>
<td>ND</td>
<td>-</td>
<td>4.03</td>
</tr>
<tr>
<td>Typic Pellustert</td>
<td>1.11</td>
<td>ND</td>
<td>-</td>
<td>$S_f &gt; S_i$</td>
</tr>
</tbody>
</table>

AEG for chloride-sulfate, chloride, and bicarbonate 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 Mekhail 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 ($r$)<sup>a</sup> between different soil P extraction methods for topsoil samples.

<table>
<thead>
<tr>
<th></th>
<th>Resin P</th>
<th>Isotope P&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Mod. Truog P</th>
<th>Bray P</th>
<th>Double Acid P</th>
<th>$H_2SO_4$ P</th>
<th>Olsen P</th>
<th>Hydroxide P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isotope P</td>
<td>0.82</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mod. Truog P</td>
<td>0.85</td>
<td>0.78</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bray P</td>
<td>0.88</td>
<td>0.87</td>
<td>0.85</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double Acid P</td>
<td>0.85</td>
<td>0.74</td>
<td>0.74</td>
<td>0.84</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H_2SO_4$ P</td>
<td>0.49</td>
<td>0.44</td>
<td>0.67</td>
<td>0.40</td>
<td>0.32**</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Olsen P</td>
<td>0.90</td>
<td>0.89</td>
<td>0.85</td>
<td>0.98</td>
<td>0.84</td>
<td>0.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydroxide P</td>
<td>0.39</td>
<td>0.37</td>
<td>0.44</td>
<td>0.34</td>
<td>--</td>
<td>0.81</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>Solution P</td>
<td>0.92</td>
<td>0.98</td>
<td>0.92</td>
<td>0.97</td>
<td>0.91</td>
<td>0.45**</td>
<td>0.97</td>
<td>0.38**</td>
</tr>
</tbody>
</table>

<sup>a</sup> **significant at P $\leq 0.01$ all other coefficients of correlation are significant at P $\leq 0.001$.

<sup>b</sup> 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.

<table>
<thead>
<tr>
<th></th>
<th>Resin P</th>
<th>Isotope P (^{b})</th>
<th>Mod. Truog P</th>
<th>Bray P</th>
<th>Double Acid P</th>
<th>(H_2SO_4) P</th>
<th>Olsen P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isotope P</td>
<td></td>
<td>(--)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mod. Truog P</td>
<td>0.44</td>
<td>(--)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bray P</td>
<td>0.83</td>
<td>(--)</td>
<td>0.38</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double Acid P</td>
<td>0.69</td>
<td>(--)</td>
<td>0.39</td>
<td>0.74</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(H_2SO_4) P</td>
<td>0.33</td>
<td>(--)</td>
<td>0.70</td>
<td>0.30</td>
<td>0.24(\ast)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Olsen P</td>
<td>0.75</td>
<td>(--)</td>
<td>0.53</td>
<td>0.77</td>
<td>0.56</td>
<td>0.52</td>
<td></td>
</tr>
<tr>
<td>Hydroxide P</td>
<td>0.46</td>
<td>(--)</td>
<td>0.39</td>
<td>0.50</td>
<td>(--)</td>
<td>0.56</td>
<td>0.66</td>
</tr>
<tr>
<td>Solution P</td>
<td>0.71(\ast)</td>
<td>0.41(\ast)</td>
<td>(--)</td>
<td>(--)</td>
<td>(--)</td>
<td>(--)</td>
<td>(--)</td>
</tr>
</tbody>
</table>

\(^{a}\) *, ** 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.

<table>
<thead>
<tr>
<th>Soil property</th>
<th>Number of observations</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil P methods (mg/kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mod. Truog P</td>
<td>91</td>
<td>56.2</td>
<td>0.4</td>
<td>770.8</td>
<td>98.4</td>
</tr>
<tr>
<td>Bray I P</td>
<td>91</td>
<td>8.9</td>
<td>0.18</td>
<td>203.6</td>
<td>21.2</td>
</tr>
<tr>
<td>Olsen P</td>
<td>91</td>
<td>14.9</td>
<td>0.12</td>
<td>375.8</td>
<td>39.6</td>
</tr>
<tr>
<td>Double Acid P</td>
<td>91</td>
<td>5.0</td>
<td>0.13</td>
<td>81.5</td>
<td>10.5</td>
</tr>
<tr>
<td>Hydroxide-carb P</td>
<td>91</td>
<td>416.2</td>
<td>8.2</td>
<td>2580.4</td>
<td>603.9</td>
</tr>
<tr>
<td>Chloride-sulfate resin P</td>
<td>91</td>
<td>22.34</td>
<td>0.10</td>
<td>255.6</td>
<td>33.2</td>
</tr>
<tr>
<td>Chloride resin P</td>
<td>24</td>
<td>34.8</td>
<td>0.0</td>
<td>170.8</td>
<td>39.1</td>
</tr>
<tr>
<td>Isotope carrier P</td>
<td>77</td>
<td>16.2</td>
<td>0.0</td>
<td>324.9</td>
<td>41.5</td>
</tr>
<tr>
<td>Solution P</td>
<td>77</td>
<td>2.3</td>
<td>0.04</td>
<td>45.0</td>
<td>6.7</td>
</tr>
<tr>
<td>0.5 N H₂SO₄ P</td>
<td>91</td>
<td>350.7</td>
<td>16.0</td>
<td>1524.8</td>
<td>373.8</td>
</tr>
<tr>
<td>Organic P (mg kg⁻¹)</td>
<td>91</td>
<td>402.2</td>
<td>1.4</td>
<td>1983.2</td>
<td>360.9</td>
</tr>
<tr>
<td>P Buffering Capacity (1 kg⁻¹)</td>
<td>66</td>
<td>5062</td>
<td>45</td>
<td>38340</td>
<td>7416</td>
</tr>
</tbody>
</table>

P sorption (mg kg⁻¹) at:

<table>
<thead>
<tr>
<th>Concentration (mg P l⁻¹)</th>
<th>Number of observations</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>59</td>
<td>162</td>
<td>-150</td>
<td>1065</td>
<td>214</td>
</tr>
<tr>
<td>0.10</td>
<td>63</td>
<td>303</td>
<td>-80</td>
<td>1840</td>
<td>44.2</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>72</td>
<td>43.8a</td>
<td>2.5</td>
<td>85</td>
<td>44.2</td>
</tr>
<tr>
<td>pH</td>
<td>77</td>
<td>5.7</td>
<td>3.8</td>
<td>9.0</td>
<td>1.0</td>
</tr>
<tr>
<td>pH (KCl)</td>
<td>45</td>
<td>4.7</td>
<td>3.5</td>
<td>6.4</td>
<td>0.7</td>
</tr>
<tr>
<td>Organic C (%)</td>
<td>72</td>
<td>3.9</td>
<td>0.16</td>
<td>16.2</td>
<td>3.5</td>
</tr>
</tbody>
</table>
Table 5.5 (continued) Number of observations, mean, range and standard deviation for soil test P and other soil properties in topsoils.

<table>
<thead>
<tr>
<th>Soil property</th>
<th>Number of observations</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total N (%)</td>
<td>72</td>
<td>0.33</td>
<td>0.02</td>
<td>1.38</td>
<td>0.31</td>
</tr>
<tr>
<td>CEC (cmol(+)/kg⁻¹)</td>
<td>65</td>
<td>28.0</td>
<td>0.23</td>
<td>97.8</td>
<td>26.7</td>
</tr>
<tr>
<td>Base Saturation (%)</td>
<td>65</td>
<td>54.8</td>
<td>5.0</td>
<td>100.0</td>
<td>30.2</td>
</tr>
<tr>
<td>Exchangeable bases (cmol (+)/kg⁻¹)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>73</td>
<td>11.8</td>
<td>0.10</td>
<td>66.9</td>
<td>13.3</td>
</tr>
<tr>
<td>Mg</td>
<td>73</td>
<td>5.1</td>
<td>0.08</td>
<td>39.6</td>
<td>6.2</td>
</tr>
<tr>
<td>K</td>
<td>73</td>
<td>0.87</td>
<td>0.0</td>
<td>5.76</td>
<td>1.12</td>
</tr>
<tr>
<td>Na</td>
<td>73</td>
<td>0.69</td>
<td>0.0</td>
<td>6.20</td>
<td>1.08</td>
</tr>
<tr>
<td>Ex. Al (cmol (+)/kg⁻¹)</td>
<td>73</td>
<td>0.62</td>
<td>0.0</td>
<td>0.20</td>
<td>1.08</td>
</tr>
<tr>
<td>ECEC (cmol(+)/kg⁻¹)</td>
<td>73</td>
<td>19.3</td>
<td>1.8</td>
<td>104.0</td>
<td>1.17</td>
</tr>
<tr>
<td>Al Saturation (%)</td>
<td>73</td>
<td>10.1</td>
<td>0</td>
<td>89.8</td>
<td>19.9</td>
</tr>
<tr>
<td>Dith. Cit. extr. Fe (%)</td>
<td>50</td>
<td>6.1</td>
<td>0.13</td>
<td>33.0</td>
<td>5.7</td>
</tr>
<tr>
<td>Oxalate extr. Fe (%)</td>
<td>29</td>
<td>0.98</td>
<td>0.06</td>
<td>4.50</td>
<td>1.11</td>
</tr>
<tr>
<td>Phosphate retention (%)</td>
<td>36</td>
<td>54.1</td>
<td>1.00</td>
<td>100.0</td>
<td>27.4</td>
</tr>
<tr>
<td>Lime required (kg ha⁻¹)</td>
<td>73</td>
<td>0.70</td>
<td>0</td>
<td>6.4</td>
<td>1.31</td>
</tr>
<tr>
<td>CaCO₃ (%)</td>
<td>91</td>
<td>0.79</td>
<td>0.0</td>
<td>33.0</td>
<td>4.73</td>
</tr>
</tbody>
</table>

^ 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.

<table>
<thead>
<tr>
<th>Soil property</th>
<th>Number of observations</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil P methods</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(mg/kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mod. Truog P</td>
<td>142</td>
<td>17.1</td>
<td>0.20</td>
<td>194.1</td>
<td>25.3</td>
</tr>
<tr>
<td>Bray I P</td>
<td>142</td>
<td>2.1</td>
<td>0.02</td>
<td>13.4</td>
<td>2.9</td>
</tr>
<tr>
<td>Olsen P</td>
<td>142</td>
<td>4.4</td>
<td>0.10</td>
<td>41.9</td>
<td>5.7</td>
</tr>
<tr>
<td>Double Acid P</td>
<td>142</td>
<td>1.1</td>
<td>0.01</td>
<td>7.6</td>
<td>1.4</td>
</tr>
<tr>
<td>Hydroxide-carbonate P</td>
<td>142</td>
<td>160.4</td>
<td>2.1</td>
<td>3626.9</td>
<td>361.4</td>
</tr>
<tr>
<td>Choloride-sulfate resin P</td>
<td>142</td>
<td>6.0</td>
<td>0.10</td>
<td>45.5</td>
<td>9.0</td>
</tr>
<tr>
<td>Isotope carrier P</td>
<td>57</td>
<td>14.1</td>
<td>0.01</td>
<td>33.5</td>
<td>49.9</td>
</tr>
<tr>
<td>Solution P</td>
<td>39</td>
<td>0.23</td>
<td>0.02</td>
<td>0.68</td>
<td>0.17</td>
</tr>
<tr>
<td>0.5 N H₂SO₄ P</td>
<td>142</td>
<td>176.8</td>
<td>7.1</td>
<td>1256.2</td>
<td>210.3</td>
</tr>
<tr>
<td>Organic P (mg kg⁻¹)</td>
<td>142</td>
<td>182.7</td>
<td>0.0</td>
<td>936.4</td>
<td>142.9</td>
</tr>
<tr>
<td>P Buffering Capacity (1 kg⁻¹)</td>
<td>51</td>
<td>6319.0</td>
<td>131.0</td>
<td>33310.0</td>
<td>6878.0</td>
</tr>
<tr>
<td>P sorption (mg kg⁻¹) at:</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.02 mg P 1⁻¹</td>
<td>51</td>
<td>220.0</td>
<td>5.0</td>
<td>760.0</td>
<td>207.0</td>
</tr>
<tr>
<td>0.10 mg P 1⁻¹</td>
<td>51</td>
<td>521.0</td>
<td>51.0</td>
<td>2000.0</td>
<td>468.0</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>116</td>
<td>53.3a</td>
<td>0.7</td>
<td>88.7</td>
<td>46.2</td>
</tr>
<tr>
<td>pH</td>
<td>116</td>
<td>6.1</td>
<td>4.05</td>
<td>9.30</td>
<td>1.2</td>
</tr>
<tr>
<td>pH (KCl)</td>
<td>57</td>
<td>4.7</td>
<td>3.60</td>
<td>6.40</td>
<td>0.74</td>
</tr>
<tr>
<td>Organic C (%)</td>
<td>116</td>
<td>1.3</td>
<td>0.06</td>
<td>12.8</td>
<td>1.9</td>
</tr>
</tbody>
</table>
Table 5.6 (continued) Number of observations, mean, range and standard deviation for soil test P and other soil properties in subsoils.

<table>
<thead>
<tr>
<th>Soil property</th>
<th>Number of observations</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total N (%)</td>
<td>106</td>
<td>0.11</td>
<td>0.01</td>
<td>0.85</td>
<td>0.14</td>
</tr>
<tr>
<td>CEC (cmol(+)kg(^{-1}))</td>
<td>116</td>
<td>25.8</td>
<td>2.4</td>
<td>100.6</td>
<td>26.4</td>
</tr>
<tr>
<td>Base saturation (%)</td>
<td>116</td>
<td>61.2</td>
<td>1.0</td>
<td>100.0</td>
<td>33.3</td>
</tr>
<tr>
<td>Exchangeable bases (cmol(+) kg(^{-1}))</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>116</td>
<td>11.9</td>
<td>0.0</td>
<td>69.2</td>
<td>16.1</td>
</tr>
<tr>
<td>Mg</td>
<td>116</td>
<td>7.7</td>
<td>0.0</td>
<td>45.2</td>
<td>11.04</td>
</tr>
<tr>
<td>K</td>
<td>116</td>
<td>0.32</td>
<td>0.0</td>
<td>2.8</td>
<td>0.53</td>
</tr>
<tr>
<td>Na</td>
<td>116</td>
<td>2.2</td>
<td>0.0</td>
<td>23.6</td>
<td>5.1</td>
</tr>
<tr>
<td>Exch. Al (cmol(+) kg(^{-1}))</td>
<td>116</td>
<td>0.56</td>
<td>0.0</td>
<td>7.2</td>
<td>1.15</td>
</tr>
<tr>
<td>ECEC (cmol(+)kg(^{-1}))</td>
<td>116</td>
<td>21.3</td>
<td>0.30</td>
<td>120.0</td>
<td>29.6</td>
</tr>
<tr>
<td>Al saturation (%)</td>
<td>116</td>
<td>13.9</td>
<td>0.0</td>
<td>91.7</td>
<td>25.7</td>
</tr>
<tr>
<td>Dith.Cit.extr.Fe (%)</td>
<td>88</td>
<td>5.2</td>
<td>0.10</td>
<td>31.0</td>
<td>4.6</td>
</tr>
<tr>
<td>Oxalate extr.Fe (%)</td>
<td>25</td>
<td>1.2</td>
<td>0.0</td>
<td>57.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Phosphate retention (%)</td>
<td>52</td>
<td>53.1</td>
<td>0.0</td>
<td>100.0</td>
<td>26.6</td>
</tr>
<tr>
<td>Lime required (kg ha(^{-1}))</td>
<td>116</td>
<td>0.63</td>
<td>0.0</td>
<td>8.1</td>
<td>1.3</td>
</tr>
<tr>
<td>CaCO(_3) (%)</td>
<td>116</td>
<td>4.0</td>
<td>0.0</td>
<td>61.0</td>
<td>13.5</td>
</tr>
</tbody>
</table>

\(^a\) 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 ($P_{l1}$).

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).

<table>
<thead>
<tr>
<th>Equation</th>
<th>Number of observations</th>
<th>Root mean square error</th>
<th>$r^2$ a</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{il} = 0.28 \text{ MTP} + 6.15$</td>
<td>91</td>
<td>17.58</td>
<td>0.72</td>
</tr>
<tr>
<td>1.35 BP + 10.24</td>
<td>91</td>
<td>15.76</td>
<td>0.78</td>
</tr>
<tr>
<td>2.65 DP + 9.39</td>
<td>91</td>
<td>17.40</td>
<td>0.73</td>
</tr>
<tr>
<td>0.74 OP + 11.39</td>
<td>91</td>
<td>14.31</td>
<td>0.82</td>
</tr>
<tr>
<td>0.020 HP + 13.43</td>
<td>91</td>
<td>30.80</td>
<td>0.15</td>
</tr>
<tr>
<td>5.80 WP + 13.97</td>
<td>77</td>
<td>17.20</td>
<td>0.84</td>
</tr>
<tr>
<td>0.67 IP + 9.54</td>
<td>77</td>
<td>19.91</td>
<td>0.67</td>
</tr>
</tbody>
</table>

Subsoil

<table>
<thead>
<tr>
<th>Equation</th>
<th>Number of observations</th>
<th>Root mean square error</th>
<th>$r^2$ a</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{il} = 0.16 \text{ MTP} + 3.85$</td>
<td>142</td>
<td>8.37</td>
<td>0.14</td>
</tr>
<tr>
<td>2.66 BP + 0.73</td>
<td>142</td>
<td>4.96</td>
<td>0.70</td>
</tr>
<tr>
<td>4.66 DP + 1.64</td>
<td>142</td>
<td>6.68</td>
<td>0.47</td>
</tr>
<tr>
<td>1.18 OP + 1.11</td>
<td>142</td>
<td>5.95</td>
<td>0.57</td>
</tr>
<tr>
<td>0.011 HP + 4.23</td>
<td>142</td>
<td>8.00</td>
<td>0.21</td>
</tr>
<tr>
<td>1.10 WP + 3.30</td>
<td>57</td>
<td>9.49</td>
<td>0.003ns</td>
</tr>
<tr>
<td>-0.01 IP + 8.60</td>
<td>57</td>
<td>10.35</td>
<td>0.002ns</td>
</tr>
</tbody>
</table>

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 clay. Soils with CEC less than 16 cmol(+)/kg 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 deviation 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 $P_{11}$ was explained by the regression equations (Table 5.8). The strong extractants like 0.5 M $\text{H}_2\text{SO}_4$ and 0.25 M NaOH with 0.1 M Na$_2$CO$_3$ which assessed the quantity factor explained about 60% of the variation in $P_{11}$. 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 $P_{11}$. 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).

<table>
<thead>
<tr>
<th>Equation</th>
<th>Number of observations</th>
<th>Root mean square error</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{il} = 0.34 \text{ MTP} + 3.35$</td>
<td>120</td>
<td>8.91</td>
<td>0.91</td>
</tr>
<tr>
<td>$1.37 \text{ BP} + 6.77$</td>
<td>120</td>
<td>13.71</td>
<td>0.78</td>
</tr>
<tr>
<td>$2.71 \text{ DP} + 5.82$</td>
<td>120</td>
<td>14.65</td>
<td>0.76</td>
</tr>
<tr>
<td>$0.76 \text{ OP} + 6.53$</td>
<td>120</td>
<td>12.45</td>
<td>0.83</td>
</tr>
<tr>
<td>$0.07 \text{ HP} + 1.49$</td>
<td>120</td>
<td>18.38</td>
<td>0.61</td>
</tr>
<tr>
<td>$0.08 \text{ SP} + 3.89$</td>
<td>120</td>
<td>18.65</td>
<td>0.60</td>
</tr>
<tr>
<td>$5.97 \text{ WP} + 9.03$</td>
<td>68</td>
<td>14.02</td>
<td>0.86</td>
</tr>
<tr>
<td>$0.80 \text{ IP} + 6.92$</td>
<td>68</td>
<td>15.75</td>
<td>0.82</td>
</tr>
<tr>
<td>$187.30 \text{ SOLP} + 11.87$</td>
<td>73</td>
<td>19.70</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Slightly weathered soils

<table>
<thead>
<tr>
<th>Equation</th>
<th>Number of observations</th>
<th>Root mean square error</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{il} = 1.07 \text{ MTP} - 1.49$</td>
<td>70</td>
<td>5.14</td>
<td>0.85</td>
</tr>
<tr>
<td>$2.88 \text{ BP} - 0.30$</td>
<td>70</td>
<td>3.71</td>
<td>0.92</td>
</tr>
<tr>
<td>$5.97 \text{ DP} - 0.21$</td>
<td>70</td>
<td>3.41</td>
<td>0.93</td>
</tr>
<tr>
<td>$2.50 \text{ OP} - 2.19$</td>
<td>70</td>
<td>4.85</td>
<td>0.86</td>
</tr>
<tr>
<td>$0.094 \text{ SP} + 1.29$</td>
<td>70</td>
<td>11.08</td>
<td>0.29</td>
</tr>
<tr>
<td>$2.36 \text{ IP} + 3.89$</td>
<td>44</td>
<td>9.23</td>
<td>0.50</td>
</tr>
<tr>
<td>$658.98 \text{ SOLP} + 10.70$</td>
<td>15</td>
<td>8.23</td>
<td>0.59</td>
</tr>
</tbody>
</table>

Highly weathered soils

<table>
<thead>
<tr>
<th>Equation</th>
<th>Number of observations</th>
<th>Root mean square error</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{il} = 0.27 \text{ MTP} - 0.73$</td>
<td>21</td>
<td>5.19</td>
<td>0.92</td>
</tr>
</tbody>
</table>

Andisols
Table 5.8 (continued) Relationship between labile P $P_{\text{lab}}$ 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).

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

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 coefficients 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.

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

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

<table>
<thead>
<tr>
<th>Equation</th>
<th>Number of observations</th>
<th>Root mean square error</th>
<th>R² a</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Slightly weathered soils</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SP= 2.66 MTP + 140.59</td>
<td>120</td>
<td>166.9</td>
<td>0.64</td>
</tr>
<tr>
<td>8.49 BP + 172.21</td>
<td>120</td>
<td>223.4</td>
<td>0.34</td>
</tr>
<tr>
<td>15.53 DP + 175.25</td>
<td>120</td>
<td>235.6</td>
<td>0.29</td>
</tr>
<tr>
<td>4.70 OP + 172.85</td>
<td>120</td>
<td>221.0</td>
<td>0.36</td>
</tr>
<tr>
<td>0.73 HP + 83.34</td>
<td>120</td>
<td>125.5</td>
<td>0.79</td>
</tr>
<tr>
<td>36.14 WP + 202.3</td>
<td>68</td>
<td>258.1</td>
<td>0.39</td>
</tr>
<tr>
<td>4.61 IP + 142.94</td>
<td>68</td>
<td>191.6</td>
<td>0.49</td>
</tr>
<tr>
<td><strong>Highly weathered soils</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MTP= 2.34 BP + 2.93</td>
<td>70</td>
<td>4.6</td>
<td>0.84</td>
</tr>
<tr>
<td>4.94 DP + 2.76</td>
<td>70</td>
<td>3.4</td>
<td>0.91</td>
</tr>
<tr>
<td>2.18 OP + 0.30</td>
<td>70</td>
<td>3.6</td>
<td>0.90</td>
</tr>
<tr>
<td>0.036 HP + 8.31</td>
<td>70</td>
<td>10.6</td>
<td>0.15</td>
</tr>
<tr>
<td>0.11 SP + 1.97</td>
<td>70</td>
<td>8.5</td>
<td>0.45</td>
</tr>
<tr>
<td>2.24 IP + 4.85</td>
<td>44</td>
<td>7.8</td>
<td>0.56</td>
</tr>
<tr>
<td>BP= 0.34 MTP - 0.28</td>
<td>70</td>
<td>1.73</td>
<td>0.84</td>
</tr>
<tr>
<td>1.86 DP + 0.34</td>
<td>70</td>
<td>1.35</td>
<td>0.90</td>
</tr>
<tr>
<td>0.79 OP - 0.44</td>
<td>70</td>
<td>1.64</td>
<td>0.85</td>
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</table>
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.

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

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

<table>
<thead>
<tr>
<th>Equation</th>
<th>Number of observations</th>
<th>Root mean square error</th>
<th>R²a</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Andisols</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>HP = 48.66 OP + 820.47</td>
<td>21</td>
<td>698.4</td>
<td>0.43</td>
</tr>
<tr>
<td>1.83 SP + 76.48</td>
<td>21</td>
<td>563.1</td>
<td>0.64</td>
</tr>
<tr>
<td>SP = 4.50 MTP + 466.50</td>
<td>21</td>
<td>281.6</td>
<td>0.51</td>
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<tr>
<td>24.11 OP + 430.85</td>
<td>21</td>
<td>270.5</td>
<td>0.55</td>
</tr>
<tr>
<td>0.35 HP + 216.63</td>
<td>21</td>
<td>241.8</td>
<td>0.64</td>
</tr>
<tr>
<td><strong>Calcareous soils</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MTP = 19.61 + 41.93</td>
<td>22</td>
<td>46.4</td>
<td>0.63</td>
</tr>
<tr>
<td>17.49 OP + 17.00</td>
<td>22</td>
<td>57.4</td>
<td>0.44</td>
</tr>
<tr>
<td>BP = 0.03 MTP - 0.69</td>
<td>22</td>
<td>1.88</td>
<td>0.63</td>
</tr>
<tr>
<td>DP = 0.0027 SP - 0.05</td>
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<td>1.14</td>
<td>0.40</td>
</tr>
<tr>
<td>OP = 0.025 MTP + 1.52</td>
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<td>2.17</td>
<td>0.44</td>
</tr>
<tr>
<td>0.015 HP + 2.86</td>
<td>22</td>
<td>2.34</td>
<td>0.35**</td>
</tr>
<tr>
<td>0.0057 SP + 0.56</td>
<td>22</td>
<td>2.13</td>
<td>0.46</td>
</tr>
<tr>
<td>HP = 23.86 OP - 41.61</td>
<td>22</td>
<td>94.5</td>
<td>0.35**</td>
</tr>
<tr>
<td>148.05 DP + 315.6</td>
<td>22</td>
<td>268.7</td>
<td>0.40</td>
</tr>
<tr>
<td>81.22 OP + 231.2</td>
<td>22</td>
<td>254.9</td>
<td>0.46</td>
</tr>
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</table>

a: ** significant at p≤0.01 all other coefficients of determination are significant at p≤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 $r$) between different soil properties.

<table>
<thead>
<tr>
<th></th>
<th>pH</th>
<th>Organic C</th>
<th>Total N</th>
<th>Base Saturation</th>
<th>CEC</th>
<th>KCl-Al Extracted Al</th>
<th>Dith-cit. Extr. Fe-Fe retention</th>
<th>Phosphate Ca</th>
<th>Exch. cations Mg K Na</th>
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<td>-0.48</td>
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<td>Organic C</td>
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<td>Delta pH</td>
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Table 5.10 (continue) Some significant (<0.01) coefficients of correlation (Pearson's r) between different soil properties.

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<th>Total N</th>
<th>Base Saturation</th>
<th>CEC</th>
<th>KCl-Al Fe retention</th>
<th>Dith-cit. Phosphate</th>
<th>Exch. cations</th>
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<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
</tr>
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<td>0.63</td>
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<td>Exch. Ca</td>
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<table>
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<th>CaCO₃ (%)</th>
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<th>Total N</th>
<th>Clay (%)</th>
<th>CEC</th>
</tr>
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<tbody>
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<td>-0.55</td>
<td>0.92</td>
<td>0.51</td>
<td>0.59</td>
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</tr>
</tbody>
</table>

Calcareous soils

<table>
<thead>
<tr>
<th></th>
<th>(%)</th>
<th>(cmol(+)) kg⁻¹</th>
<th>(%)</th>
<th>(cmol(+)) kg⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaCO₃ (%)</td>
<td>-0.55</td>
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<td>0.56</td>
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</tr>
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<td>--</td>
<td>0.61</td>
<td>0.53</td>
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</tr>
<tr>
<td>Total N</td>
<td>--</td>
<td>0.51</td>
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</tr>
<tr>
<td>Clay (%)</td>
<td>--</td>
<td>0.59</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>CEC</td>
<td>--</td>
<td>0.89</td>
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</tr>
</tbody>
</table>

241
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.

<table>
<thead>
<tr>
<th></th>
<th>Resin P</th>
<th>Mod. Truog P</th>
<th>Bray P</th>
<th>Double Olsen acid P</th>
<th>Sulfuric Hydroxide acid P</th>
<th>Solution P</th>
<th>Isotope Organic P</th>
<th>F₁</th>
<th>Buffering capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Slightly weathered soils</strong></td>
<td></td>
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<td>Clay</td>
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<tr>
<td>Exch Ca</td>
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<td></td>
<td></td>
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<tr>
<td>Exch K</td>
<td>0.72</td>
<td>0.64</td>
<td>0.57</td>
<td>0.61</td>
<td>0.56</td>
<td>0.60</td>
<td>0.54</td>
<td>0.61</td>
<td>0.69</td>
</tr>
<tr>
<td>pH (KCl)</td>
<td>0.38</td>
<td>0.35</td>
<td>--</td>
<td>0.41</td>
<td>0.26*</td>
<td>0.45</td>
<td>0.32</td>
<td>0.37</td>
<td>0.36*</td>
</tr>
<tr>
<td>pH</td>
<td>0.18*</td>
<td>--</td>
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<td>--</td>
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<tr>
<td>Organic C</td>
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<td>Total N</td>
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<td></td>
</tr>
<tr>
<td>Base saturation</td>
<td>0.21*</td>
<td>0.19*</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.21*</td>
<td>--</td>
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</tr>
<tr>
<td>KCl-extr Al</td>
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<tr>
<td>Dith.-cit. Extr. Fe</td>
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<tr>
<td>Phosphorus retention</td>
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<tr>
<td>Organic P</td>
<td>0.35</td>
<td>0.36</td>
<td>0.26</td>
<td>--</td>
<td>0.22*</td>
<td>0.54</td>
<td>0.54</td>
<td>0.25*</td>
<td>1.00</td>
</tr>
<tr>
<td>Buffering capacity</td>
<td>-0.22*</td>
<td>--</td>
<td>--</td>
<td>-0.23*</td>
<td>--</td>
<td>--</td>
<td>--</td>
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</tr>
<tr>
<td>F₁</td>
<td>0.35</td>
<td>0.38</td>
<td>0.39</td>
<td>0.48</td>
<td>0.39</td>
<td>--</td>
<td>0.41</td>
<td>0.36</td>
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</tr>
</tbody>
</table>

| **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                     | --         | --                | --         | --                | --                     |
| Total N                  |         |              |        |                     |                          |            |                   |            |                   |
| Base saturation          | 0.39*   | --           | --     | --                  | --                       | --         | --                | --         | --                | --                     |
| KCl-extr Al              | -0.40*  | --           | --     | -0.44*              | --                       | -0.38*     | --                | --         | --                | --                     |
| Organic P                |         |              |        |                     |                          |            |                   |            |                   |
| Buffering capacity       | -0.57*  | --           | --     | -0.52*              | -0.54*                   | --         | --                | --         | --                | --                     |
| F₁                       | 0.86    | 0.83         | 0.80   | 0.86                | 0.78                     | --         | --                | --         | --                | 1.00                   |

243
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.

<table>
<thead>
<tr>
<th></th>
<th>Resin P</th>
<th>Mod. Truog P</th>
<th>Bray P</th>
<th>Double Olen P</th>
<th>Sulfuric acid P</th>
<th>Hydroxide Solution acid P</th>
<th>Isotope P</th>
<th>Organic P</th>
<th>Buffering capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Exch bases:</strong></td>
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<td>Organic C</td>
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<td>Base saturation</td>
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<td>Oxalate-Fe</td>
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<td>Organic P</td>
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<tr>
<td><strong>Andisols</strong></td>
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<tr>
<td><strong>Calcareous soils</strong></td>
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</tbody>
</table>
| *r significant at <5%, rest of the values presented are significant at <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 $P_{ill}$ 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 $P_{i1}$, (mg P/kg soil), soil test P (mg P/kg soil), and soil properties in four groups of soil.

<table>
<thead>
<tr>
<th>Equation</th>
<th>Number of observations</th>
<th>Root mean square error</th>
<th>$R^2$ b</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Slightly weathered soils</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{i1} = 0.30 \text{ MTP} + 5.85 \text{ K} + 1.48$</td>
<td>120</td>
<td>7.96</td>
<td>0.93</td>
</tr>
<tr>
<td>1.09 \text{ BP} + 10.59 \text{ K} + 2.71</td>
<td>120</td>
<td>11.39</td>
<td>0.85</td>
</tr>
<tr>
<td>2.16 \text{ DP} + 9.58 \text{ K} + 2.42</td>
<td>120</td>
<td>13.03</td>
<td>0.81</td>
</tr>
<tr>
<td>0.62 \text{ OP} + 10.09 \text{ K} + 2.62</td>
<td>120</td>
<td>10.02</td>
<td>0.89</td>
</tr>
<tr>
<td>0.05 \text{ HP} + 13.02 \text{ K} - 2.16</td>
<td>120</td>
<td>15.26</td>
<td>0.73</td>
</tr>
<tr>
<td>4.82 \text{ WP} + 10.01 \text{ K} + 4.12</td>
<td>68</td>
<td>11.06</td>
<td>0.91</td>
</tr>
<tr>
<td>0.64 \text{ IP} + 11.02 \text{ K} + 2.49</td>
<td>68</td>
<td>14.20</td>
<td>0.85</td>
</tr>
<tr>
<td>24.03 \text{ KC} + 1.67</td>
<td>120</td>
<td>20.56</td>
<td>0.52</td>
</tr>
<tr>
<td><strong>Highly weathered soils</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{i1} = 2.32 \text{ Ca}^2 - 5.32 \text{ Ca} + 2.62$</td>
<td>30</td>
<td>5.70</td>
<td>0.75</td>
</tr>
<tr>
<td>15.70 \text{ CaK} + 0.24</td>
<td>30</td>
<td>4.25</td>
<td>0.86</td>
</tr>
<tr>
<td>51.05 \text{ K} - 0.89</td>
<td>30</td>
<td>7.91</td>
<td>0.52</td>
</tr>
<tr>
<td><strong>Andisols</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{i1} = -11.97 + 60.37 \ln(1 - \Delta \text{pH})$</td>
<td>13</td>
<td>8.91</td>
<td>0.53*</td>
</tr>
<tr>
<td>$-76.09 [\text{Na} \times \ln(1 - \Delta \text{pH})]$*</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th>Equation</th>
<th>Number of observations</th>
<th>Root mean square error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcareous soils</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{il} = 0.074 \text{CEC}^{d} - 0.0032 \times \text{Na} \times \text{CEC} + 0.20$</td>
<td>22</td>
<td>2.82</td>
</tr>
</tbody>
</table>


b All coefficient of determination ($r^2$) are significant 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 variable 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 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).

$$\sigma_v = \left(\frac{2nekT}{\pi}\right)^{1/2} \sinh 1.15z(pH_0 - pH)$$

(5.6)

where $\sigma_v = \text{surface charge density for variable charge colloids in C/m}^2$
Thus, it would be possible to increase the cation retention of variable charged soil by lowering pH$_0$. 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$_0$). The negative slope is due to adsorption of P on positively charge colloids. Ayres and Hagihiara (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 surface 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.

Highly weathered soils

RESIN P = 2.32Ca² - 5.32Ca + 2.62

$R^2 = 0.75^{***}$
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 anomalous 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,

\[ \text{Olsen P} = 0.33 \times \text{Ca} + 0.26 \times (\text{Ca} \times \text{K}) - 1.58 \quad (r^2=0.37, P>0.999, N=50) \]

**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<sub>O</sub>) (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<sub>2</sub>SO<sub>4</sub> after ignition at 550°C was increased and resulted in erroneously high P<sub>O</sub> values. In the present study 0.5 N H<sub>2</sub>SO<sub>4</sub> 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.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Ignition</th>
<th>Extraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torroxic Haplustoll</td>
<td>126.0</td>
<td>144.1</td>
</tr>
<tr>
<td>Typic Eutrandept</td>
<td>917.3</td>
<td>885.4</td>
</tr>
<tr>
<td>Oxic Dystrandept</td>
<td>755.7</td>
<td>1173.6</td>
</tr>
<tr>
<td>Hydric Dystrandept</td>
<td>62.2</td>
<td>1094.5</td>
</tr>
<tr>
<td>Ustoxic Humitropept</td>
<td>832.0</td>
<td>706.5</td>
</tr>
<tr>
<td>Tropeptic Eutrustox</td>
<td>239.5</td>
<td>145.3</td>
</tr>
<tr>
<td>Typic Gibbsihumox</td>
<td>285.1</td>
<td>267.4</td>
</tr>
<tr>
<td>Typic Paleudult</td>
<td>75.6</td>
<td>92.6</td>
</tr>
</tbody>
</table>
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:

$$P_o = 754.5 \times \text{Total N} + 122.8$$  \hspace{1cm} (5.7)

$$= 67.9 \times \text{Organic C} + 110.3$$  \hspace{1cm} (5.8)

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

$$P_o = 812.6 \times \text{Total N} + 116.3$$  \hspace{1cm} (5.9)

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

$$P_o = 71.4 \times \text{Organic C} + 112.8$$  \hspace{1cm} (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,

$$P_o = 754.5 \times \text{Total N} + 114.8$$  \hspace{1cm} (5.11)

or to ($R^2 = 0.5$, $P > 0.999$, $N = 105$) to organic C,

$$P_o = 64.7 \times \text{Organic C} + 109.9$$  \hspace{1cm} (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 available. In the highly weathered soils hydroxide- P (N = 70) and CEC/Z clay (N = 28) explained 47% and 41% of the variation in P₀, respectively. Together the two (N = 28), explained 64% of the variation (Table 5.14). The R² of 0.47 may be preferred over R² = 0.64 because errors in estimation of P₀ 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 P₀ was positively related to Pᵢ₁, 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.

<table>
<thead>
<tr>
<th>Equation</th>
<th>Number of observations</th>
<th>Root mean square error</th>
<th>$R^2$ a</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Slightly weathered soils</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{o}= 91.72 + 88.25 \text{ Org C} - 4.32 \times (\text{Org C})^2$</td>
<td>120</td>
<td>118.0</td>
<td>0.45</td>
</tr>
<tr>
<td>$92.07 + 74.19 \text{ Org C} - 3.94 \times (\text{Org C})^2 + 22.56(\text{Org C} \times K)$</td>
<td>120</td>
<td>114.3</td>
<td>0.49</td>
</tr>
<tr>
<td>$74.47 + 80.94 \text{ Org C} - 3.85 \times (\text{Org C})^2 + 0.17 \text{ HP}$</td>
<td>120</td>
<td>106.9</td>
<td>0.55</td>
</tr>
<tr>
<td><strong>Highly weathered soils</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{o}= 0.48 \text{ HP} + 117.20$</td>
<td>70</td>
<td>63.9</td>
<td>0.47</td>
</tr>
<tr>
<td>$10.19 \text{ CEC}^b + 65.15$</td>
<td>28</td>
<td>85.6</td>
<td>0.41</td>
</tr>
<tr>
<td>$0.42 \text{ HP} + 6.62 \text{ CEC} + 58.5$</td>
<td>28</td>
<td>67.8</td>
<td>0.64</td>
</tr>
<tr>
<td><strong>Andisols</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{o}= 331.03 \text{ K} + 608.91$</td>
<td>20</td>
<td>310.1</td>
<td>0.54</td>
</tr>
<tr>
<td>$266.21 \text{ K} + 360.43 \text{ N}^* + 394.1$</td>
<td>20</td>
<td>300.3</td>
<td>0.61</td>
</tr>
</tbody>
</table>

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 \( P \) sorption curve utilized the procedure of Fox and Kamprath (1970). A wide range of \( P \) sorption values ranging from \(-150 \text{ mg } P \text{ kg soil}^{-1}\) to \(1065 \text{ mg } P \text{ kg soil}^{-1}\) were required to achieve a solution \( P \) level of \(0.02 \text{ mg } P \text{ l}^{-1}\) (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 (1/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/1) was also determined at the above range of P in solution. The availability index of P for all soils ranged from \( 2.61 \times 10^{-5} \) to \( 0.02 \) kg \( 1^{-1} \) (Appendix 5.3-5.6). The calcareous soils (mean = \( 3.26 \times 10^{-3} \) kg \( 1^{-1} \)) in general had the highest P availability as P in solution per unit of P fertilizer applied while the Andisols (mean = \( 9.65 \times 10^{-5} \) kg \( 1^{-1} \)) 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 \( F_{11} \) (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/l), buffering capacity (1/kg) and soil properties.

<table>
<thead>
<tr>
<th>Equation</th>
<th>Number of observations</th>
<th>Root mean square error</th>
<th>$R^2$ a</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Slightly weathered soils</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_1 = 0.0000354 P_{ill} + 0.0000435 PR + 0.026$</td>
<td>48</td>
<td>0.0013</td>
<td>0.64***</td>
</tr>
<tr>
<td>$= 0.0000356 P_{ill} + 0.0000138 BS + 0.000011 CEC^2 - 0.000114$</td>
<td>76</td>
<td>0.0016</td>
<td>0.49***</td>
</tr>
<tr>
<td>$BC = 131.9 PR - 78.92 BS + 190.82$</td>
<td>48</td>
<td>2990.0</td>
<td>0.70***</td>
</tr>
<tr>
<td>$= 541.7 Org C - 324.9 BS + 2.13 BS^2 + 12900$</td>
<td>76</td>
<td>3336.0</td>
<td>0.54***</td>
</tr>
<tr>
<td>$= 253.7 CEC - 318.3 BS + 1.92 BS^2 - 2.48 CEC^2 + 10660$</td>
<td>76</td>
<td>191.0</td>
<td>0.59***</td>
</tr>
<tr>
<td><strong>Highly weathered soils</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_1 = 0.0000185 P_{ill} + 0.00000318 BS + 0.00000581$</td>
<td>13</td>
<td>0.00012</td>
<td>0.78***</td>
</tr>
<tr>
<td>$BS = 21311.9 Na - 408.46 P_{ill} + 5125.4$</td>
<td>13</td>
<td>3874.0</td>
<td>0.56**</td>
</tr>
<tr>
<td><strong>Andisols</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_1 = 0.000128 \ln(1- \Delta pH) + 0.000067 K \ln(1- \Delta pH) + 0.0000301$</td>
<td>12</td>
<td>0.000036</td>
<td>0.87***</td>
</tr>
<tr>
<td>$BC = 48200 \ln(1- \Delta pH) - 4380 K + 45300$</td>
<td>12</td>
<td>3717.0</td>
<td>0.90***</td>
</tr>
<tr>
<td><strong>Calcareous soils</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_1 = 0.00724 pH - 0.055$</td>
<td>9</td>
<td>0.002</td>
<td>0.73**</td>
</tr>
<tr>
<td>$0.0186 - 0.0109 Fe$</td>
<td>9</td>
<td>0.0014</td>
<td>0.94**</td>
</tr>
<tr>
<td>$0.0185 - 0.0088 Fe - 0.003 Org C$</td>
<td>9</td>
<td>0.0008</td>
<td>0.99**</td>
</tr>
<tr>
<td>$BC = 14.04 CEC - 41.64 P_{ill} + 263.27$</td>
<td>9</td>
<td>150.0</td>
<td>0.85**</td>
</tr>
</tbody>
</table>

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

** Significant at $p \leq 0.01$. 

- Slightly weathered soils
- Highly weathered soils
- Andisols
- Calcareous soils
P sorption is reduced by additions of fertilizer P (Barrow, 1974). Since phosphate retention is not routinely measured for slightly weathered soils, $F_1$ was related to CEC. For these soils an increase in $P_{ill}$ 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 $\Delta pH$ of the soils and exchangeable K content (cmol(+)/kg soil$^{-1}$). A decrease in $\Delta pH$ 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 $\Delta pH$ 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 $\Delta pH$ 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 \( \text{NH}_4\text{OAc} \) (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/l (PS02) and 0.10 mg P/l (PS10) from buffering capacity and soil properties

<table>
<thead>
<tr>
<th>Equation</th>
<th>Number of observations</th>
<th>Root mean square error</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Slightly weathered soils</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PS02=0.024 BC + 45.78</td>
<td>72</td>
<td>100.47</td>
<td>0.58</td>
</tr>
<tr>
<td>1.90 BS + 4.18 PR + 48.46</td>
<td>44</td>
<td>116.03</td>
<td>0.58</td>
</tr>
<tr>
<td>1.638 + 5.19 PR - 20.25 Org C + 37.55</td>
<td>44</td>
<td>111.92</td>
<td>0.62</td>
</tr>
<tr>
<td>PS10=0.074 BC + 77.01</td>
<td>75</td>
<td>143.66</td>
<td>0.86</td>
</tr>
<tr>
<td>9.08 BS + 5.51 CEC + 782.69</td>
<td>75</td>
<td>293.74</td>
<td>0.44</td>
</tr>
<tr>
<td>5.54 BS + 12.12 PR + 112.73</td>
<td>47</td>
<td>243.80</td>
<td>0.72</td>
</tr>
<tr>
<td><strong>Highly weathered soils</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PS02=0.037BC-11.08</td>
<td>15</td>
<td>79.8</td>
<td>0.87</td>
</tr>
<tr>
<td>1048.94 Na - 16.51 Pᵢl + 154.09</td>
<td>12</td>
<td>126.6</td>
<td>0.72</td>
</tr>
<tr>
<td>PS10=0.065 BC - 81.86</td>
<td>15</td>
<td>84.0</td>
<td>0.95</td>
</tr>
<tr>
<td>1572.23 Na - 29.17 Pᵢl + 418.33</td>
<td>12</td>
<td>205.98</td>
<td>0.72</td>
</tr>
<tr>
<td>1302.96 Na - 4.82 BS - 23.00 Pᵢl</td>
<td>12</td>
<td>192.38</td>
<td>0.80</td>
</tr>
<tr>
<td><strong>Andisols</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PS02=0.025BC + 51.82</td>
<td>15</td>
<td>92.40</td>
<td>0.90</td>
</tr>
<tr>
<td>-1224.99 ln ΔpH - 147.21 K + 1246.57</td>
<td>12</td>
<td>102.80</td>
<td>0.90</td>
</tr>
<tr>
<td>PS10=0.1040 BC + 442.90</td>
<td>15</td>
<td>271.78</td>
<td>0.74</td>
</tr>
<tr>
<td>-2174.26 ln ΔpH - 272.75 K + 2535.89</td>
<td>12</td>
<td>224.42</td>
<td>0.86</td>
</tr>
<tr>
<td><strong>Calcareous Soils</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PS10=0.41 CEC + 50.07</td>
<td>9</td>
<td>3.22</td>
<td>0.56*</td>
</tr>
<tr>
<td>PS10=0.038 BC + 47.67</td>
<td>9</td>
<td>14.52</td>
<td>0.46*</td>
</tr>
</tbody>
</table>

* Significant at p ≤ 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-Na₂SO₄ resin instead of NaHCO₃ 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
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.
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 unsatisfactory under non-equilibrium conditions (recently disturbed and highly fertilized soils).
Figure 5.8 Validation of the relationship between (A) modified Truong P and Olsen P, (B) Bray I P and Olsen P, and (C) Bray I P and modified Truong P for the Andisols.
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_i1, CEC and (CEC)^2 as independent variables) and highly weathered soils (with P_i1 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.
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 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 \( P_{\text{ill}} \) was not related to double acid P.

5. Labile P was positively correlated with exchangeable bases. On slightly weathered soils, exchangeable K alone explained more than 50% of the variation in \( P_{\text{ill}} \). On low activity clays K x Ca interaction explained more than 85% of variability in \( P_{\text{ill}} \). 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 \( P_{\text{ill}} \) 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 \( P_{\text{ill}} \) and base saturation explained over 75% of variation in P availability. 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 oversimplification 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 (P_{ia}) is simulated as:

\[ R_{la} = 0.1[P_{il} - P_{ia}]F_l/(1-F_l) \]

(6.1)

The initial size of P_{ia} is estimated as:

\[ P_{ia} = P_{il}(1-F_l) \]

(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:

\[ P_{il} = P_{ia}F_l/(1-F_l) \]

(6.3)

In the above equations F_l is the fraction of fertilizer P (P_f) which is labile after the incubation period:

\[ F_l = (P_{i1f} - P_{i1i})/P_f \]
\( P_{li} \) and \( P_{lf} \) are labile P value prior to and after fertilization, respectively. In Equation (6.1) \( F_i \) and \( F_m \) 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:

\[
R_{as} = K_{as}(4P_{ia} - P_{is})
\] (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 be 0.00076 d\(^{-1}\) in all calcareous soils. They also reanalyzed available data on noncalcareous soils (Cox et al., 1981; Yost et al., 1981; Russell, 1973) and came up with:

\[
K_{as} = \exp(-1.77F_1 - 7.05)
\] (6.5)

In their model the immobilization of labile P and mineralization of organic P is similar to the N mineralization-immobilization routine of PAPRAN (Seligman and Van Keulen, 1981). PAPRAN allows the availability of inorganic N and P 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 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 $P_{c1}$ (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$^{-1}$ 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.

<table>
<thead>
<tr>
<th>Site/block</th>
<th>Type of Experiment</th>
<th>Soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAL-B21</td>
<td>P-residual</td>
<td>Hydric Dystrandept</td>
</tr>
<tr>
<td>KUK-A21</td>
<td>P-residual</td>
<td>Hydric Dystrandept</td>
</tr>
<tr>
<td>KUK-C11</td>
<td>P-residual</td>
<td>Hydric Dystrandept</td>
</tr>
<tr>
<td>KUK-C12</td>
<td>P-residual</td>
<td>Hydric Dystrandept</td>
</tr>
<tr>
<td>KUK-D11</td>
<td>P-residual</td>
<td>Hydric Dystrandept</td>
</tr>
<tr>
<td>KUK-D20</td>
<td>P-applied</td>
<td>Hydric Dystrandept</td>
</tr>
<tr>
<td>MOL-A10</td>
<td>P-applied</td>
<td>Tropeptic Eutrustox</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Site/Block</th>
<th>Phosphorus Applied (Coded level)</th>
<th>-.85</th>
<th>Opt</th>
<th>+.85</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAL-B21a</td>
<td>Observed</td>
<td>7697±525</td>
<td>8194±264</td>
<td>8169±815</td>
</tr>
<tr>
<td></td>
<td>Simulation 1</td>
<td>7100</td>
<td>8210*</td>
<td>8848*</td>
</tr>
<tr>
<td></td>
<td>Simulation 2</td>
<td>7950*</td>
<td>8002*</td>
<td>8600*</td>
</tr>
<tr>
<td>KUK-A21a</td>
<td>Observed</td>
<td>6039±917</td>
<td>6993±607</td>
<td>7852±1591</td>
</tr>
<tr>
<td></td>
<td>Simulation 1</td>
<td>5780*</td>
<td>7004*</td>
<td>8692*</td>
</tr>
<tr>
<td></td>
<td>Simulation 2</td>
<td>5284*</td>
<td>6190</td>
<td>7408*</td>
</tr>
<tr>
<td>KUK-C11a</td>
<td>Observed</td>
<td>7123±539</td>
<td>8917±100</td>
<td>8768±433</td>
</tr>
<tr>
<td></td>
<td>Simulation 1</td>
<td>6004</td>
<td>8991*</td>
<td>9179</td>
</tr>
<tr>
<td></td>
<td>Simulation 2</td>
<td>6775*</td>
<td>9213</td>
<td>9213</td>
</tr>
<tr>
<td>KUK-C12a</td>
<td>Observed</td>
<td>8462±697</td>
<td>9230±550</td>
<td>9262±509</td>
</tr>
<tr>
<td></td>
<td>Simulation 1</td>
<td>8972*</td>
<td>10009</td>
<td>10009</td>
</tr>
<tr>
<td></td>
<td>Simulation 2</td>
<td>9327</td>
<td>10031</td>
<td>10031</td>
</tr>
<tr>
<td>KUK-D11a</td>
<td>Observed</td>
<td>7003±1132</td>
<td>7937±835</td>
<td>8471±354</td>
</tr>
<tr>
<td></td>
<td>Simulation 1</td>
<td>7450*</td>
<td>9460</td>
<td>9700</td>
</tr>
<tr>
<td></td>
<td>Simulation 2</td>
<td>7933*</td>
<td>9340</td>
<td>9582</td>
</tr>
<tr>
<td>KUK-D20</td>
<td>Observed</td>
<td>6751±1200</td>
<td>8212±533</td>
<td>8828±365</td>
</tr>
<tr>
<td></td>
<td>Simulation 1</td>
<td>5200</td>
<td>7942*</td>
<td>9802</td>
</tr>
<tr>
<td></td>
<td>Simulation 2</td>
<td>7697*</td>
<td>8519*</td>
<td>9904</td>
</tr>
<tr>
<td>MOL-A10</td>
<td>Observed</td>
<td>8451±477</td>
<td>9887±478</td>
<td>10460±650</td>
</tr>
<tr>
<td></td>
<td>Simulation 1</td>
<td>7780</td>
<td>9723*</td>
<td>11034*</td>
</tr>
<tr>
<td></td>
<td>Simulation 2</td>
<td>8600*</td>
<td>9948*</td>
<td>11018*</td>
</tr>
</tbody>
</table>

a  Phosphorus - residual experiments.
* Within $\pm$ 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 1\(^{-1}\)) 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 data 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 Eutrudept 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\(^{\circ}\)S latitude to 21\(^{\circ}\) 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
00050 C
00060 C
00070 C
00080 C
00090 C
00100 C
00110 C
00120 C
00130 C
00140 C
00150 C
00160 C
00170 C
00180 C
00190 C
00200 C
00210 C
00220 C
00230 C
00240 C
00250 C
00260 C
00270 C
00280 C
00290 C
00300 C
00310 C
00320 C
00330 C
00340 C
00350 C
00360 C
00370 C
00380 C
00390 C
00400 C
00410 C
00420 C
00430 C
00440 C
00450 C
00460 C
00470 C
00480 C
00490 C
00500 C

CERES CORN NITROGEN MODEL

00190 REAL LAT, LAI, LL, LFWT, NDEF1, NDEF2, NDEF3, NDEF4, INSOL
00200 COMMON /PARAM/ ISOIL, IIRR, IWETH, ISOW, PLANTS, KOUTGR, KOUTWA, SDEPTH,
00210 LAT, KVARTY, KIRR, KSOIL, IQUIT, NEWSOL, NEWWET, MULTY, ISWSWB
00220 , PRINT, KNIT, IODEATE, XYIELD, XGRWT, XGPFM, XGPA, XLAI, XBIOM, ISLKD,
00230 3 MATJD, INSOIL
00240 COMMON /YLDLS/ YIELD
00250 COMMON /GENET/ P1, P2, P3, P4, P5, G2, C3
00260 COMMON /SOIL/ SALB, U, SWCON, DLAYR(10), DUL(10), LL(10), SW(10),
00270 1 SAT(10), DEPNX, TDL, NLAYR, SMX, WF(10), WR(10), RWU(10), SWEP, CN2
00280 COMMON /IRRIG/ NRWR, 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), NIRS
00320 COMMON /WATER/ SMS2, SMS2P, T, TLL, PESW, TSW, COMDEP, ESW(10),
00330 1 CSDI, CSDB, SIL6, SIL6, LCSURD, ES, EF, ET, ES, CES, CEP, CET,
00340 1 RLW(10), PRECIP, CRAIN, DRAIN, IDBSW, BTDEP, SWDF1, SWDF2,
00350 1 SWDF3, SWUW, RWUX,
00360 COMMON /WRITS/ AES, AEP, AET, AEO, ASOLR, ATENH, ATEMN, ARUNOF,
00370 1 ADRAIN, APREC, ASWDF1, ASWDF2, IOUTGR, IOUTWA, JHEAD, KHEAD,
00380 2 TPRECP, RUNOFF
00390 COMMON /PHNL/ P9, CUMDTH, TBASE, SUMDTH, S1, C1, ISTATE,
00400 1 DTT, IDUR, SIND, TEMPM
00410 COMMON /GROTH/ GPM, GPP, GORT, 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, TILNO, SMAX, FACILI,
00440 IRWDT, SUMP, IDURP, FLAG, EGFT, GROSTM, CARBO, BLAMX(35), GBLA(35),
00450 1 SLA(35), NLI, NLMAX, EARS
00460 COMMON /NCTRL/ ROUTMA, ROUTNU, ROUTNU, MINCK, NHDMN, NHDOF,
00470 1 IFPERT, KPERT, ISWIT, MGMD, XSTRAW, GRFTCN, GRFTN, XTOTNP, XAPTNP
00480 2, XGNUP
00490 COMMON /NFERTB/ JFDAY(10), AFERT(10), DFERT(10), NFERT, IFTYPE(10)
00500 COMMON /NROOT/ RNFACT(10), RNLOSS(10), JJ
Appendix 3.1 (continued) Program listing of CERES maize model.

```
00510 COMMON /NSPOOL/ SNAH4(10),SN03(10),NH4(10),NO3(10),FAC(10),
00520 1 BD(10),PH(10)
00530 COMMON /NPLANT/ GRAINN,ROOTN,STOVN,PDWI,STOVWT,PGRONT,NDEM
00540 COMMON /NWRITE/ ATANC,ATCNP,ARCNP,ARDEM2,AXNUP,ARTN,ASTOVN,
00550 1 AGR,CTNUP,TMUP,APTUP
00560 COMMON /NAMCL/ TANC,TCNP,RCNP,RANC,TMNC,VANC,VNNC,XSTAGE
00570 10 CALL PROGRI
00580 40 REWIND IWETH
00590 0000600 IYR = 1
00600 000610 IF (ISWSWB.NE.0) CALL SOILRI
00620 NYRS = MULTYR + 1
00630 IF (ISWSWB.NE.0) CALL SOILNI
00640 60 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 (ISWSWB.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 (ISWSWB.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
00870 C
00880 C
00890 C
00900 C
00910 C
00920 C
00930 C
00940 C
00950 C
00960 C
00970 C
00980 C
00990 C
01000 C
01010 C
```

Program initialization
Appendix 3.1  (continued) Program listing of CERES maize model;

01020 COMMON /WRITS/ AES, AEP, AET, AEO, ASOLR, ATEMX, ATENN, ARUJOYF,
01030 1 ADRAIN, APREC, ASDF1, ASDF2, IOUTGR, IOUTWA, JHEAD, KHEAD,
01040 2 TPREC, RUNOFF
01050 COMMON /PHENL/ P9, CUMDTT, TBASE, SUMDTT, S1, C1, ISTAGE,
01060 1 DTT, IDUR, SINC, TEMPM
01070 COMMON /GROTH/ GPSM, GPP, GRROT, PTF, LAI, DM, BIOMAS, PLA, SENLA,
01080 1 LFWT, SEEDRVD, RCHM, XPLANT, WIDT, EMAT, SWL, PLAT, PLAX,
01090 1 RTWT, STMWT, GRWNT, SWMIN, LN, EARWT, TLNO, SWMAX, FACLI,
01100 IKWID, SUMP, IDURF, PLAG, SGHF, GROSTM, CARBO, BLAMX(35), GBLA(35),
01110 1 SIA(35), NLI, NLMAX, EARS
01120 COMMON /NCTRL/ KOOTMN, IOOTMN, KOOTNU, IOOTNU, MINCK, NHDMN, NHDUP,
01130 1 IFRNT, KFERT, ISWINIT, DMOIT, XSTRAW, GRPCTN, CRPTN, XTOTNP, XAPTNP
01140 2, XGNUP
01150 COMMON /NDFPG/ NDEF1, NDEF2, NDEF3, NDEF4, GNP, CNSD1, CNSD2
01160 COMMON /NWRITP/ ATANC, ATCHP, ATANC, ARCHF, ANDEM2, ATNUP, ARTN, ASTOVN,
01170 1 AGRN, CTNUP, TNUM, APTNUP
01180 COMMON /NCONC/ TANC, TCNP, BCNP, RANC, TMNC, VANC, VMNC, XSTAGE
01190 COMMON /NPLANT/ GRAINN, ROOTN, STOVN, PDWI, STOVWT, PGRWT, NDEM
01200 COMMON /NSPOOL/ SNH4(10), SNO3(10), NH4(10), NO3(10), FAC(10),
01210 1 BD(10), PH(10)
01220 DIMENSION VARTY(5)
01230 NAMELIST /FARM/ IRSOL, IRWTH, ISOW, PLANTS, SDEPTH,
01240 1 LAT, KVARY, KIRR, KSOL, IQUIT, NEWSOL, NEWWET, MULTR,
01250 2 IOUTWA, KOUTGR, ISWSWB, ISWINIT, PRINT, KNIT, U
01260 3 IODATE, XYIELD, XGRWT, GPSSM, XGPF, XLAI, XBOM, ISLKD, MATJD, ISOIL
01270 NAMELIST /NPARM/ KOOTMN, IOOTMN, KOOTNU, IOOTNU, MINCK,
01280 1 IFRNT, KFERT, DMOIT, XSTRAW, GRPCTN, CRPTN, XTOTNP, XAPTNP, XGNUP
01290 COMMON (13,80) TITLE
01300 WRITE (6,90) TITLE
01310 READ (13,FARM,END=10)
01320 COMMON (13,SPARM,END=20)
01330 READ (13,FARM,END=10)
01340 20 IF (IQUIT.EQ.999) GO TO 70
01350 IF (NEWWET.EQ.0) REWIND IYETH
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=0.0
01480 DO 12 I=1,8
01490 TMFAC(I)=0.931+.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 NDEFl=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 ROOTW=0.0
01680 GN=1.0
01690 TNUP=0.0
01700 NHDMN=0
01710 NHDUP=0
01720 IF (ISWNIT.EQ.0) GO TO 30
01730 CALL OOTNU
01740 CALL OUTNU
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 PRECP=0.
01850 REMIND 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 (6,1A0) 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.

02040 120 FORMAT (' CROP VARIETY INFORMATION IS MISSING FOR ',I5)
02050 130 FORMAT (6X,'VARIETY NUMBER ',14,' VARIETY NAME ',5A4)
02060 140 FORMAT (/IX,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 NATURE FOR SINGLE YEAR RUN')
02090 END
02100 C
02110 C
02120 C
02130 SUBROUTINE SOILRI
02140 REAL LAT,NOUT,NUP,LL,LAI,LFWr,INSOIL
02150 COMMON /PARAM/ ISOIL,IIRR,IWETH,ISOW,PLANTS,KOUTGR,KOUTWA,SDEPTH,
02160 1 LAT,KVARTY,KIRR,KSOIL,QUIT,NEWSOL,NEWWET,MULTTR,ISWSWB
02170 2 ,PRINT,KNIT,IODATE,XYIELD,XGRWT,XGPSM,XGPE,XLAI,EBIOM,ISLKJD,
02180 3 ,MATJD,INSOIL
02190 COMMON /SOILI/ SALB,D,SWCON,DLAYR(10),DUL(10),LL(10),SW(10),
02200 1 SAT(IO),DEFMAX,TDUL,NLAYR,SWX,WF(10),WR(10),RWU(IO),SWF(10),CN2
02210 COMMON /IRRIG/ NIRR,JDAY(26),AIRR(26)
02220 COMMON /WATER/ SUMS1,SUMS2,T,TL,PESW,TSW,CUMDEP,ESW(IO),
02230 1 CSOL,CSOL,SOI1,SI2(6),ICSDUR,ES,ET,EO,CES,CEP,CET,
02240 2 ,RLV(IO),PRECIP,CRAIN,DRAIN,IDRSW,RDEP,SDWP1,SDWP2,
02250 3 ,SDWP3,TBWN,RWUMX
02260 COMMON /NSPOOL/ SNH4(IO),SN03(IO),NH4(IO),N03(IO),FAC(IO),
02270 1 BD(IO),PB(10)
02280 COMMON /PREKL/ P9,CUMDTT,TSBASE,SUNDTT,SI,Cl,ISTAGE,
02290 1 DTT,DIUR,SIN,S2PM,
02300 COMMON /GROTH/ GPSM,GPP,GRO,PTL,LA,DM,BIOM,PLA,SENLA,
02310 1 LFWD,SEEDEW,ECM,TDUL,SLW,PLAY,PLAX,
02320 2 ,RTW,TSTW,GRNWT,SWMIN,LN,EARWT,TLNO,SWMAX,FACLI,
02330 3 ,RWID,SUMP,DIURR,PLAG,EFGT,GROSTM,CARBO,BLAXM35,GRAL35,
02340 4 ,SLA(35),NLI,NLMAX,EAR
02350 COMMON /NMOYE/ FLUX(IO),SMA(IO),FLOW(IO),MU,NOUT(IO),NUP(IO)
02360 COMMON /NSTEMP/ ST(IO),ANC,XNM,AMP
02370 COMMON /NROOT/ RNSAT(IO),RNLOSS(IO),JJ
02380 IF (NEWSOL.EQ.O) 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 DEFMAX=0.
02460 CUNDEF=0.
02470 DO 40 NLAYR=1,10
02480 READ (ISOIL,130) DLAYR(NLAYR),LL(NLAYR),DUL(NLAYR),SAT(NLAYR),
02490 WR(NLAYR)
02500 40 IF (NLAYR.LT.1) GO TO 27
02510 38 IF (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  CUMDEF=CUMDEF+DLAYR(NLAYR)
02550  IF(CUMDEF.LE.110.) GO TO 39
02560  DLL=0.008*(CUMDEF-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) IIRR
02690  IF(IIRR.NE.IIRR) 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=0
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  CUMDEF=0.
02970  DLL=0.
02980  IDRISW=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)
03030  110  CONTINUE
Appendix 3.1 (continued) Program listing of CERES maize model.

03030 DL1=DL2
03040 CUMDEF=CUNDEF+DLAYR(L)
03050 TSW=TSW+SW(L)*DLAYR(L)
03060 TPSW=TPSW+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)) DRSW=1
03110 WX=1.016*(1.-EXP(-4.16*CUM/DEPMAX))
03120 IF (L.1.E.5) FLOW(L)=0.0
03130 RTDEF=DEPMAX
03140 WHITE (6,170) RTDEP,TLL,TDUL,TSAT,TPESW,TSW
03150 CN1=-16.91+1.348*CN2-0.01379*CN2**2+0.0001172*CN2**3
03160 SWEF=0.9-0.00038*(DLAYR(1)-30.)**2
03170 CET=0.
03180 RTDEF=DEPMAX
03190 IF (F(L).GT.LT.1.2) FLOW(L)=0.0
03200 IF (L.1.E.5) FLOW(L)=0.0
03210FORMAT (I3,5X,'SOIL ALBEDO= ',F4.2,2X,'D= ',F5.1,2X,'SWCON= ',F6.2,10X)
03220 FORMAT (4F10.3,10X,F10.3)
03230 FORMAT (1X,F10.3)
03240 FORMAT (I3)
03250 FORMAT (I5,F6.2)
03260 FORMAT (' SOIL DATA IS MISSING')
03270 RETURN
03280 END

******* OUTPUT SUBROUTINE FOR WATER BALANCE***************

03310 120 FORMAT (I3,5X,'SOIL ALBEDO= ',F4.2,2X,'D= ',F5.1,2X,'SWCON= ',F6.2,10X)
03320 FORMAT (4F10.3,10X,F10.3)
03330 FORMAT (1X,F10.3)
03340 FORMAT (I3)
03350 FORMAT (I5,F6.2)
03360 FORMAT (' SOIL DATA IS MISSING')
03370 RETURN
03380 END

SUBROUTINE OUTWA

COMMON /TITL/ TITLE(20)
COMMON /PARAM/ ISOIL, IIRR, IWETH, ISOW, PLANTS, ROUTGR, KOUTWA, SDEPTH,
LAT, KAVITR, KIRR, KSOIL, QQUIT, NEWSOL, NEWWET, MULTR, ISWSWB

CET-0.
CET-0.
CET-0.
CRAIN-0.
APESW=TPESW/DEPMAX
RWUMX=0.03
RETURN
END

CET-0.
CET-0.
CET-0.
CRAIN-0.
APESW=TPESW/DEPMAX
RWUMX=0.03
RETURN
END

CET-0.
CET-0.
CET-0.
CRAIN-0.
APESW=TPESW/DEPMAX
RWUMX=0.03
RETURN
END

CET-0.
CET-0.
CET-0.
CRAIN-0.
APESW=TPESW/DEPMAX
RWUMX=0.03
RETURN
END

CET-0.
CET-0.
CET-0.
CRAIN-0.
APESW=TPESW/DEPMAX
RWUMX=0.03
RETURN
END

CET-0.
CET-0.
CET-0.
CRAIN-0.
APESW=TPESW/DEPMAX
RWUMX=0.03
RETURN
END

CET-0.
CET-0.
CET-0.
CRAIN-0.
APESW=TPESW/DEPMAX
RWUMX=0.03
RETURN
END

CET-0.
CET-0.
CET-0.
CRAIN-0.
APESW=TPESW/DEPMAX
RWUMX=0.03
RETURN
END

CET-0.
CET-0.
CET-0.
CRAIN-0.
APESW=TPESW/DEPMAX
RWUMX=0.03
RETURN
END

CET-0.
CET-0.
CET-0.
CRAIN-0.
Appendix 3.1 (continued) Program listing of CERES maize model.

03530 2, PRINT, KNIT, IDATE, XYIELD, XGRWT, XGPSM, XGPE, XLAI, XBiom, ISLKD,
03540 3, MATJD, INSOIL
03550 COMMON /SOIL/ SALBU, SWCON, DLAYR(10), DUL(10), LL(10), SW(10),
03560 1 SAT(10), DEPMAX, TDATE, NMAX, DDATEX, IDIM(12), Irys
03570 COMMON /DATEC/ MO, ND, YR, JDAT, JDATX, DATEC, IDIM(12), Irys
03580 COMMON /WATER/ SUM1, SUM2, Z, TLL, PESW, TSW, CUMDEP, ESW(10),
03590 1 CSD1, CSD2, S11(6), S12(6), ICSDB, ES, EP, ET, EO, CES, SCP, CE1, CET,
03600 1 RLV(10), PRECIP, CRAIN, DRAIN, IDRWS, BTDEP, SWDF1, SWDF2,
03610 1 SWDF3, TRWU, EWUMX
03620 COMMON /WRITS/ AES, AEP, AET, AEO, ASOLR, ATEMX, ATEMX, ARUNOF,
03630 1 ADRAIN, APREC, ASWDF1, ASWDF2, IOUTGR, IOUTWA, JHEAD, KHEAD,
03640 2 TPSEP, RUNOFF
03650 COMMON /NROOT/ ENFAC(10), RNLOSS(10), JJ
03660 DIMENSION AVEARG(1)
03670 EQUIVALENCES (AVEARG(I), 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 CONTINUE
03770 CALL CALDAT
03780 WRITE (10,70) MO, ND, YR, JDAT, AVEARG, SW, PESW
03790 DO 40 I = 1, 10
03800 AVEARG(I) = 0
03810 CONTINUE
03820 IOUTWA = 0
03830 RETURN
03840 C
03850 50 FORMAT (1H1, 20X, 20A4//)
03860 60 FORMAT (1H1, 9X, 'JUL', 2X, 12('-', ), ' AVERAGE ', 12('-', ), 2X,
03870 1 '----- PERIOD ------', 2X, 8('-', ), ' SOIL WATER CONTENT',
03880 2 'WITH DEPTH', 9('-', ), 'TI23, TOTAL', '/4X', 'DAY', 3X, 'DAY', 3X, 'ES',
03900 4 ' DRAIN PREC SW1 SW2 SW3 SW4 SW5 SW6 SW7 SW8 SW9 SW10
03910 5 PESW')
03920 70 FORMAT (1X, I2, '/', I2, '/', I2, 14, 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
03970 C
03980 C
03990 C
04000 C
04010 C
04020 C

*************** OUTPUT SUBROUTINE FOR GROWTH ***************

SUBROUTINE OUTGR
04030 REAL LAT, LL, LAI, LFWT
04040 COMMON /TITL/ TITLE(20)
04050 COMMON /CLIMT/ TEMPN, TEMPMX, RAIN, SOLRAD, TMFAC(8)
04060 COMMON /PARAM/ ISOIL, IIBR, IWH, ISOW, PLANTS, KOUTGR, KOUTWA, SDEPTH,
Appendix 3.1 (continued) Program listing of CERES maize model.

```
04030  1 LAT,KVARTY,KIRR,KSOIL,QUIT,NEWSOL,NEWWET,MULTYR,ISWSWB
04040  2 PRINT,KHIT,IODATE,XIELD,XRWT,XGPM,XPGE,XLAI,XPBIOM,ISLKD,
04050  3 MATJD,INSOIL
04060  COMMON /WATER/ SUMES1,SUMES2,T,TTIL,PESW,TSTW,CURMDEP,ESW(10),
04070  1 CSSD1,CSSD2,SS1(6),SS2(6),ICSDUR,ES,EP,ET,EO,CE,CEP,CET,
04080  1 RLV(10),PRCP,CRAIN,DRAIN,IDRSW,ETDEF,SWDF1,SWDF2,
04090  1 SWD3,TRWW,RUWMX
04100  COMMON /DATEC/ MD,ND,IIYR,JDATE,JDATX,DI1M(12),NYRS
04100  COMMON /WRIT/ AES,AEP,AET,AE0,ASOLR,ATEMX,AETRN,ARUNOF,
04120  1 ADRAIN,APECP,ASWDF1,ASWDF2,IOUTGR,IOUTWA,JHEAD,KHEAD,
04130  2 TPRECP,RUNOFF
04140  COMMON /PHENV/ F9,CUMD,TTBASE,SUMDTT,SL1,CL,INSTAGE,
04150  1 DTM,IDUR,SIND,TEMPM
04160  COMMON /GROTH/ GPM,S,GRALT,PTY,LAI,DM,BIOMAS,PLA,SENDLA,
04170  1 LFVT,SEEDBW,RECM,XPLT,WDTL,EMAT,SLW,PLAY,PLAMX,
04180  1 RTWT,STEMW,GRWT,SMWIN,LW,EART,TLNO,SWMAX,FCALI,
04190  LSWD1,SWP,IDUPR,PLAG,EGFT,GRTSTM,CARBO,BLAMX(35),GBLA(35),
04200  1 SLA(35),ML,MLMAX,EMRS
04210  COMMON /NROOT/ RNCFAC(10),RNLOSS(10),JJ
04220  IF (KHEAD.EQ.1) GO TO 10
04230  IF (KOUTGR.NE.1) WRITE (9,30) TITLE
04240  IF (KOUTGR.NE.0) WRITE (9,40) TITLE
04240  IF (KOUTGR.NE.0) WRITE (9,40) TITLE
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) MD,ND,IIYR,JDATE,BIOMAS,LN,SUMDTT,TRWU,RTWT,
04320  1 STEMW,GRWT,LFVT,SENDLA,ASWDF1,ASWDF2,RTDEF,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 (1H1,4X,'DATE JUL BIO LEAF LAI SUMDTT TRWU',2X,
04420  1 'ROOT STEM GRAIN LEAF SEN SW SW SW ROOT',5X,
04430  1 'ROOT LENGTH VOLUME',1X,'1X','DAY MASS NO.',2X,'WT',5X,'WT',4X,
04440  3 'WT',5X,'WT LFA DF1 DF2 DFTH PTF',L1 L3 L2 L3',2X,
04450  4 'L4 5 5 6 L7 L8//')
04460  50 FORMAT (1X,I2,'/',12,'/',12,'/',12,14,1X,F5.0,F5.0,F4.1,F5.2,1X,F5.0,F6.1,
04470  1 4(I1X,F6.1),1X,F5.0,2(I1X,F3.1),1X,F4.0,F5.2,8(1X,
04480  2 F3.1))
04490  60 FORMAT (1X,I3,F9.3,F6.3)
04500  END
04510  C
04520  C ********** SUBROUTINE TO CONVERT JULIAN DAY TO CALENDAR DATE *****
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Appendix 3.1 (continued) Program listing of CERES maize model.

```fortran
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 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,/) END
04780 C
04790 C
04800 C
04810 C
04820 C
04830 C
04840 COMMON /SOIL/ SALB,D,SWCON,DLAYR(10),DUL(10),LL(10),SW(10),
04850 1 SAT(10),DEPHAX,TDUL,NLAYR,SNX,WF(10),WR(10),SWE(10),SWE2,
04860 COMMON /IRRIG/ NIRR,JDAY(26),AIRH(26)
04870 2 MATJD,INSOIL
04880 COMMON /WATER/ SUMES1,SUMES2,T,LLL,PESW,TSW,CUMDEP,ESW(10),
04890 1 CSD1,CSD2,SI(6),SI2(6),ICSDUR,ES,ET,EO,CES,CET,
04900 1 RLV(10),PRECIP,CRAIN,DRAIN,IRDSW,RTDEP,SWDF1,SWDF2,
04910 1 SWDF3,TRWU,AWUMX
04920 COMMON /WATER/ SUMES1,SUMES2,T,LLL,PESW,TSW,CUMDEP,ESW(10),
04930 COMMON /WATER/ SUMES1,SUMES2,T,LLL,PESW,TSW,CUMDEP,ESW(10),
04940 1 CSD1,CSD2,SI(6),SI2(6),ICSDUR,ES,ET,EO,CES,CET,
04950 1 RLV(10),PRECIP,CRAIN,DRAIN,IRDSW,RTDEP,SWDF1,SWDF2,
04960 1 SWDF3,TRWU,AWUMX
04970 COMMON /WRITS/ AES,AEP,AET,AEQ,ASOLR,ATEMX,ATEMN,ARUNOF,
04980 COMMON /WRITS/ AES,AEP,AET,AEQ,ASOLR,ATEMX,ATEMN,ARUNOF,
04990 1 ARAIN,APRECP,ASWDF1,ASWDF2,OUTGR,LOUTWA,HEAD,KHEAD,
04990 1 TPRECP,RUNOFF
05000 COMMON /PHENL/ P9,CUMDTE,TS,SL,C1,ISTAGE,
05010 1 DTT,IED,SM,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, STNWT, GRNWT, SWMIN, LN, EARWT, TLMG, SWMAX, FACLI,
05050  1  IRWID, SUMP, IDURP, FLAG, EGFT, GHSTOM, CARBO, BLAMX(35), GBLA(35),
05060  1  SLA(35), NL1, NLMAX, EARSW
05070  COMMON /NCTRL/ KOOTMN, IOOTMN, KOOTNU, IOUTNU, MINCK, NHDMN, NHDFP,
05080  1  IFERT, KFERT, ISWNIT, DMOD, XSTRAW, GRPCTN, GRPTN, XTOTNP, XAPTNP
05090  2, XGNUP
05100  COMMON /NMOVE/ FLUX(IO), SWX(10), FLOW(10), MU, NOUT(10), NUP(10)
05110  COMMON /NROOT/ RNFACT(IO), RNLOSS(IO), JJ
05120  COMMON /NSPOOL/ SNH4(10), SN03(10), NH4(10), NO3(10), FAC(IO),
05130  1  BD(IO), PH(IO)
05140  DIMENSION RLDF(IO)
05150  ICSDUR = ICSDUR + 1
05160  PRECIP = 0.
05170  IOFF = 0.
05180  IF (IIRR.EQ.0) GO TO 20
05190  IF (IIRR.EQ.99) GO TO 15
05200  DO 10 J = 1, NIRR
05210  IF (JDATE.EQ.JDAY(J)) PRECIP = AIRR(J)
05220  10 IOFF = 1
05230  15 IF (SWDF3.GE.0.9) GO TO 20
05240  DO 99 L = 1, NLAYR
05250  TAIR = TAIR + (DDL(L) - SW(L)) * DLAYR(L) * 10
05260  99 CONTINUE
05270  CONTINUE
05280  20 PRECIP = PRECIP + RAIN + TAIR
05290  PPRECIP = PRECIP
05300  DRAIN = 0.
05310  PINF = 0.
05320  WINF = 0.
05330  RUNOFF = 0.
05340  IF (PRECIP.EQ.0.) GO TO 70
05350  CONTINUE
05360  C **CALCULATE RUNOFF BY WILLIAMS - SCS CURVE NO. TECHNIQUE********
05370  50 CONTINUE
05380  SUM = 0.
05390  DO 50 L = 1, NLAYR
05400  50 SUM = SUM + WF(L) * (SW(L) - LL(L)) / ESW(L)
05410  CONTINUE
05420  R2 = SMX(1 - SUM)
05430  IF (R2.LT.2.54) R2 = 2.54
05440  IF (PB.LT.0.2) PB = PB * 0.2 * R2
05450  IF (PB.LE.0.) GO TO 60
05460  RUNOFF = PB * PB / (PRECIP .8 * R2)
05470  IF (IOFF.EQ.1) RUNOFF = 0.
05480  60 PINF = PRECIP - RUNOFF
05490  C **CALCULATE DRAINAGE AND SOIL WATER REDISTRIBUTION************
05500  WINF = PINF
05510  FLUX(1) = PINF * 0.1
05520  IDRSW = 1
05530  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.DOL(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=5ALB
05830 IF (ISTAGE.LT.5.) ALBEDO=0.23-(0.23-SALB)*EXP(-0.75*LAI)
05840 EEQ=SOILRAD*(2.04-0.183*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=0-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   ES=(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=0.8*EXP(3.54*(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(L).GT.WAT1)FLOW(L)=WAT1
06450       IF(WAT1.LT.0.0)FLOW(L)=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 (ISWIT.NE.0) CALLNFLUX(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.

```plaintext
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
06610  ET=ES
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
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          LL=L
06760          CUMDEP=CUMDEP+DLAYR(L)
06770  310 CONTINUE
06780  IF (SW(L)-LL(L).LT.0.25*ESW(L)) SWDF=4.*(SW(L)-LL(L))/ESW(L)
06790  1
06800  IF (SWDF.LT.0.0) 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((SWDF+.20),SWDF)
06840  IF (RTDEP.GT.1.25*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.0.0)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
07000  340 IF (EP.EQ.0.) GO TO 390
07010  EPL=EP*0.1
07020  TSWD=0.
```

Appendix 3.1 (continued) Program listing of CERES maize model.

```plaintext
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.RWDMX) RWU(L)=RWUMX
07080 RWU(L)=RWU(L)*DLAYR(L)*RLV(L)
07100 TRWU=TRWU+RWU(L)
07110 CONTINUE
07120 IF (EP1.LE.TRWU) WUF=EP1/TRWU
07130 TSW=0.
07140 DO 370 L=1,NLAYR
07150 RWU(L)=RWU(L)*WUF
07160 IF (SW(L).LE.1.0*LL(L)) RWU(L)=0.0
07170 SW(L)=SW(L)-RWD(L)/DLAYR(L)
07180 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 DO 380 L=1,NLAYR
07240 SWDF1=1.00*TRWU/EP1
07250 SWDF1=SWDF1*WUF
07260 IF (SW(L).LE.1.0*LL(L)) RWU(L)=0.0
07270 TSW=TSW+SW(L)*DLAYR(L)
07280 END
07290 CONTINUE
07300 RETURN
07310 ********** SUBROUTINE TO CALCULATE PHENOLOGICAL STAGE **********
07320 SUBROUTINE PHENOL (*)
07330 REAL LAT, NFAC, NDEF1, NDEF2, NDEF3, NDEF4, LL, LAI, LFWT, NDEM, MAXLAI
07340 COMMON /PARAM/ ISOIL, IIRR, IWETH, ISOW, PLANTS, KOUTGR, KOUTWA, SDEPTH,
07350 1 LAT, KVARTY, KIRR, KSOIL, IQUIT, NEWSOL, NEWWET, MULTR, ISWSWB
07360 2 PHINT, KNIT, IDATE, XYIELD, XGRWT, XGPSM, XGPE, XLAI, XBIOM, ISLKJD,
07370 3 MATJD, INSOIL
07380 COMMON /YLDS/ YIELD
07390 COMMON /GENET/ PI, P2, P3, P5, G2, G3
07400 COMMON /DATEC/ MO, ND, IYR, JDATE, JDATEX, IDIM(12), NYRS
07410 COMMON /WATER/ SUMES1, SUMES2, T, TLL, PESW, TSW, CUMDEF, ESW(10),
07420 1 SWD1, SWD2, SWD3, SWD4, SWD5, SWD6, SWD7, SWD8, SWD9, SWD10
07430 2 SWDF1, SWDF2, SWDF3, SWDF4, SWDF5, SWDF6, SWDF7, SWDF8, SWDF9, SWDF10
07440 COMMON /SOIL/ SOIL, SOIL, SOIL, SOIL, SOIL, SOIL, SOIL, SOIL, SOIL, SOIL,
07450 1 RWU, RWU, RWU, RWU, RWU, RWU, RWU, RWU, RWU, RWU
07460 COMMON /SHFT/ SHFT, SHFT, SHFT, SHFT, SHFT, SHFT, SHFT, SHFT, SHFT, SHFT,
07470 1 SHFT, SHFT, SHFT, SHFT, SHFT, SHFT, SHFT, SHFT, SHFT, SHFT,
07480 COMMON /DATE/ MO, ND, IYR, JDATE, JDATEX, IDIM(12), NYRS
07490 COMMON /WATER/ SUMES1, SUMES2, T, TLL, PESW, TSW, CUMDEF, ESW(10),
07500 1 SWD1, SWD2, SWD3, SWD4, SWD5, SWD6, SWD7, SWD8, SWD9, SWD10
07510 2 SWDF1, SWDF2, SWDF3, SWDF4, SWDF5, SWDF6, SWDF7, SWDF8, SWDF9, SWDF10
07520 COMMON /DATEC/ MO, ND, IYR, JDATE, JDATEX, IDIM(12), NYRS
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```plaintext
310
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Appendix 3.1 (continued) Program listing of CERES maize model.

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07530  COMMON /WRITS/ AES,AEP,AET,AEO,ASOLR,ATEMX,ATEMN,ABUNOF,
07540  1 ADRAIN,APRECP,ASWDF1,ASWDF2,IOUTGR,IOUTWA,JHEAD,KHEAD,
07550  2 TDRECP,RUNOFF
07560  COMMON /PHRL/  P9,CUMDTT,ISUMO,SUMDTT,S1,S2,ISTAGE,
07570  1 DTT,IDUR,SIND,TEMPM
07580  COMMON /GROTH/ GPSM,GPP,GRORT,PTF,LA1,DIM,BIOMAS,PLA,SEMLA,
07590  1 LFYT,SEEDR,REGM,XPLANT,WIDTL,EMAT,SLW,PLAY,PLAX,
07600  1 RTW,STDIS,GRWNT,SWMIN,IM,EARW,TLNO,SWMAX,FACLI,
07610  1 IRWD,SUMP,IDURP,PLAG,EGFT,GROSTM,CARBO,GRAMX(15),SLA(15),
07620  1 SLA(35),NLI,NILAX,EARLS
07630  COMMON /CLMT/ TEMPMN,TEMPMX,RAIN,SOLRAD,TMFAC(8)
07640  COMMON /NCONC/ TANC,TCNP,RCNP,RANG,TMNC,TANC,VMNC,XSTAGE
07650  COMMON /NDFPG/ NDEFl,NDEF2,NDEF3,NDEF4,GRNP,CNSD1,CNSD2
07660  COMMON /NPLANT/ GRAINN,ROOTN,STOVN,PDWN,STOVWT,PGRWT,NDEM
07670  COMMON /NWRITP/ ATANC,ATCNP,ARCNP,ANDEM2,ATNUP,AART,ASTOVN,
07680  1 AGRN,CTNUP,TNUP,AFTNUP
07690  COMMON /OUTER/ISUMO
07700  COMMON /NCTR/ KOUTMN,KOUTNU,KOUTMN,KOUTNM,KHDDM,NIUDDP,
07710  1 IFERT,KFERT,ISWUNT,DMDM,XSTRAW,GRSTM,GRPTN,XOTNP,XAPTNP
07720  2,XTNUP
07730  COMMON /NNN/ NFAC,DSTOVN
07740  COMMON /NTEMP/ 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=O.
07790  GO TO 20
07800  31 IF(TEMPMX.TBASE) GO TO 20
07810  TCM=(TEMPMX-TBASE)/(TEMPMX-TEMPMN)
07820  DTT=(TEMPMX-TBASE)/2.*TCM
07830  IF(IISTAGE.LE.2.OR.ISTAGE.GT.6) GO TO 19
07840  TDM=TEMPM-TBASE
07770  IF(TEMPMX.GT.TBASE) GO TO 31
07780  DTT=O.
07790  GO TO 20
07800  31 IF(TEMPMN.GE.TBASE) GO TO 20
07810  TCM=(TEMPMX-TBASE)/(TEMPMX-TEMPMN)
07820  DTT=(TEMPMX-TBASE)/2.*TCM
07830  GO TO 20
07840  19 DTM=ST(1)-TBASE
07850  IF (ST(1).LT.TBASE) DTT=O.0
07860  IF (SOLRAD.LT.300.) DTT=DTR*SOLRAD/300.
07870  SIMDTT=SIMDTT+DTT
07880  CUMDTT=CUMDTT+DTT
07890  GO TO (1,2,3,4,5,6,7,8,9), ISTAGE
07900  20 IF(IISTAGE.LE.2.OR.ISTAGE.GT.6) GO TO 19
07910  CUMDTT=CUMDTT+DTT
07920  IF(ISWNSW.EQ.0) RETURN
07930  19 DTM=ST(1)-TBASE
07940  IF (ST(1).LT.TBASE) DTT=O.0
07950  IF(SOLRAD.LT.300.) DTT=DTR*SOLRAD/300.
07960  SIMDTT=SIMDTT+DTT
07970  CUMDTT=CUMDTT+DTT
07980  CUMDTT=CUMDTT+DTT
07990  RETURN
08000  DO 30 L=1,NLAYS
```
Appendix 3.1 (continued) Program listing of CERES maize model.

08010 CUMDEP=CUMDEP+DLAYR(L)
08020 IF (SDEPH.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
08280 CALL CALDAT
08290 WRITE(6,290) MO,ND,IYR,JDATE,CUMDTT
08300 WRITE(6,230)
08310 IF (ISWSWB.NE.0) WRITE (6,330) NFAC,CES,CEP,CRAIN,PESW
08320 CALL PHASEI
08330 RETURN
08340 10 XSTAGE=SUMDTT/P1
08350 1 IF (SUMDTT.LT.P1) RETURN
08360 CALL CALDAT
08370 WRITE (6,290) MO,ND,IYR,JDATE,CUMDTT
08380 WRITE (6,240)
08390 150 GO TO 150
08400 C ****************DETERMINE DATE OF TASSEL INITIATION ************
08410 2 XSTAGE=1.0+0.5*SIND
08420 DEC=0.4093*SIN((0.0172*(JDATE-82.2))
08430 DLV=(-S1*SIN(DEC)-0.1047)/(C1*COS(DEC))
08440 IF(DLV.LT.-.87) DLV=-.87
08450 HRLT=7.639*ARCCOS(DLV)
08460 C IF(HRLT.LT.12.5)FACLI=1.0-(12.5-HRLT)*0.05
08470 IF(HRLT.LT.12.5) HRLT=12.5
08480 RATEIN=1./(4.+P2*(HRLT-12.5))
08490 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
08611 IF (SUMDTT.LT.P3) RETURN
08612 CALL CALDAT
08613 ISDATE=JDATE
08614 MAXLAI=LAI
08615 WRITE (6,290) MO,ND,IYR,JDATE,CUMDTT
08616 WRITE (6,260) TLNO
08617 GO TO 150
08618 C ******Determine beginning of effective grain filling period ******
08620 4 XSTAGE=4.5+1.5*SUMDTT/(P5*.95)
08621 IF (SUMDTT.LT.P5*0.25) RETURN
08622 CALL CALDAT
08623 PSKER=SUMP*1000/IDURP
08624 GPP=G2*PSKER/7500.+50.
08625 IF (GPP.GT.G2) GPP=G2
08626 GPP=GPP*AMIN1(NDEF3,SWDF1)
08627 IF(GPP.LE.50.0) GPP=50.0
08628 EARS=PLANTS
08629 C ************* Determine barrenness ************
08630 IF(GPP.LT.G2*0.25) EARS=PLANTS*((GPP-50.)/(G2-50.))**0.33
08631 IF(EARS.LE.0.0) EARS=0.0
08632 GFSM=GPP*EARS
08633 WRITE (6,290) MO,ND,IYR,JDATE,CUMDTT
08634 WRITE (6,270) GFSM
08635 GO TO 150
08636 C ******Determine end of effective filling period ************
08640 5 XSTAGE=6.0+4.0*SUMDTT/P5
08641 IF (SUMDTT.LT.P5*0.95) RETURN
08642 CALL CALDAT
08643 WRITE (6,290) MO,ND,IYR,JDATE,CUMDTT
08644 WRITE (6,275) GFSM
08645 GO TO 150
08646 C ************** Determine physiological maturity **************
08650 6 IF (DTT.LT.2.0) SUMDTT=P5
08651 IF(SUMDTT.LT.P5) RETURN
08652 CALL CALDAT
08653 MDATE=JDATE
08654 WRITE (6,290) MO,ND,IYR,JDATE,CUMDTT
08655 WRITE(6,280)
08656 YIELD=GRNWT*10.*EARS
08657 GFSM=PSM/GPP
08658 STOVER=BIOMAS*10.-YIELD
08659 YIELD=YIELD/0.845
Appendix 3.1 (continued) Program listing of CERES maize model.

09030 YIELD=YIELD/62.8
09040 XGNP=(GRAINS/GRNWT)*100.0
09050 XPTN=XGNP/5.80
09060 GNUP=GRAINW*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=3
09110 IF(PLSEPR.EQ.0) PLSEPR=ISDATE-ISOW
09120 IF(PLSEPR.EQ.0) PLSEPR=365.-ISOW+ISLKJD
09130 IF(MATJD.EQ.0.AND.ISLKJD.EQ.0) SEMTMS=365.-ISDATE+MDATE
09140 IF(MATJD.EQ.0.AND.ISLKJD.EQ.0) SEMTMS=365.-ISDATE+MDATE
09150 IF(SEMTPR.LT.0) SEMTPR=365.-MDATE+ISDATE
09160 XANC=(STOVN+GRAINN)/(STOVWT+GRNWT)*100.
09180 1 NFAC,CES,CEP,CRAIN,PESW
09190 PLANTS=XPLANT
09200 IF(ISDATE.EQ.0) WRITE (6,320) BIOMAS,LAI,APTNUP,XANC,
09210 IF(ISDATE.EQ.0) WRITE (6,320) BIOMAS,LAI,APTNUP,XANC,
09240 IF(ISDATE.EQ.0) WRITE (6,320) BIOMAS,LAI,APTNUP,XANC,
09250 CALL PHASE1
09260 RETURN
09270 WRITE (6,310) ISDATE,ISLKJD,MDATE,MATJD,YIELD,XYIELD,SKERWT,XGRWT,
09280 1XANC,CES,CED,CEP,CRAIN,PESW
09290 DO 170 1=1,5
09300 WRITE (6,190) 1,SI1(I),SI2(I),SI3(I),SI4(I)
09310 CONTINUE
09320 CALL PHASE1
09330 1 CONTINUE
09340 WRITE (6,305) 1CONTINUE
09350 WRITE (6,310) ISDATE,ISLKJD,MDATE,MATJD,YIELD,XYIELD,SKERWT,XGRWT,
09360 1XANC,CES,CED,CEP,CRAIN,PESW
09370 DO 170 1=1,5
09380 WRITE (6,190) 1,SI1(I),SI2(I),SI3(I),SI4(I)
09390 CONTINUE
09400 WRITE (17,311) KVARTY,YIELD,XYIELD,CPP,GPP,XGPE,APTNUP,PLSEPR,PLSEMS,SEMTPR,
09410 1SEMTPR
09420 DO 170 1=1,5
09430 WRITE (6,200) 1,SI1(I),SI2(I),SI3(I),SI4(I)
09440 CONTINUE
09450 IF (IYR.EQ.NYRS) RETURN 1
09460 CALL PHASE1
09470 RETURN
09480 FORMAT (/1X,'GROWTH STAGE',6X,'CSD1',6X,'CSD2',5X,'CNSD1',5X,
09490 1'CNSD2')
09500 FORMAT (1X,16,D16.2)
09510 FORMAT (16X,'SOWING',20X,'BIOMASS',5X,'LAI',6X,'NUPTK',4X,
09520 1XANC',5X,'NFAC',6X,'ES',7X,'EP',6X,'PRES',5X,'PESW/')
Appendix 3.1 (continued) Program listing of CERES maize model.

```plaintext
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')
09580  270  FORMAT (1H+,21X,'BEGIN GRAIN FILL---GPHM=',10X,'F6.0')
09590  275  FORMAT (1H+,21X,'END GRAIN FILL')
09600  280  FORMAT (1H+,21X,'PHYSIOLOG. MAT.')
09610  290  FORMAT (1X,I2,20X,'JITL',20X,'CUM',81X,'WATER BALANCE COMPONENTS',/)
09620  300  FORMAT (1H ,10X,'PREDICTED VALUES',5X,'MEASURED VALUES',/)
09630  310  FORMAT (1X,'SILKING DATE',21X,'MATURITY DATE',/)
09640  320  FORMAT (1X,'GRAIN YIELD KG/HA (15.5X)',3X,'F7.0',11X,'F7.0',/)
09650  330  FORMAT (1X,'GRAINS/EAR',20X,'F6.0',12X,'F6.0',/)
09660  340  FORMAT (1X,'MAX. LAI',24X,1X)
09670  350  FORMAT (1H+,21X,'BIOMASS KG/HA',17X,'F7.1',10X,'F8.1',/)
09680  360  FORMAT (1H+,21X,'STOVER KG/HA',17X,'F8.1',10X,'F8.1',/)
09690  370  FORMAT (1X,'N UPTAKE KG/HA',9X,'F8.1',10X,'F8.1',/)
09700  380  FORMATE(1H+,51X,'GROWTH SUBROUTINE Garnel g)
09710  390  SUBROUTINE GROSUB
09720  400  REAL LAT,LL,LA,LFWT,NDEF1,NDEF2,NDEF3,NDEF4,NDEM,NSINK,NPOOL1,
09730  410  NPOOL2,NPOOL,NSDR,NSAC,NSOIL
09740  420  COMMON /NNN/ NFAC,DSTOVN
09750  430  COMMON /CLIMT/ TEMPMN,TEMPMX,RAIN,S0LRAD,TMFAC(8)
09760  440  COMMON /PARAM/ ISOIL,IIRR,IWETH,ISOW,PLANTS,KOUTG,KOUTA,SDPETH,
09770  450  COMMON /GENET/ PI,P2,P3,P5,G2,G3
09780  460  COMMON /PHENL/ P9,CUMDT,TMP,TDMDT,STAGE
09790  470  COMMON /GROTH/ GPSM,GPP,GRO,PTF,LAI,DM,BIOMAS,PLA,SEN1A
09800  480  COMMON /GENET/ P5,GPP,GRO,PTF,LAI,DM,BIOMAS,PLA,SEN1A
09810  490  COMMON /WATER/ SUMES1,SDMES2,T,TLL,PESW,TSW,CUMDTT,ESW(10),
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**FORMAT (1H+,21X,'GERMINATION')**

**FORMAT (1H+,21X,'EMERGENCE')**

**FORMAT (1H+,21X,'END JUVENILE STAGE')**

**FORMAT (1H+,21X,'TASSEL INITIATION')**

**FORMAT (1H+,21X,'SILKING')**

**FORMAT (1H+,21X,'BEGIN GRAIN FILL---GPHM=',10X,'F6.0')**

**FORMAT (1H+,21X,'END GRAIN FILL')**

**FORMAT (1H+,21X,'PHYSIOLOG. MAT.')**

**FORMAT (1X,I2,20X,'JITL',20X,'CUM',81X,'WATER BALANCE COMPONENTS',/)**

**FORMAT (1H ,10X,'PREDICTED VALUES',5X,'MEASURED VALUES',/)**

**FORMAT (1X,'SILKING DATE',21X,'MATURITY DATE',/)**

**FORMAT (1X,'GRAIN YIELD KG/HA (15.5X)',3X,'F7.0',11X,'F7.0',/)**

**FORMAT (1X,'GRAINS/EAR',20X,'F6.0',12X,'F6.0',/)**

**FORMAT (1X,'MAX. LAI',24X,)**

**FORMAT (1H+,21X,'BIOMASS KG/HA',17X,'F7.1',10X,'F8.1',/)**

**FORMAT (1H+,21X,'STOVER KG/HA',17X,'F8.1',10X,'F8.1',/)**

**FORMAT (1X,'N UPTAKE KG/HA',9X,'F8.1',10X,'F8.1',/)**

**FORMAT (1H+,51X,'GROWTH SUBROUTINE Garnel g)**

**SUBROUTINE GROSUB**

**REAL LAT,LL,LA,LFWT,NDEF1,NDEF2,NDEF3,NDEF4,NDEM,NSINK,NPOOL1,**

**NPOOL2,NPOOL,NSDR,NSAC,NSOIL**

**COMMON /NNN/ NFAC,DSTOVN**

**COMMON /CLIMT/ TEMPMN,TEMPMX,RAIN,S0LRAD,TMFAC(8)**

**COMMON /PARAM/ ISOIL,IIRR,IWETH,ISOW,PLANTS,KOUTG,KOUTA,SDPETH,**

**COMMON /GENET/ PI,P2,P3,P5,G2,G3**

**COMMON /PHENL/ P9,CUMDT,TMP,TDMDT,STAGE**

**COMMON /GROTH/ GPSM,GPP,GRO,PTF,LAI,DM,BIOMAS,PLA,SEN1A**

**COMMON /GENET/ P5,GPP,GRO,PTF,LAI,DM,BIOMAS,PLA,SEN1A**

**COMMON /WATER/ SUMES1,SDMES2,T,TLL,PESW,TSW,CUMDTT,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(IO), PRECIP, CRAIN, DRAIN, IDRSW, RTDEP, SWDF1, SWDF2,
10060 1 SWDF3, TRWU, RWUNX
10070 COMMON /NCTRL/ KODTMN, IOOTMN, KOUTNU, IOUTNU, MINGX, WHDMN, WHDUP,
10080 1 IFERT, KFERT, ISWNIT, DMOD, XSTRAW, GRPTN, GEPTN, XOTNP, XAPTNP
10090 2 XGNUP
10100 COMMON /NDFPG/ NDEF1, NDEF2, NDEF3, NDEF4, GNP, CNSD1, CNSD2
10110 COMMON /NCONC/ TANC, TCNP, RANC, VMNC, VANC, XSTAGE
10120 COMMON /NPLANT/ GRAINN, ROOTN, STOVN, PDWI, STOWT, PGORT, NDEM
10130 COMMON /DATEC/ MO, ND, IYR, JDATE, JDATEX, IDIM(12), NIRS
10140 COMMON /NROOT/ RNFAC(IO), 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 IF (F.LT.0.) PRFT=0.
10250 IF (ISTAGE.LE.2) PCTSK=CDMDTT/900.
10260 IF (ISTAGE.GE.3) PCTSK=CDMDTT/(((TLNO-2.)*42.9)+96.)
10270 PTF=1.100*PCTSK/(0.259 + PCTSK)
10280 IF (PCTSK.GE.1.0) PTF=1.0
10290 IF (ISTAGE.GT.3) GO TO 12
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 GROTR=CARBO*(1.- PTF)
10400 CARBO=CARBO+GROTR
10410 CALL LEAF
10420 RTWT=RTWT + GROTR
10430 GO TO 40
10460 2 GROTR=CARBO*(1.- PTF)
10470 CARBO=CARBO+GROTR
10480 CALL LEAF
10490 RTWT=RTWT + GROTR
10500 GO TO 40
10501 3 GROTR=(1.- PTF)*CARBO
10502 CARBO=CARBO+GROTR
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+GROSTM
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 FILLING')
10880 CONTINUE
10890 300 EMAT=0
10900 301 CONTINUE
10910 IF (ISWINIT.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=0.64+.0125*TEMPM
10950 SFAC=1.125-1.125*SWDF2
10960 GMP=(.008+.010*NDEF4)*AMAX1(TFAC,SFAC)
10970 NSINK=GROGRN*GMP
10980 IF (NSINK.EQ.0.0) GO TO 100
10990 RMNC=0.75*RCNP
11000 VANC=STOVN/STOVWT
11010 NPOOLI=STOVWT*(VANC-VMNC)
Appendix 3.1 (continued) Program listing of CERES maize model.

```plaintext
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*GPF
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 R00TN=RTWT*RMNC+NPOOL2
11130 RANC=R00TN/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 PG0RT=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 SUMDTT/(0.95*P5))**0.21*(AMIN1(SLFC,SLFT))**0.10
11350 IF (PLA.LT.PLAYAND.ISTAGE.GE.4)PLA=PLAY
11360 IF (ISTAGE.GT.4) LFWT=LFWT-(PLAY-PLA)/600.
11370 PLAY=PLA
11380 LAF=PLA*PLANTS*0.0001
11390 BIOMAS=(LFWT+STMWT+GRNWT)*PLANTS
11400 DM=BIOMAS*10.
11410 STOVWT=LFWT+STMWT
11420 $ RETURN
11430 END
11440 C *********************************/WRITE SUBROUTINE **********
11460 C SUBROUTINE WRITE
11470 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   1 COMMON /CROTH/ GPSM, CCP, CROFT, PTT, LAI, DM, BIOMAS, PLA, SENLA,
11510   1 LFWT, SEEDRV, REGM, XPLANT, WIDTL, EMAT, SLW, PLAY, PLANX,
11520   1 RTWT, STMWT, GRNWT, SWMIN, LN, EARWT, TLNO, SWMAX, FACLI,
11540   1 1RWD, SUMP, IDURP, PLAG, EGFT, GROSTM, CARBO, BLANX(35), GBLA(35),
11542   1  SLA(35), NLI, NLMAX, EARS
11550   1 COMMON /WATER/ SUMES1, SUMES2, T, TLL, PESW, TSW, CUMDEF, ESW(10),
11560   1 CSD1, CSD2, SI1(6), SI2(6), ICSDUR, ES, ET, EO, CES, CEF, CET,
11570   1 RLV(10), PRECIP, CRAIN, DRAIN, IDRWS, RTDEF, SWDF1, SWDF2,
11590   1 SWDF3, TRW, RWME
11590   1 COMMON /PARAM/ ISOIL, IIRR, IWETH, ISOW, PLANTS, KOUTGR, KOUTWA, SDEPTH,
11600   1 LAT, KVARTY, KIRR, KSOIL, IQQUIT, NEWSOL, NEWWET, MLTR, ISWSWB
11610   1 PHINT, KNIT, IDDATE, XFIELD, XGRWT, XGFSM, XGPF, XLAI, XBIOM, ISLKD,
11620   1 MJTJ, ISOIL
11630   1 COMMON /WRITS/ AES, AEP, AET, AEO, ASOLR, ATEMX, ATEMN, ARUNOF,
11640   1 ADRRAIN, APRREC, ASWDF1, ASWDF2, IOUTGR, IOOUTWA, JHEAD, KHEAD,
11650   1 2 TPRECIP, RUNOFF
11660   1 COMMON /CLIMT/ TEMPMN, TEMPMX, RAIN, SOLRAD, TMFAC(8)
11670   1 1 TEMPMN = TEMPMN + RAIN, SOLRAD
11680   1 IF (KOUTWA.EQ.0) GO TO 10
11700   1 IOOUTWA = IOOUTWA + 1
11700   1 AES = AES + ES
11710   1 AEP = AEP + EP
11720   1 AET = AET + ET
11730   1 AEO = AEO + EO
11740   1 ASOLR = ASOLR + SOLRAD
11750   1 ATEMX = ATEMX + TEMPMX
11760   1 ATEMN = ATEMN + TEMPMX
11770   1 ARUNOF = ARUNOF + RUNOFF
11780   1 ADRRAIN = ADRRAIN + DRAIN
11790   1 APRREC = APRREC + TPRECIP
11800   1 IF (IOOUTWA.EQ.KOUTWA) CALL OUTWA
11810   1 IF (IOOUTGR.EQ.0) RETURN
11820   1 IF (ISTAGE.GT.6) RETURN
11830   1 IOOUTGR = IOOUTGR + 1
11840   1 ASWDF1 = ASWDF1 + SWDF1
11850   1 ASWDF2 = ASWDF2 + SWDF2
11860   1 IF (IOOUTGR.EQ.KOUTGR) CALL OUTGR
11870   1 RETURN
11880   1 END
11880   1 C
11880   1 C
11880   1 C
11900   1 SUBROUTINE LEAF
11920   1 REAL LAT, LL, LAI, LFWT, MAXLAI, LAWR
11920   1 REAL NDEM, NDEF1, NDEF2, NDEF3, NDEF4, ISOIL, SWMAX, FACLI
11950   1 COMMON /CLIMT/ TEMPMN, TEMPMX, RAIN, SOLRAD, TMFAC(8)
11960   1 COMMON /DATEC/ MD, ND, TYR, JDATE, JDATEX, IDIM(12), NYRS
11970   1 COMMON /PARAM/ ISOIL, IIRR, IWETH, ISOW, PLANTS, KOUTGR, KOUTWA, SDEPTH,
11980   1 LAT, KVARTY, KIRR, KSOIL, IQQUIT, NEWSOL, NEWWET, MLTR, ISWSWB
```

*************** LEAF SUBROUTINE ***************
Appendix 3.1 (continued) Program listing of CERES maize model.

11990 2 ,PRINT,KHIT,IODEATE,XYIELD,XGRWT,XGPM,XPFE,XMLAI,XBIOM,ISLKD.
12000 3 MATJD,INSOIL
12010 COMMON /GENET/ P1,P2,P3,P5,G2,G3
12020 COMMON /PHENL/ P9,CUMDIT,TBASE,SUMDIT,S1,C1,ISTAGE,
12030 1 DTT,IDDR,SIND,TEMPM
12040 COMMON /GROTH/ GPSM,GPFE,GRKT,PTF,LA1,DM,BIOMAS,PLA,SENLA,
12050 1 LFWT,SEEDRY,REGM,XPLANT,WITDL,EMAT,SLW,PLAY,PLANX,
12060 1 ETWT,STMW1,GRNW1,SWMIN,LN,EARWT,TLNO,SWMAX,FACLI,
12070 1 IRVIK,STEP,UPR,PLAG,EFT,GROSTM,CARBO,BLANX35,CELA35,
12080 1 SLA35,NL1,NLMAX,EEARS
12090 COMMON /WATER/ SUMES1,SUMES2,TL,TLL,FTSW,CUMDFT,ESW10,
12100 1 GSD1,GSD2,SI1(6),SI2(6),ICSDUR,ES,EP,ET,E0,CES,CEP,CET,
12110 1 RLV10,PRECIP,GRAIN,IRDRW,KRTDEP,SWDF1,SWDF2,
12120 1 SWDF3,TRW1,צרכים
12130 COMMON /NDFPG/ NDEFl,NDEF2,NDEF3,NDEF4,NDFP1,DFP2,GNP,CNSD1,CNSD2
12140 SLAW=1.0
12150 LAW=LINA/PLWT
12157 IF(LAW.GT.130.0.AND.LAI.GT.1.0) SLAW=(170.-LAW)/20.
12160 IF (LDEF4.GT.0.40) GO TO 11
12170 IF(LAW.GT.130.0.AND.LAI.GT.1.0) SLAW=(190.-LAW)/20.
12171 11 IF(SLAW.LT.0) SLAW=0.0
12172 IF (SLAW.LT.1.0) SLAW=1.0
12180 M1=M1+1.
12190 EXTRA=0.0
12200 M2=M1+2.
12210 TGRLOT=0.
12220 DO 501 L=M1,M2
12230 IF (L.GT.TLNO) GO TO 501
12240 LN=L
12250 LN=LN + 1
12260 LN=LN + 2
12270 LN=LN + 3
12280 IF(CARBO.EQ.0.)GO TO 30
12290 PRINT=96.
12300 IF(LN.GT.1)PRINT=114.
12320 TTAP=(LN-2)*38.+20.
12330 IF(TTAP.LT.0.)TTAP=0.
12340 IF(CUMDIT.LT.TTAP)GO TO 51
12370 TTCCOL=96.*LN1.*38.
12380 SUMTTY=CUMDIT-NDT
12390 IF(CUMDIT.LT.TTCCOL OR.LN.NE.M)GO TO 21
12400 0**********ONLY FOR FIRST LEAF AND WHEN IT COLLARS********
12410 NLL=NL1+1.
12420 EXTRA=CUMDIT-TTCCOL
12430 IF(LN.GT.NLMAX) GO TO 661
12440 IF(GBLA(LN2).LT.4.)GBLA(LN2)=4.
12450 FRAC=(SUMTTY-TTAP)=76.//114.
12460 BLANX(LN3)=((GBLA(LN2)+(1.-FRAC)*BLANX(LN2)=0.75)*
12470 1 6.127-16.7
12480 0 TO 662
Appendix 3.1 (continued) Program listing of CERES maize model.

CONTINUE

BLX=0.0

FRAC=(SUMTTY-TTAP/76.)/114.

IF(LN.GE.NLMAX)FRAC=1.0

IF(LN1.EQ.NLMAX)FRAC=(SUMTTY-TTAP/38.)/114.

IF(LN2.GE.NLMAX)BLX=GBLA(NLMAX)+(1-FRAC)*BLAMX(NLMAX)

IF(LN.NE.NLMAX AND BLX.LT.4.)BLX=GBLA(NLMAX)+(1-FRAC)*BIA(NLMAX)

IF(LN2.GE.NLMAX)BLAMX(LN)=BXX(NLMAX)*(10*(LN3-NLMAX/114.)-0.06048*(LN3-NLMAX)**2)-0.0020122*(LN3-NLMAX)**2)

GROLF=(DDT-EXTRA)/PHIHT*BLAMX(LN)*AMIN1(SWDF2,SLAWR)

GO TO 9

IF(LN.GT.1)GO TO 22

*******QNLT FOR THE FIRST LEAF AND BEFORE IT COLLARS********

1. DTT-EXTRA FOR THE LOWEST LEAF ON THE DAY IT COLLARS
2. DTT FOR THE FIRST LEAF ALL OTHER TIMES
3. AND FOR THE SECOND AND THIRD LEAF WHEN THE THIRD LEAF COLLARS.

IF(CARBO .EQ.0.)GO TO 30

DTT2=DTT

GROLF=DTT2/PHT*BLAMX(LN)*AMIN1(SWDF2,SLAWR)

GBLA(LN)=GBLA(LN)+GROLF

SLA(LN)=SLA(LN)+GROLF

SENLA=0.

PHFRA=DTT/PHT

IF(LN.NE.S) GO TO 31

SENLA=PHFRA*GBLA(1)

LNS=1

IF(LN.NE.7)GO TO 32

SENLA=PHFRA*GBLA(2)

LNS=2

IF(LN.LT.15)G0 TO 33

SENLA=PHFRA*GBLA(LN-12)

LNS=LNS-12

IF(SENLA.LE.0)GO TO 41

SLA(LNS)=SLA(LNS)-SENLA

IF(SLAD(LNS).GE.0.)GO TO 41

SENLA=SLAD(LNS)-SENLA

SLA(LNS)=0.

PLA=PLA+GROLF-SENLA

LFWT=LFWT-SENLA/200.

IF(CARBO.EQ.0.0)GO TO 51

IF(LN.NE.M2.OR.EXTRA.LE.0.)GO TO 50

LN=LN+1
Appendix 3.1 (continued) Program listing of CERES maize model.

12990 DTG2=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 C SUBROUTINE PHASEI
13130 REAL LAT,LAI,LL,LFWT,NDEM,NDEF1,NDEF2,NDEF3,NDEF4,SWMAX,
13140 1 FACLI
13150 COMMON /PARAM/ ISOIL,IIRR,IVETH,ISOW,PLANTS,KOUTGR,KOUTWA,SDEPTH,
13160 1 LAT,KR fict,KS,KSII,QLQW,new,NEWET,NEWT,MULTYR,ISWSWB
13170 2 PR,KNIT,IODATE,XYIELD,XGRWT,XGPSM,XGPE,XLAI,EBIOii,LISLKD,
13180 3 MATJD,INSOIL
13190 COMMON /SOIL/ SALD,USWCON,DLATR(10),DUL(10),LL(10),SW(10),
13200 1 SAT(10),DEPMAX,TL,NAHR,SMX,WF(10),WR(10),BWU(10),NEWT,CH2
13210 COMMON /WATER/ SUMESL,SUMES2,T,TLL,PE,TSW,CUMDEP,ESW(IO),
13220 1 CSD1,CSD2,SI1(6),SI2(6),ICSDUR,ES,ET,EC,ESW,CEF,CEF,CEF,
13230 1 RLV(10),PRECAP,CHAIN,DRAIN,IRDRW,RTDEP,SWDF1,SWDF2,
13240 1 SWDF3,TRDW,RWUMX
13250 COMMON /PHENL/ T9,CUMDTT,TBASE,SUMDTT,SI,CI,ISTRAGE,
13260 1 DT,LDUR,SLN,TEMPS
13270 COMMON /GROTH/ GPSM,GPP,GRLOT,PTF,LAI,DM,BIOMAS,PLA,SENLA,
13280 1 LFWT,SEEDRV,REGM,XPLANT,WIDDL,EMST,SLW,PLAY,PLMAX,
13290 1 RTWT,SMWT,GRWT,SMWHE,LF,W,TLNO,SMAX,FACLI
13300 IRWDT,SUMP,LDUR,PAGT,GROTH,GRNWT,CARBO,BLAMX(35),GBLA(35),
13310 1 SLA(35),MLI,NMLNW2,EARS
13320 COMMON /GENET/ P1,P2,P3,P5,G3
13330 COMMON /NCTRL/ KOUTM,OUTM,KOUTNM,OUTNU,MINCK,NMDN,NHDUP,
13340 1 IFERT,ISWNT,DMOD,ESMAX,GRPCTM,GRPWM,MXTHM,MXPMP
13350 2 XGNUP
13360 COMMON /NCONC/ TANG,TCNP,RCNP,RCNT,THNC,VANC,VMNC,ISTAGE
13370 COMMON /NPLANT/ GRAINM,ROOTM,POWT,POVT,STOWT,PGRWT,NDM,
13380 COMMON /NDFPG/ NDFE1,NDFE2,NDFE3,NDFE4,GNP,CNSD1,CNSD2
13390 IF (ISTRAGE.GT.5) GO TO 10
13400 SI1(ISTRAGE)=CSD1
13410 SI2(ISTRAGE)=CSD2
13420 CNSD1=0.0
13430 CNSD2=0.0
13440 CSD1=0.0
13450 CSD2=0.0
13460 ICSDUR=0
13470 10 GO TO(1,2,3,4,5,6,7,8,9),ISTRAGE
13480 1 ISTRAGE=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  VMHC=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  RTDEF=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  NLI=1
14180  DO 90 I=1,35
14190  SLA(I)=0.0
14200  GBLA(I)=0.0
14210  90 CONTINUE
14220  BLAMX(I)=7.65
14230  WIDTL=3.0
14240  GROSTM=0.
14250  GBNWT=0.
14260  SENLA=0.
14270  GROTW=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  TRASE=0.0
14370  CUMDEF=0.
14380  RWID=0.023
14390  IF(ISWSWB.EQ.0) RETURN
14400  DO 100 L=1,NLAYR
14410  CUMDEF=CUMDEF+DLAYR(L)
14420  RLV(L)=0.20*PLANTS/DLAYR(L)
14430  IF (CUMDEF,GT,RTDEP) GO TO 110
14440  100 CONTINUE
14450  RLV(L)=RLV(L)*(1.-(CUMDEF-RTDEP)/DLAYR(L))
14460  110 CONTINUE
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*RTVJT
14590 STOVN=STOVWT*TANC
14600 150 RETURN
14610 END
14620 C
14630 C*****************S0IL NITROGEN INITIALIZATION SUBROUTINE***********
14640 C
14650 SUBROUTINE SOILNI
14660 REAL NH4,N03,NHUM,IF0M,IF0H,LL,N0DT,NUP,NN0M,MF
14670 DIMENSION L0C(4),FTYPE(6,6)
14680 COMMON /SOILI/ SALB,0,SWCON,DLAYR(IO),DUL(10),SW(10),
14690 1 SAT(10),DEPMAX,TDUL,NLAYR,SMX,WF(10),WR(10),RWU(10),SWEF,CN2
14700 COMMON /NNHR/ 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 SD(10),PB(10)
14740 COMMON /NCTRL/ KODTMN,IOOTMH,KODTNO,IOUTND,MINCK,NHDMN,NHDUP,
14750 1 IFERT,KFERT,ISWNIT,DMOD,KSTRAW,GRPCTM,GRPHTM,GRTPM,IFA,TMTP,
14760 1 XGNUP
14770 COMMON /NFERTB/ JFDAY(IO),AFERT(IO),DFERT(IO),NFERT,IFTYPE(IO)
14780 COMMON /NWRITP/ ATAHC,ATCNP,ARANC,ARCNP,ANDEN2,ATNUP,ARTN,ASTOWN,
14790 1 AGRN,CTNUP,NTNUP,ATNUP
14800 COMMON /NBALT/ PNUP(IO),NNOM(IO),DNOX(IO)
14810 COMMON /NDN/ FLUX(10),SWM(10),FLOW(IO),MU,NOUT(IO),NUP(IO)
14820 COMMON /NSTEMP/ ST(IO),ANG,TMN,AMP
14830 COMMON /NitRF/ CNJ(IO),FJY(10),TFY(10),RNTRF(IO)
14840 COMMON /NTINIT/ TLCH(IO),TUPFLX(IO),TPNUP(IO),TNOM(IO),
14850 1 TNNOX(IO),TST(IO),TNREF(IO)
14860 COMMON /NROOT/ RNFAC(IO),RNLOSS(IO),JJ
14870 COMMON /NENZ/ STRAW,SED,SGN,ROOT,SGN,OC(IO)
14880 COMMON /DATEC/ MO,ND,1YR,JDATE,JDATEX,IDIEM(12),NYRS
14890 COMMON /PARAM/ ISOIL,IRR,IVETR,ISOW,PLANTS,KOUTGR,KOUTWA,SDEPTH,
14900 1 LAT,KVARTY,KIVE,SOIL,IQUII,NEWSOL,NEWWT,MULTYR,ISNOWB
14910 2 PHINT,ENIT,SGDATE,XYIELD,AGRWT,XPFSM,XPGE,XMLAI,XMLAI,ISLKJD,
14920 3 MATJD,INSOIL
14930 DIMENSION WRN(IO)
14940 CHARACTER FTYPE*36
14950 DATA FTYPE/'UREA', 'AMMO', 'NIUM', 'NIT', 'RATE',
14960 * 'AMMO', 'NIUM', 'NIT', 'RATE',
14970 * 'AMMO', 'DROU', 'S AM', 'MONI', 'A',
14980 * 'CALC', 'TIAM', 'AMNO', 'NIUM', 'NIT', 'RATE',
14990 * 'M NI', 'TRAT', 'EE',
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),N03(I),BD(I),PH(I)
15100 10 CONTINUE
15110 C*****INPUT RESIDUE PARAMETERS
15120 READ (1,210) STRAW,SDEP,SCN
15130 READ (1,210) R00T,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 (FERT,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=J
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+WSN(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)=RHKG*FACTOR
15610 30  CONTINUE
15620  DEPTH=0.0
15630  IOUT=1
15640  DO 70 I=1,NLAYR
15650  DEPTH=DEPTH+DLAYR(I)
15660  FR=LAYR(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/SON
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  TIFOM=TIFOM+IFOM(I)
15860  TIFON=TIFON+IFON(I)
15870 95  CONTINUE
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  SN03(L)=N03(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)*1.0-E02-(SNu3(L)+SNH4(L))
16020 IF (MINCK.NE.0) WRITE (2,250) L,DL1,DL2,NH4(L),SNH4(L),N03(L),
16030 SG03(L),BD(L),P blamed (L)
16040 DLI=DL2
16050 110 CONTINUE
16060 IF (MINCK.NE.0) WRITE (2,260)
16070 DLI=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 DLI=DL2
16120 120 CONTINUE
16130 IF (MINCK.EQ.0) GO TO 130
16140 WRITE (2,270) STRAW,SDON,SNKG,ROOT,RCN,RRK,
16150 WRITE (2,280) RDCARB,RDCELL,RDLINE,DMINR
16160 C********** INITIALIZE SOIL TEMPERATURE ROUTINE
16170 130 ANG=0.01724
16180 ALX=ANG*FLOAT(JDATE)
16190 ZYl=0.
16200 XX=0.
16210 DD=DEPMAX*10.0
16220 DO 140 L=1,NLAYR
16230 ZZ=(DLAYR(L)*10.0+XX)/2.0.
16240 ZZ=ZY-ZY1
16250 ZD=-ZZ/DD
16260 YY=ZD+ALX
16270 ST(L)=TAV+DTDZ+DTDZ*ZZ
16280 AE=AMP*EXP(ZD)
16290 DTDZ=AE*ST*ANG
16300 DTDZ=AE*COS(ZY)-ST/YY/DD
16310 ST(L)=ST(DTDZ+DTDZ*ZZ)
16320 XX=DLAYR(L)*10.0+XX
16330 ZZ=ZY
16340 140 CONTINUE
16350 C********** INITIALIZE NITRIFICATION ROUTINE
16360 DO 170 L=1,NLAYR
16370 CMH(L)=0.1
16380 WFY(L)=SW(L)-LL(L))/DUL(L)
16390 IF (SW(L),GT.0.0) WFY(L)=1.0-(SW(L)-DUL(L))
16400/(SAT(L)-DUL(L))
16410 IF (WFY(L),LT.0.0) WFY(L)=0.0
16420 TSY(L)=0.0009766*ST(L)*ST(L)
16430 IF (ST(L),LT.5.0) TSY(L)=0.0
16440 TLCH(L)=0.0
16450 TUPFLX(L)=0.0
16460 TNUP(L)=0.0
16470 TNOM(L)=0.0
16480 TTNOX(L)=0.0
16490 TST(L)=0.0
16500 TBNTRF(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(T3)
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(/,'INITIAL MINERAL N IN LAYERS',/,1X,27('-'),//,5X,
16630 1 'LAYER','DEPTH','AMMONIUM','NITRATE',//,37X,'PPM',5X,
16640 2 'KG/HA',7X,'PPM',5X,'KG/HA',/
16650 250 FORMAT(110,4X,F4.0,1X,'-',/1X,F4.0,4X,6F10.1)
16660 260 FORMAT(/,'INITIAL ORGANIC MATTER IN LAYERS',/,1X,32('-'),//,
16670 1 5X,'LAYER',10X,'DEPTH',6X,'ORGANIC',5X,'HUMUS',5X,'HUMIC N',//,
16680 2 34X,'CARBON',5X,'KG/HA',5X,'KG/HA',/
16690 270 FORMAT(/,'FRESH ORGANIC MATTER',1X,/,20('-'),//,IX,
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,='F7.1,2X',
16730 4 F7.1,2X,'KG N/HA',//,IX,'TOTAL ROOT RESIDUE',T35,='F7.1,2X',
16740 5 'KG/HA',//,IX,'DISTRIBUTED ACCORDING TO F*EXP(-3*DEPTH/DEPMAX)',
16750 6 /,IX,'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(/,'MAXIMUM DECAY RATES OF OM FRACTIONS:',//,1X,
16780 1 36('-'),//,T37,'CARBOHYDRATE',T50,='F10.6,/'57 CELLULOSE',
16790 2 T50,='F10.6,/'57 LIGNIN',T50,='F10.6,/'57 HUMUS',T50,
16800 3 '}',F7.1,/) 
16810 290 FORMAT(/,'FERTILIZER INPUTS',//,'JULIAN DAY',5X,'KG/HA',5X,
16820 1 'DEPTH',15X,'SOURCE',/) 
16830 300 FORMAT(5X,I3,2F6.1,I2)
16840 310 FORMAT(110,2F10.2,3X,6A4)
16850 END
16860 C
16870 C********************************************************************
16880 CMINERALIZATION AND IMMOBILIZATION ROUTINE**********
16890: C
16900 SUBROUTINE MINIMO
16910 REAL IF0M,IF0N,MF,NHUM,LL,N03,NH4,SNOM
16920 COMMON /SOILI/ SALB,U,SWCON,DLAYR(10),DUL(10),LL(10),SW(10),
16930 1 SAT(10),DEPMAX,TBUL,NAFLYR,SMX,WF(10),WR(10),SWEF,CM2
16940 COMMON /CLIMT/ TEMPMN,TEMPMX,RAIN,SOLRAD,TMFAC(8)
16950 COMMON /NMINR/ RDLIGN,RDCELL,RDCARB,FOM(10),IFOM(10),FON(10),
16960 1 IE0N(10),DMINR,NHUM(10),HUM(10),TIFOM,TIFON
16970 COMMON /NOMT/ TMINH,TMINF,DECR(10),CNR(10),TNOM,PORH,PORN,
16980 1 FOCNR(10),SCNR(10)
16990 COMMON /NPOOL/ SBF(10),SNR(10),NH4(10),NO3(10),PAC(10),
17000 1 BD(10),PH(10)
Appendix 3.1 (continued) Program listing of CERES maize model.

17010 COMMON /NSTEMP/ ST(IO),ANG,TMN,AMP
17020 COMMON /NFERTB/ JFDAY(IO),AFERT(IO),DFERT(IO),NFERT,IFTYPE(IO)
17030 COMMON /NCTRL/ KOUTMN,IOOTMN,KOUTNU,IOOTNU,MINCK,NHDMN,NHDUF,
17040 1 IFERT,KFERT,ISWNIT,DMOD,XSTRAW,GRPTN,ATOTNP,KAPTNP
17050 2,XGNUP
17060 COMMON /DATEC/ MO,ND,IYR,JDATE,JDATEX,IDIM(12),NYRS
17070 COMMON /NBALT/ PNUP(IO),NNOM(IO),DTNOX(IO)
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 =NITRATE
17260 30 SNO3(L)=SNO3(L)+AFERT(J)
17270 GO TO 70
17280 40 SNO3(L)=SNO3(L)+0.5*AFERT(J)
17290 SNO3(L)=SNO3(L)+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 TIMB=0.0
17380 TMHB=0.0
17390 TMB=0.0
17400 TMMH=0.0
17410 TON=0.0
17420 TCN=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)-0.01*DLAYR(I))
17470 NO3(I)=SNO3(I)*FAC(I)
17480 NH4(I)=SNO3(I)*FAC(I)
17490 TCAC=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 RATI0=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 CNRF=EXP(-0.693*(CNR(I)-25)/25.0)
17590 IF (CNRF.GT.1.0) CNRF=1.0
17600 DECR(I)=RDECR*TFAC*MF*CNRF
17610 GRNOM=DECR(I)*FOM(I)
17620 RHMIN=HOM(I)*DMINR*TFAC*MF
17630 HUM(I)=HOM(I)-RHMIN*10.0-0.2*GRNOM/0.04
17640 NNOM(I)=HNOM(I)-RHMIN*0.2*GRNOM
17650 RNAC=AMIN*(TOTN,DECR(I)*FOM(I)*(0.02-FON(I)/FOM(I)))
17660 FOM(I)=FOM(I)-DECR(I)*FOM(I)
17670 POMR=TOM/TIFOM
17680 PONR=TON/TIFON
17690 CALL NITRIF
17700 CONTINOE

C***************DETAILED NITROGEN BALANCE OUTPUT ROUTINE**********
C
SUBROUTINE NBAL
REAL MF,IFOM,IFON,NHUM,LL,NOUT,NUP,NNOM
COMMON /CLIMT/ TEMPN,TEMPMX,RAIN,SOLRAD,TMFAC(8)
COMMON /DATEC/ MO,ND,IYR,JDATE,JDATEX,IDIM(12),NYRS
Appendix 3.1 (continued) Program listing of CERES maize model.

17960 COMMON /NMINR/ RDLIGN,RECELL,RECARB,FOM(10),FON(10),
17970 1 IFOM(10),DNINR,REHUM(10),HUM(10),TIFOM,TIFON
17980 COMMON /NOMT/ TIMOB,TMINF,TMINH,DECR(10),CNR(10),TNOM,FOMR,PONR,
17990 1 FOCN(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,MLAYR,SMX,WF(10),WR(10),SWP,CN2
18040 COMMON /NCTRL/ KOUTMN,LOTMN,KOUTNU,IOOTND,MINCK,NHDMN,NHDUP,
18050 1 IFERT,KFERT,ISWNIT,DMOD,XSTRAW,GRPTN,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(IO),WFY(10),TFY(10),RNTRF(10)
18100 COMMON /NSTEMP/ ST(IO),ANG,TMN,AMP
18110 COMMON /NTINIT/ TLCH(IO),TUFFLX(IO),TPNUP(IO),TNOM(IO),
18120 1 TTNOX(IO),TST(IO),TRNTRF(IO)
18130 DO 10 L=1,NLAYR
18140 TLCH(L)=TLCH(L)+NODT(L)
18150 TUFFLX(L)=TUFFLX(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*MINTK.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(MINTK)
18330 WRITE (2,60) L,FOM(L),FON(L),TST(L),SNO3(L),SNH4(L),TRNTRF(L),
18340 1 CNR(L),FCNR(L),SCNR(L),TLCH(L),TUFFLX(L),TPNUP(L),TNOM(L),
18350 2 TTNOX(L)
18360 TLCH(L)=0.0
18370 TUFFLX(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 =',4X,20X,'GROSS N IMMOBILIZATION IN FILE =',
18470 20X,'GROSS N RELEASE FROM FRESH OM =',20X,'N RELEASED FROM HUMUS =',
18480 3',T70,F7.2,'KG N/HA',/,20X,'GROSS N RELEASE FROM FRESH OM =',
18490 2INERALIZATION =',T70,F7.2,'KG N/HA',/,20X,'N RELEASED FROM HUMUS =',
18500 3',T70,F7.2,'KG N/HA')
18510 50 FORMAT (IX,'LAYER',6X,'POM',5X,'FON',6X,'TEMP',4X,'SN03',4X,
18520 1 'SNH4',2X,'NITRIF',5X,'C:N*',2X,'F0M C:N',1X,'SOIL C:N',4X,
18530 2 'LEACH',4X,'UPFLX',5X,'UPTK',5X,'MINN',4X,'DENIT')
18540 60 FORMAT (17,F9.0,F8.1,F8.0,2F8.1,F9.3,3F9.2,5F9.3)
18550 END
18560 C*************************************************************
18570 C NITROGEN UPTAKE ROUTINE***************************************
18580 C
18590 SUBROUTINE NUPTAK
18600 REAL NOB,NNOM,NH4,NDEM,NUF,LL,LAT,LFWT,N0UT,NUP,LAI
18610 COMMON /PARAM/ ISOIL,IIRR,IWETH,ISOW,PLANTS,KOUTGR,KOUTWA,SDEPTH,
18620 1 LAT,KVARTY,KIRR,KS0IL,IQUIT,NEWSOL,NEWWET,MULTYR,ISWSWB
18630 2 MATJD,INSOIL
18640 COMMON /SOILI/ SALB,U,SWC0N,DLAYR(10),DDL(10),LL(10),SW(10),
18650 1 LAT,KVARTY,KIRR,KS0IL,IQUIT,NEWSOL,NEWWET,MULTYR,ISWSWB
18660 COMMON /GROTH/ GPSM,GPP,GRORT,PTF,LAI,DM,BIOMAS,PLA,SENL,
18670 1 LFYT,SEEDBR,REGM,PLAY,PLAMX,
18680 1 RTWT,SMWT,GMWT,SWMIN,LM,EARWT,TINO,SMAX,PGCLI
18690 COMMON /WATER/ SUMESl,SUMES2,T,TLL,PESW,TSW,CUMDEP,ESW(10),
18700 1 CSDl,CSD2,SI1(6),SI2(6),CSDOR,ES,EP,ET,EO,CES,CEP,CT,
18710 1 RLV(10),PRECP,CRAIN,DRAIN,IDRSW,RTDEP,SWDF1,SWDF2,
18720 1 SWDF3,REWU,REWUX
18730 COMMON /NSPOOL/ SNH4(10),SN03(10),NH4(10),NO3(10),FAC(10),
18740 1 BD(10),PH(10)
18750 COMMON /NCONC/ TANC,TCNF,RCNF,RANC,TMNC,TANC,YMNC,XSTATE
18760 COMMON /PHENL/ P9,CUMDTT,TBASE,SUMDTT,S1,C1,ISTAGE,
18770 1 DTT,INDT,IND,TEMPH
18780 COMMON /NPLANT/ GRAINN,ROOTN,STOVN,FDWI,STOWT,PGROOT,NDEM
18790 COMMON /NBROOT/ RFAC(10),RNLOSS(10),JJ
18800 COMMON /NBDATE/ MO,HY,AT,DATE,JDAT,IDIM(12),MYRS
18810 COMMON /NWRTPI/ ATANC,ATCNP,ARANC,ARCNP,ANDEM2,ATNUP,ARTN,ASTOVN,
18820 1 AGRM,CTNUP,TNUP,APTNUP
18830 COMMON /NBALT/ TNP(10),NMON(10),DTMONX(10)
18840 COMMON /NMVE/ FLUX(10),SWX(10),FLOW(10),HU,NOUT(10),NUP(10)
18850 COMMON /NNH/ NFAC,DSTOVN
18860 DIMENSION RNJU30(10),RNNH4U(10)
18870 TNU=0.0
18880 TRNLOS=0.0
18890 DO 10 L=1,NLAYB
18900 NO3(L)=SN03(L)*FAC(L)*BD(L)
18910 NH4(L)=SNH4(L)*FAC(L)*BD(L)
18920 TOTN=NO3(L)+NH4(L)
18930 RFAC(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.0.0) 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 DRROOTN=0.0
19070 DSTDV=N=0.0
19080 TRNU=0.0
19090 TNU=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 L=L
19140 FNH4=1.0-EXP(-0.030*NH4(L))
19150 FNO3=1.0-EXP(-0.025*N03(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)=(RWD(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 RFAC*FNO3*0.008*SMDFR
19242 UPL=SNO3(L)-RNO3U(L)
19250 SMIN=1.0/FAC(L)
19260 IF (UP1.LT.SMIN) RNO3U(L)=SNO3(L)-SMIN
19261 IF (RNO3D(L).LT.0.) RNO3D(L)=0.0
19270 RHH4D(L)=RFAC*FNH4*0.008
19280 IF (SMDFR.LT.0.50.AND.NFAC.LT.0.70) RNN4D(L)=
19281 RFAC*FHH4*0.008
19290 IF (SMDFR.LT.1.00) RHH4D(L)=SMDFR
19292 UFD=SNO3U(L)-RNN4D(L)
19293 IF (UP2.LT.SMIN) RNN4D(L)=SNO3U(L)-SMIN
19294 IF (RNN4D(L).LT.0.) RNN4D(L)=0.0
19295 TRNU=TRNU+RNO3U(L)+RNN4D(L)
19300 CONTINUE
19310 20 CONTINUE
19320 30 IF (ANDEM.GT.TRNU) ANDEM=ANDEM
19330 IF (TRNU.EQ.0.0) GO TO 60
19340 NUF=ANDEM/ANDEM
19350 TRNU=TRNU*NUF
19360 TNUS=0.0
19370 DO 40 L=1,L1
19380 UNO3=RNO3U(L)*NUF
Appendix 3.1 (continued) Program listing of CERES maize model.

19390 \texttt{UNH4=RNH4(L)*NUT}
19400 \texttt{SN03(L)=SN03(L)-UN03}
19410 \texttt{SNH4(L)=SNH4(L)-UNH4}
19420 \texttt{PNUP(L)=UN03+UNH4}
19430 \texttt{RNLOSS(L)=RANC*RLV(L)*0.006665}
19440 \texttt{TRNLOS=TRNLOS+RNLOSS(L)}
19450 \texttt{TNUP=TNUP+PNUP(L)}
19460 \texttt{TRNS=TRNS+SN03(L)+SNH4(L)}
19470 \texttt{40 CONTINUE}
19480 \texttt{TNUP=TNUM/(PLANTS*10.0)}
19490 \texttt{DSTOVN=TNDEM/NDEM*TRNU}
19500 \texttt{DROOTN=RNDEM/NDEM*TRNU*0.985}
19510 \texttt{STOVN=STOVN+DSTOVN}
19520 \texttt{50 TANC=STOVN/STOVWT}
19530 \texttt{DROOTN=DROOTN-TXNLOS}
19540 \texttt{ROOTN=ROOTN+DROOTN}
19550 \texttt{RATION=ROOTN/(RTWT+0.5*GRDT-0.01*RTWT)}
19560 \texttt{60 RETURN}
19570 \texttt{END}
19580 \texttt{C}
19590 \texttt{C*****************DRAINAGE AND LEACHING ROUTINE******************}
19600 \texttt{C}
19610 \texttt{SUBROUTINE NFLUX (ICODE)}
19620 \texttt{REAL N03,LL,NH4,NOUT,NUP,NHOM}
19630 \texttt{COMMON /SOILI/ SALB,U,SWCON,DLAYR(10),DUL(10),LL(10),SW(10),}
19640 \texttt{1 SAT(10),DEPMAX,TDnL,NLAYR,SMX.WF(10),WR(10),RWU(10).SWEF,CN2}
19650 \texttt{COMMON /NSPOOL/ SNH4(10),SN03(10),NH4(10),N03(10),FAC(10),}
19660 \texttt{1 BD(10),PH(10)}
19670 \texttt{COMMON /NMOVE/ FLUX(10),SWX(10),FLOW(10),HU,NOUTU(10),NUPU(10)}
19680 \texttt{COMMON /NBALT/ PNUPU(10),NHOMU(10),DTN0X(10)}
19690 \texttt{COMMON /NROOT/ RNFC(10),RNLOSS(10),JJ}
19700 \texttt{COMMON /DATEC/ MO,WD,YR,JDATE,JDATEX,IDIM(12),NYRS}
19710 \texttt{IF(ICODE.EQ.1) GO TO 38}
19720 \texttt{10 DO L=1,NLAYR}
19730 \texttt{NOUT(L)=0.0}
19740 \texttt{10 CONTINUE}
19750 \texttt{OUTN=0.0}
19760 \texttt{DO 35 L=1,NLAYR}
19770 \texttt{SN03(L)=SN03(L)-OUTN}
19780 \texttt{NO3(L)=SN03(L)*FAC(L)}
19790 \texttt{IF (NO3(L).GT.1.0) GO TO 20}
19800 \texttt{OUTN=0.0}
19810 \texttt{GO TO 35}
19820 \texttt{20 NOUTL=SN03(L)*FLUX(L)/(SW(L)*DLAYR(L)+FLUX(L))}
19830 \texttt{SMIN=1.0/FAC(L)}
19840 \texttt{IF (SN03(L).LT.SMIN)NOUT(L)=SN03(L)-SMIN}
19850 \texttt{OUTN=OUTN(L)}
19860 \texttt{SN03(L)=SN03(L)-OUTN}
19870 \texttt{NO3(L)=SN03(L)*FAC(L)}
19880 \texttt{35 CONTINUE}
Appendix 3.1 (continued) Program listing of CERES maize model.

19890 RETURN
19900 38 DO 40 L=1,NLAYR
19910 NUP(L)=0.0
19920 40 CONTINUE
19930 OUTN=0.0
19940 DO 50 J=1,MU
19950 K=MU+1-J
19960 SN03(K)=SN03(K)-OUTN
19970 IF(FLOW(K).LT.0.) GO TO 50
19980 NUP(K)=SN03(K)*FLOW(K)/(SW(K)*DLAYR(K)+FLOW(K))*0.5
19990 OUTN=OUTN(K)
20000 IF(K.EQ.1) GO TO 50
20010 SN03(K)=SN03(K)-OUTN
20020 50 CONTINUE
20030 RETURN
20040 DO 60 J=1,MD
20050 SN03(J)=SN03(J)-OUTN
20060 IF(FLOW(J).GT.0.) GO TO 60
20070 NUP(J)=SN03(J)*FLOW(J)/(SW(J)*DLAYR(J)+FLOW(J))*0.5
20080 OUTN=OUTN(J)
20090 SN03(J)=SN03(J)+OUTN
20100 60 CONTINUE
20110 RETURN
20120 END
20130 C
20140 C*********************NITROGEN DEFICIENCY FACTOR ROUTINE************
20150 C
20160 SUBROUTINE NFACTO
20170 COMMON /NNN/ NFAC,DSTOVN
20180 COMMON /GENET/ P1,P2,P3,P5,G1,G2,G3
20190 COMMON /PHENL/ P9,CUMDTT,TBASE,SUMDTT,S1,C1,ISTAGE,
20200 1 DTT,IDUR,SIND,TEMPM
20210 COMMON /NDFPG/ NDEF1,NDEF2,NDEF3,NDEF4,CNSD1,CNSD2
20220 COMMON /NCONC/ TANC,TCNP,RANC,TNC,CANC,VMNC,XSTAGE
20230 COMMON /DATEC/ MO,ND,YR,JDATE,JDATEX,IDIM(12),NYRS
20240 REAL NPAC,NDEF1,NDEF2,NDEF3,NDEF4
20250 TCNP=EXP(1.52-.221*XSTAGE)/100.0
20260 TMNC=.0025
20270 IF(XSTAGE.LT.4.) TMNC=(1.25-.20*XSTAGE)/100.0
20280 RCNP=1.06/100.0
20290 NFAC=1.0-(TCNP-TANC)/(TCNP-TMNC)
20300 IF (NFAC.GT.1.0) NFAC=1.0
20310 IF (NFAC.LT.0.) NFAC=0.
20320 NDEF1=1.0
20330 NDEF2=1.0
20340 NDEF3=1.0
20350 IF(NFAC.LT.0.80)NDEF1=0.90*NFAC+0.3
20360 IF(NFAC.LT.0.4)NDEF2=1.00*NFAC+0.60
20370 IF(NFAC.LT.0.5)NDEF3=0.35+1.30*NFAC
20380 NFAC=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/ K0DTMN, I0DTMN, K00TNU, I0DTN0, MINCR, HDMN, HNDUP,
20500 1 IFERT, KFERT, ISWNIT, DMOD, XSTRAW, GRPCTN, CRPTN, XTOTP, XAPTNP
20510 2, XGNUP
20520 COMMON /SWRITP/ ATANC, ATCNP, ARANC, ARCPNP, ANDEMP, ANDEMP2, ATNUP, ARTN, ASTRVN,
20530 1 AGRN, CTNUP, TNUP, APTNUP
20540 COMMON /NAMIN/ APOMR, APONR, ACNHR, ADECR, AIMOBR, AMINR, AMHR, ANOM
20550 COMMON /NPLANT/ GRAINN, ROOTN, STOVN, PDWN, STOVWT, PGRTN, NDEN
20560 COMMON /NCONC/ TANC, TCNP, RCNP, RANC, TMNC, VMNC, XSTAGE
20570 COMMON /NOMT/ TIMOB, TMINF, TMINH, DECR(10), CNR(10), TNOM, POMR, PONR,
20580 1 FCNR(10), SCNR(10)
20590 COMMON /PHENL/ P9, CUMDTT, TBASE, SUMDTT, S1, C1, ISTAGE,
20600 1 DTT, IDOR, SIND, TEMPM
20610 COMMON /DATEC/ NO, ND, IYR, JDATE, JDATEX, IDIM(12), NYRS
20620 COMMON /PARAM/ ISOIL, IIRR, IWETH, ISOW, PLANTS, KOUTGR, KOUTWA, SDEPTH,
20630 1 LAT, KVAR, KERR, KSOIL, IQQUIT, NEWSOL, NNEWWT, MULYR, ISWSWB
20640 2, PRINT, KNIT, IDATE, XYIELD, XGRWT, XGPM, XGPE, XLAH, XBIOM, ISLKJ,
20650 3 MATJD, INSOIL
20660 COMMON /F90/ P9, CUMDTT, TBASE, SUMDTT, S1, C1, ISTAGE,
20670 COMMON /DATEC/ NO, ND, IYR, JDATE, JDATEX, IDIM(12), NYRS
20680 COMMON /PARAM/ ISOIL, IIRR, IWETH, ISOW, PLANTS, KOUTGR, KOUTWA, SDEPTH,
20690 1 LAT, KVAR, KERR, KSOIL, IQQUIT, NEWSOL, NNEWWT, MULYR, ISWSWB
20700 IF (MINCR.GE.1) CALL NBAL
20710 CTNUP = CTNUP + TNUP
20720 IF (KOUTMN.EQ.0) GO TO 10
20730 IOUTMN = IOUTMN + 1
20740 APOMR = APOMR + POMR
20750 APONR = APONR + PONR
20760 ACNR = ACNR + (FOCNR(1) + FOCNR(2))/2.0
20770 ADECR = ADECR + (DECR(1) + DECR(2))/2.0
20780 AIMOBR = AIMOBR + TIMOB
20790 AMINR = AMINR + TMINH
20800 AMHR = AMHR + TMINH
20810 ANOM = ANOM + TNOM
20820 IF (IOUTMN.EQ.1) CALL OOUTMN
20830 IF (IOUTMN.EQ.10) CALL OOUTMN
20840 APTNUP = APTNUP + PLANTS
20850 IF (IOUTMN.EQ.0) RETURN
20860 IF (ISTAGE.GT.6) RETURN
20870 IOUTMN = IOUTMN + 1
20880 ATANC = ATANC + TANC
20890 ATCNP = ATCNP + TCNP
20900 ARANC = ARANC + RANC
20910 ARCPNP = ARCPNP + RCNP
20920 RETURN
20930 END
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+STOWN
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,N03,NH4
21000 COMMON /DATEC/ MO,ND,ITR,JDATE,JDATEX,IDIM(12),NYSR
21010 COMMON /SOIL/ SALB,D,SWCON,DLAYR(10),DOL(10),LL(10),SW(10),
21020 1 SAT(IO),DEPMAX,TDL,NLAYR,SMX,WF(10),WR(10),RWU(10),SWEF,GN2
21030 COMMON /PHENL/ P9,CUMDTT,TBASE,SUMDTT,S1,C1,ISTAGE,
21040 1 DTT,DDUR,SNH,TEMPH
21050 COMMON /CROTH/ GPSM,GPP,GRORT,PTF,LAI,DM,BIOMAS,PLA,SENLA,
21060 1 LAWT,SEERFW,XGMC,WGMC,SLM,SLW,PLAX,PLMX,
21070 1 TEMC,STMT,GMNO,GMN(10),SWMIN,LM,EARBT,MLNO,SWMAX,FACLI,
21080 1 BWTD,SUMP,IDURP,PLAG,EGFT,GROTM,GRBMO,SLMX(35),GBlA(35),
21090 1 SLM(35),NLI,NLMAK,ears
21100 COMMON /WATER/ SUMES1,SUMES2,T,TLL,FESW,TSW,CUMDEF,ESW(10),
21110 1 CS1,CS2,SL1(6),SL2(6),ICS0DUR,ES,EF,ET,EO,CES,CEP,CET,
21120 1 RLV(IO),PRECIP,RAIN,ICRSM,IRDEP,ICDFL,ICDF2,ICDF3,
21130 1 ICFU,ICMV,ICMWK
21140 COMMON /NCTRL/ KOUTMN,IOnTMN,KOUTNU,IOOTNU,MNCE,NHDMN,NHDUP,
21150 1 IFERT,KFERT,ISWTN,DSMR,STRW,GRFCTN,CRFTN,XTUOTNP,LAPTNP
21160 2,ICJNUP
21170 COMMON /NWRITP/ ATANC,ATCNP,ARANC,ACNFP,ANDEM2,ATNUP,ARTN,ASTOVN,
21180 1 AGRN,CTNUP,TNUP,APTNUP
21190 COMMON /NDFPG/ NDEF1,NDEF2,NDEF3,NDEF4,GNF,CNSD1,CNSD2
21200 COMMON /NPLANT/ GRAINN,ROOTN,STOVN,PDW1,STOWT,PGRONT,NDEM
21210 COMMON /NSPOOL/ SHW1(10),SN03(10),NO3(10),NH4(10),PAC(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 DAUP=FLOAT(IOUTNU)
21300 ATANC=(ATANC/DAUP)*100.0
21310 ATCNP=(ATCNP/DAUP)*100.0
21320 ARANC=(ARANC/DAUP)*100.0
21330 ACNFP=(ACNFP/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.

```fortran
21370  ASTOVN=(ASTOVN/DAOP)*1000.0
21380  AGRN=1000.0*AGRN/DAOP
21390  XGNP=0.0
21400  IF (GRNWT.GT.0.) XGNP=GRAIN*100.0/GRNWT
21410  TNH4=0.0
21420  TN03=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   TN03=TN03+SN03(L)
21480   TNH4=TNH4+SNH4(L)
21490  CONTINUE
21500  CALL CALDAT
21510  WRITE (4,70) MO,ND,IYR,JDATE,ATANC,ATCNP,ARANC,ARCNP,ANDEM2,ATNUP,
21520     1 ARTH,ASTOVN,AGRN,XGNP,CTNDP,APTNUP,TN03,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  ARTH=0.0
21600  ASTOVN=0.0
21610  AGRN=0.0
21620  IOUTMN=0
21630  RETURN
21640  C
21650  50 FORMAT (/10X,'JUL',1X,'------TOPS N------',2X,'------ROOT N------',2X,
21660     1 '-----N (KG/RA)-----',2X,-----------MG N/PLANT----------',4X,'GRAIN',1X,
21670     2 'N UPTAKE KG/HA',2X,PLANT EXTR N-1',/3X,'DAY',4X,'DAY',2(5X,
21680     3 'ACT',4X,'CRIT'),2X,'DEMAND',2X,'OPTAKE',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  C SUBROUTINE OUTMN
21770  REAL NH4,N03
21780  COMMON /NAMIN/ APOMR,APONR,ACHN,ACECR,AIMOB,AMINF,AMINH,ANOM
21790  COMMON /SNPOOL/ SN03(10),NO3(10),NH4(10),NO3(10),FAC(10),
21800     1 ED(10),PH(10)
21810  COMMON /DATEC/ MO,ND,IDR,JDATE,JDATEX,IDIM(12),NTRS
21820  COMMON /NCTRL/ KOUTMN,IOUTMN,JOUTMN,JOUTNU,KOUTNU,MINCK,NHDMN,NHDUP,
21830     1 IFEET,KEFT,ISWNIT,SNOM,KSTRAW,CRFTN,CRPTH,KTOTNP,RAFTNP
21840  2,XGNUP
21850  COMMON /TITL/ TITLE(20)
21860  IF (NHDMN.EQ.1) GO TO 10
```
IF (KOUTMN.NE.0) WRITE (3,50) TITLE
IF (KOOTMN.NE.0) WRITE (3,40) (L,L-1,6),(L,L-1,6)
NHDMN=1
GO TO 20
DAMN=FLOAT(IOOTMN)
APOMR=APOMR/DAMN
APONR=APONR/DAMN
ACMR=ACMR/DAMN
ADECR=ADECR/DAMN
AIMOB=AIMOB/DAMN
AMINF=AMINF/DAMN
AMINH=AMINH/DAMN
ANDEM=ANDEM/DAMN
CALL CALDAT
WRITE (3,30) MO,ND,IYR,JDATE,APOMR,APONR,ACMR,ADECR,AIMOB,AMINF,
1 AMINH,AN0M,(N03(L),L=1,6),(NH4(L),L=1,6)
APOMR=0.0
APONR=0.0
ACMR=0.0
ADECR=0.0
AIMOB=0.0
AMINF=0.0
AMINH=0.0
ANDEM=0.0
RETURN
FORMAT (1X,I2,'/',I2,'/',I2,I4,3F6.1,EB.1,10F6.1,6F5.1)
FORMAT (/,9X,'JUL',9X,'FRESH OM',17X,'ORGANIC N',19X,
1 'NITRATE (PPM)',19X,'AMMONIUM (PPM)',2X,'% OMR',
2X,'% OMN',2X,'C:N',4X,'DECR',2X,'IMOB',3X,'MIN',2X,'MINH',2X,
3 'TMIN',6(4X,'L',I1),6(3X,'L',I1))
FORMAT (/,40X,20A4,/)
Appendix 3.1 (continued) Program listing of CERES maize model.

```fortran
DO 10 L=1,NLAYR
   Z1=DLAYR(L)*10.0
   Z=Z+Z1
   P=BD(L)/(BD(L)+686.*EXP(-5.63*BD(L)))
   DP=1000.0+2500.*F
   WW=0.356-0.144*BD(L)
   P-BD(L)/(BD(L)+686.*EXP(-5.63*BD(L)))
   DW=SW(L)-LL(L)
   IF (DW.LT.0.0) DW=0.0
   AH=BD(L)
   WC=AW/(WW*(Z-XX))
   F=EXP(B*(1.-WC)/(1.+WC)**2)
   DD=F*DP
   ZT=(Z+XX)/2.0
   ZZ=ZT-ZT1
   ZZ=ZT-DD
   YT=ZT+ALX
   ST=SIN(TY)
   AE=AMP*EXP(ZD)
   DTD=AE*SY*ANG
   DTDZ=AE*(COS(YY)-ST)/DD
   TP=(ST(L)+TP+DTD+DTDZ*ZZ)/2.0
   ST(L)=TP
   ZT1=ZT
   Z=Z-XX
   CONTINUE
22650 RETURN
22660 END
C******** DENITRIFICATION SUBROUTINE **********REPLACED 4-84
C
```
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*N03(L)*FW*FT
22890     C     DNRATE=6.0*1.E-05*CW*N03(L)*BD(L)*FW*DLAYR(L)
22900     SMIN=1.0/FAC(L)
22910     SN03(L)=SN03(L)-DNRATE
22920     X=0
22930     IF(SN03(L).LT.SMIN)X=SMIN-SN03(L)
22940     SN03(L)=SN03(L)+X
22950     DNRATE=DNRATE-X
22960     DTONX(L)=DNRATE
22970     NO3(L)=NO3(L)*FAC(L)
22980     10 CONTINUE
22990     RETURN
23000     END

23010     C************* NITRIFICATION SUBROUTINE *************
23020     C
23030     C
23040     C SUBROUTINE NITRF
23050     C COMMON /NITRF/ CNT(IO),WFY(10),TFY(10),RNTRF(IO)
23060     C COMMON /SOIIL/ SALB, U, SWCON, DLAYR(IO), DUL(IO), LL(IO), SW(IO),
23070     1 SAT(IO), DFLMAX, DUL(IO), SAT(IO), DEPMAX, TDUL, NLAYR,
23080     C COMMON /NSTEMP/ ST(IO), ANG, THN, AMP
23090     C COMMON /NSPOOL/ SNH4(IO), SN03(IO), NH4(IO), NO3(IO), FAC(IO),
23100     1 BD(IO), PR(IO)
23110     C COMMON /NCTRL/ KOUTMN, IOUTMN, KOUTHU, IOUTHU, MINCK, NHDHM, NHDMU,
23120     1 IFERT, KFERT, ISWNIT, DMDL, XSTRAW, CRFTN, GRFTN, XTRTF, KAPTTF,
23130     2, XGUP
23140     REAL LL, NO3, NH4
23150     DO 10 L=1, NLAYR
23160     C
23170     SANC=1.0-EXP(-0.01363*SNH4(L))
23180     XL=(DUL(L)-LL(L))/0.25
23190     IF(SW(L).LT.XL)WFD=1.0
23200     IF(SW(L).GT.XL)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=A*AMIN1(TF,WFD,SANC)
23250     RP2=G*(TF)*EXP(2.302*ELNC)
23260     IF(RP2.LT.0.01)RP2=0.01
23270     IF(RP2.GT.1.0)RP2=1.0
23280     CNL=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     SN03(L)=SN03(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     CNL=CNL*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

<table>
<thead>
<tr>
<th>Coded level</th>
<th>*Actual level (kg ha$^{-1}$)</th>
</tr>
</thead>
<tbody>
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<td>-.85</td>
<td>30</td>
</tr>
<tr>
<td>-.40</td>
<td>70</td>
</tr>
<tr>
<td>Opt.</td>
<td>108</td>
</tr>
<tr>
<td>+.40</td>
<td>144</td>
</tr>
<tr>
<td>+.85</td>
<td>190</td>
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</table>

*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.

<table>
<thead>
<tr>
<th>SITE</th>
<th>Measured</th>
<th>Coded N level (P, N)</th>
<th>Simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Opt. 0</td>
<td>+.85, -.85</td>
</tr>
<tr>
<td>WAI-J84</td>
<td>Measured</td>
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</tr>
<tr>
<td></td>
<td>Simulated</td>
<td>0.284</td>
<td></td>
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<tr>
<td>WAI-F10</td>
<td>Measured</td>
<td>0.244</td>
<td>0.252</td>
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<tr>
<td></td>
<td>Simulated</td>
<td>0.284</td>
<td>0.284</td>
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<tr>
<td>MOL-L10</td>
<td>Measured</td>
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<td>0.251</td>
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<tr>
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<td>Simulated</td>
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<tr>
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<td>Measured</td>
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<td>Simulated</td>
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<td>MOL-N10</td>
<td>Measured</td>
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<td>0.244</td>
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<tr>
<td></td>
<td>Simulated</td>
<td>0.301</td>
<td>0.301</td>
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<tr>
<td>MOL-N20</td>
<td>Measured</td>
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<td>0.187</td>
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<tr>
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<td>Simulated</td>
<td>0.308</td>
<td>0.308</td>
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Appendix 4.2 Validation of simulated kernel numbers with observed kernel numbers on Tropeptic Eutrustox sites in Hawaii.

<table>
<thead>
<tr>
<th>SITE</th>
<th>Measured</th>
<th>Simulated</th>
<th>Coded N level (P, N)</th>
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<th></th>
<th></th>
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<tbody>
<tr>
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<td></td>
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<td>Opt, 0</td>
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<td>+.85, Opt</td>
<td>-.40, +.40</td>
<td>+.85, +.85</td>
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<td>WAI-J84</td>
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Appendix 4.3 Validation of simulated grain weights with observed weights on Typic Paleudults in Indonesia and Philippines.

<table>
<thead>
<tr>
<th>SITE</th>
<th>Coded N level (P, N)</th>
<th>Measured</th>
<th>Simulated</th>
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<tbody>
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<td>Opt, 0</td>
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<td>+.40, -.40</td>
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<td></td>
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<td>0.234</td>
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<td>0.261</td>
<td>0.245</td>
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<tr>
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<td>0.229</td>
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<tr>
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<td></td>
<td>0.266</td>
<td>0.245</td>
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</table>
Appendix 4.3 (continued) Validation of simulated grain weights with observed weights on Typic Paleudults in Indonesia and Philippines.

<table>
<thead>
<tr>
<th>SITE</th>
<th>Coded N level (P, N)</th>
<th>Measured</th>
<th>Simulated</th>
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<tbody>
<tr>
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Appendix 4.3 (continued) Validation of simulated grain weights with observed weights on Typic Paleudults in Indonesia and Philippines.

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Appendix 4.5 (continued) Validation of simulated kernel weights with observed weights on Hydric Dystrandept sites in Indonesia, Philippines, and Hawaii.

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Appendix 4.6  Validation of simulated kernels per ear with observed numbers on Hydric Dystrandept sites in Indonesia, Philippines, and Hawaii.

<table>
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<th>SITE</th>
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Appendix 4.6 (continued) Validation of simulated kernels per ear with observed numbers on Hydric Dystrandept sites in Indonesia, Philippines, and Hawaii.

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Appendix 4.7  Comparison of simulated and observed grain yields (kg ha\textsuperscript{-1}) under different population densities over nine bimonthly plantings.

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</table>

* Severe lodging encountered.
\textsuperscript{a} Source: Lee (1983).
Appendix 5.1 Sample Calculation.

Carrier Method
\[ E = x(S_i/S_t - 1) \] (2.9)

Initial activity of the sample: 1000 m Ci/m mol = 30.3 m Ci/mg P
\[ = 30.3 \frac{mCi}{mgP} \times 2.22 \times 10^6 \frac{cpm}{mCi} \]
\[ = 6.6 \times 10^{10} \frac{cpm}{mg P} \]

And \( x = 30 \frac{mg P}{kg soil} \)

For 5 mCi \(^{33}\text{P}\) and 150 mg P (amount P added to 3g soil):
\[ S_i = \frac{(5 \times 2.22 \times 10^6)}{(150 \times 10^{-3})} \frac{cpm}{mg P} \]
\[ = 7.4 \times 10^7 \frac{cpm}{mg P} \]

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 \(^{33}\text{P}\) = 25.4 d

Therefore \( S_i \) on day 2 is:
\[ = 7.40 \times 10^7 \frac{cpm}{mg P} \times \exp \left( -\frac{0.693 \times 2}{25.4} \right) \]
\[ = 7.01 \times 10^7 \frac{cpm}{mg P} \]

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 \( t = (10214 \times 30 \text{ ml} / 0.5 \text{ ml}) \text{ cpm} \)

However the instrument efficiency = 85.26%
Therefore the total corrected total count = \((10214 \times 30/0.5)/0.8526\)
\[= 7.188 \times 10^5 \text{ cpm}\]

Amount of P in solution (Ascorbic acid method) = 0.390 mg P/ml

Therefore \(S_t = 7.188 \times 10^5 \text{ cpm}/(0.390 \text{ mg P/ml} \times 30 \text{ ml} \times 10^{-3})\)
\[= 6.144 \times 10^7 \text{ cpm}\]

Substituting in Eq. (2.9):
\[E = 300 \text{ mg P/kg} (7.01 \times 10^7/6.144 \times 10^7 - 1)\]
\[= 4.22 \text{ mg P/kg soil}\]

Inverse Dilution Method
\[E = x[S_t/(S - S_t)] \quad (2.12)\]

Initial specific activity of the sample (stock) = 30.3 mCi/mg P
\[= 6.6 \times 10^{10} \text{ cpm/mg P}\]

S on day six of equilibration is determined from actual activity of \(^{33}\text{P}\) and P in solution:

Total corrected count = \((\text{actual count} \times \text{dilution factor})/\text{efficiency}\)
\[= 2.524 \times (30/0.5)/0.8526\]
\[= 1.776 \times 10^5 \text{ cpm}\]

And P in solution = 0.04 mg P/1
\[S = 1.776 \times 10^5/(0.04 \text{ mg/ml} \times 30\text{ml} \times 10^{-3}\text{mg/mg})\]
\[= 1.48 \times 10^8 \text{ cpm}\]

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 \times dilution factor \times decay factor/efficiency
(The decay factor corrects for the decay that took place on day 7)

\[
\text{Decay factor} = \frac{\exp -(0.693 \times 6/25.4)}{\exp -(0.693 \times 7/2555.4)}
\]

= 1.0277

Total count = 450.2 \times (30/0.5) \times 1.0277/0.852

= 3.258 \times 10^4 \text{ cpm}

And P in solution = 0.10 \text{ mg P/l}

\[
S_t = \frac{(3.258 \times 10^4) \text{ cpm}}{(0.10 \times 31 \times 10^{-3}) \text{ mg P}}
\]

= 1.051 \text{ cpm/mg P}

Substituting in Eq. (2.12):

\[
E = 50[1.051 \times 10^7/(1.48 \times 10^8 - 1.051 \times 10^7)] \text{ mg P/kg soil}
\]

= 3.82 \text{ 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.

<table>
<thead>
<tr>
<th>Soil property</th>
<th>Number of observations</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Standard deviation</th>
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<tbody>
<tr>
<td>Soil P methods</td>
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</tr>
<tr>
<td>(mg/kg)</td>
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</tr>
<tr>
<td>Mod. Truog P</td>
<td>120</td>
<td>34.4</td>
<td>0.2</td>
<td>770.8</td>
<td>83.9</td>
</tr>
<tr>
<td>Bray I P</td>
<td>120</td>
<td>5.5</td>
<td>0.04</td>
<td>203.6</td>
<td>18.8</td>
</tr>
<tr>
<td>Olsen P</td>
<td>120</td>
<td>10.7</td>
<td>0.12</td>
<td>375.8</td>
<td>35.4</td>
</tr>
<tr>
<td>Double Acid P</td>
<td>120</td>
<td>3.4</td>
<td>0.01</td>
<td>81.5</td>
<td>9.6</td>
</tr>
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<td>Hydroxide-carb P</td>
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<td>186.6</td>
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<td>2129.3</td>
<td>335.2</td>
</tr>
<tr>
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<td>120</td>
<td>14.4</td>
<td>0.30</td>
<td>255.6</td>
<td>29.4</td>
</tr>
<tr>
<td>Chloride resin P</td>
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<td>54.2</td>
<td>0.08</td>
<td>170.8</td>
<td>42.2</td>
</tr>
<tr>
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<td>15.0</td>
<td>0.06</td>
<td>324.9</td>
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<td>45.0</td>
<td>5.72</td>
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<td>0.5 N H₂SO₄ P</td>
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<td>219.1</td>
<td>12.4</td>
<td>4034.3</td>
<td>273.9</td>
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<td>242.1</td>
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<td>199.4</td>
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<td>0.000039</td>
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<td>0.0032</td>
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<td>Buffering Capacity (1 kg⁻¹)</td>
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<td>45</td>
<td>25210</td>
<td>4831</td>
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<td>P sorption</td>
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<td></td>
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<td>(mg kg⁻¹) at:</td>
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<td></td>
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<td></td>
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<tr>
<td>0.02 mg P l⁻¹</td>
<td>71</td>
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<td>-150</td>
<td>715</td>
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<td>0.10 mg P l⁻¹</td>
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<td>389.5</td>
<td>2.0</td>
<td>2000</td>
<td>385.7</td>
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<td>Clay (%)</td>
<td>120</td>
<td>43.9a</td>
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<td>76.9</td>
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<td>4.0</td>
<td>8.7</td>
<td>0.9</td>
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<td>pH (KCl)</td>
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<td>3.5</td>
<td>6.3</td>
<td>0.7</td>
</tr>
<tr>
<td>Organic C (%)</td>
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<td>1.9</td>
<td>0.06</td>
<td>16.2</td>
<td>2.3</td>
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</table>
Appendix 5.2 (continued) Number of observations, mean, range and standard deviation for soil test P and other soil properties in slightly weathered soils.

<table>
<thead>
<tr>
<th>Soil property</th>
<th>Number of observation</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total N (%)</td>
<td>110</td>
<td>0.18</td>
<td>0.01</td>
<td>1.38</td>
<td>0.21</td>
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<tr>
<td>CEC (cmol(+))kg(^{-1})</td>
<td>117</td>
<td>25.9</td>
<td>2.4</td>
<td>99.7</td>
<td>21.1</td>
</tr>
<tr>
<td>CEC(cmol(+)(-1) kg clay(^{-1}))</td>
<td>117</td>
<td>72.2</td>
<td>12.0</td>
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<td>78.6</td>
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<tr>
<td>Base Saturation (%)</td>
<td>117</td>
<td>61.8</td>
<td>2.0</td>
<td>100.0</td>
<td>27.8</td>
</tr>
<tr>
<td>Exchangeable bases (cmol(+) kg(^{-1}))</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>120</td>
<td>11.1</td>
<td>0.06</td>
<td>47.8</td>
<td>12.3</td>
</tr>
<tr>
<td>Mg</td>
<td>120</td>
<td>6.8</td>
<td>0.08</td>
<td>45.2</td>
<td>9.7</td>
</tr>
<tr>
<td>K</td>
<td>120</td>
<td>0.53</td>
<td>0.0</td>
<td>5.8</td>
<td>0.8</td>
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<tr>
<td>Na</td>
<td>120</td>
<td>0.73</td>
<td>0.0</td>
<td>11.50</td>
<td>1.6</td>
</tr>
<tr>
<td>Ex. Al (cmol (+) kg (^{-1}))</td>
<td>120</td>
<td>0.61</td>
<td>0.0</td>
<td>7.20</td>
<td>1.2</td>
</tr>
<tr>
<td>ECEC (cmol (+) kg(^{-1}))</td>
<td>120</td>
<td>20.0</td>
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<td>22.0</td>
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<tr>
<td>Al Saturation (%)</td>
<td>120</td>
<td>7.6</td>
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<td>90.3</td>
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<tr>
<td>Dith. Cit. extr. Fe (%)</td>
<td>88</td>
<td>4.4</td>
<td>0.10</td>
<td>19.0</td>
<td>3.3</td>
</tr>
<tr>
<td>Oxalate extr. Fe (%)</td>
<td>39</td>
<td>0.63</td>
<td>0.0</td>
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<td>2.3</td>
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<td>Phosphate retention (%)</td>
<td>71</td>
<td>49.7</td>
<td>0.00</td>
<td>99.0</td>
<td>23.1</td>
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<tr>
<td>Lime required (kg ha(^{-1}))</td>
<td>120</td>
<td>0.68</td>
<td>0</td>
<td>8.1</td>
<td>1.4</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Soil property</th>
<th>Number of observations</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Standard deviation</th>
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<tbody>
<tr>
<td>Soil P methods</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>(mg/kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mod. Truog P</td>
<td>70</td>
<td>14.1</td>
<td>0.2</td>
<td>41.3</td>
<td>11.4</td>
</tr>
<tr>
<td>Modified Bray P</td>
<td>70</td>
<td>4.3</td>
<td>0.06</td>
<td>15.6</td>
<td>4.3</td>
</tr>
<tr>
<td>Olsen P</td>
<td>70</td>
<td>5.9</td>
<td>0.10</td>
<td>16.3</td>
<td>5.0</td>
</tr>
<tr>
<td>Double Acid P</td>
<td>70</td>
<td>2.3</td>
<td>0.01</td>
<td>7.3</td>
<td>2.2</td>
</tr>
<tr>
<td>Hydroxide-carb P</td>
<td>70</td>
<td>152.3</td>
<td>8.8</td>
<td>620.6</td>
<td>124.4</td>
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<tr>
<td>Chloride-sulfate resin P</td>
<td>70</td>
<td>11.3</td>
<td>0.10</td>
<td>41.6</td>
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<tr>
<td>Isotope carrier P</td>
<td>44</td>
<td>4.3</td>
<td>0.06</td>
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<tr>
<td>0.5 N H$_2$SO$_4$</td>
<td>70</td>
<td>107.8</td>
<td>7.09</td>
<td>278.2</td>
<td>71.6</td>
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<tr>
<td>Organic P (mg kg$^{-1}$)</td>
<td>70</td>
<td>190.7</td>
<td>49.8</td>
<td>399.7</td>
<td>87.4</td>
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<tr>
<td>P Availability (kg 1$^{-1}$)</td>
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<td>0.00005</td>
<td>0.00086</td>
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<td>P Buffering Capacity (1 kg$^{-1}$)</td>
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<td>5108</td>
<td>1163</td>
<td>20105</td>
<td>5033</td>
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<tr>
<td>P sorption (mg kg$^{-1}$) at:</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.02 mg P 1$^{-1}$</td>
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<td>194</td>
<td>20</td>
<td>685</td>
<td>210</td>
</tr>
<tr>
<td>0.10 mg P 1$^{-1}$</td>
<td>15</td>
<td>439.0</td>
<td>118.0</td>
<td>1300.0</td>
<td>349.0</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>30</td>
<td>69.6$^a$</td>
<td>27.0</td>
<td>88.7</td>
<td>23.6</td>
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<tr>
<td>pH</td>
<td>30</td>
<td>5.2</td>
<td>3.8</td>
<td>6.5</td>
<td>0.5</td>
</tr>
<tr>
<td>pH (KCl)</td>
<td>16</td>
<td>4.3</td>
<td>3.6</td>
<td>5.8</td>
<td>0.7</td>
</tr>
<tr>
<td>Organic C (%)</td>
<td>30</td>
<td>1.3</td>
<td>0.18</td>
<td>4.6</td>
<td>1.2</td>
</tr>
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<td>0.02</td>
<td>0.24</td>
<td>0.08</td>
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</table>
Appendix 5.3 (continued) Number of observations, mean, range and variance for soil properties in highly weathered soils.

<table>
<thead>
<tr>
<th>Soil property</th>
<th>Number of observation</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>Standard deviation</th>
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<tbody>
<tr>
<td>CEC (cmol(+)kg⁻¹)</td>
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<td>9.8</td>
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<td>14.9</td>
<td>5.1</td>
<td>30.4</td>
<td>6.9</td>
</tr>
<tr>
<td>Base Saturation (%)</td>
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<td>33.7</td>
<td>1.0</td>
<td>87.0</td>
<td>30.0</td>
</tr>
<tr>
<td>Exchangeable bases (cmol(+) kg⁻¹)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>30</td>
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<td>0.0</td>
<td>5.0</td>
<td>1.7</td>
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<td>0.0</td>
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<td>0.00</td>
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<td>1.1</td>
</tr>
<tr>
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<tr>
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<td>2.9</td>
<td>33.0</td>
<td>7.6</td>
</tr>
<tr>
<td>Lime required (kg ha⁻¹)</td>
<td>30</td>
<td>1.2</td>
<td>0</td>
<td>5.0</td>
<td>1.3</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Soil property</th>
<th>Number of observations</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Soil P methods</strong> (mg/kg)</td>
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<tr>
<td>Mod. Truog P</td>
<td>21</td>
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<td>4.8</td>
<td>279.7</td>
<td>62.8</td>
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<td>Bray I P</td>
<td>21</td>
<td>4.9</td>
<td>0.18</td>
<td>23.0</td>
<td>5.3</td>
</tr>
<tr>
<td>Olsen P</td>
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<td>10.4</td>
<td>1.1</td>
<td>50.7</td>
<td>12.2</td>
</tr>
<tr>
<td>Double Acid P</td>
<td>21</td>
<td>1.2</td>
<td>0.04</td>
<td>7.9</td>
<td>1.8</td>
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<td>61.1</td>
<td>19.7</td>
</tr>
<tr>
<td>Isotope carrier P</td>
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<td>11.3</td>
<td>1.80</td>
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<td>7.8</td>
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<td>0.10</td>
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<td>0.68</td>
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<td>0.0004</td>
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<td>16528</td>
<td>2706</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>0.02 mg P 1$^{-1}$</td>
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<td>1065</td>
<td>285</td>
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<td>5.1</td>
<td>6.9</td>
<td>0.6</td>
</tr>
<tr>
<td><strong>pH (KCl)</strong></td>
<td>13</td>
<td>5.2</td>
<td>4.3</td>
<td>6.0</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Organic C</strong></td>
<td>19</td>
<td>8.7</td>
<td>2.7</td>
<td>14.4</td>
<td>3.4</td>
</tr>
</tbody>
</table>
Appendix 5.4 (continued) Number of observations, mean, range and standard deviation for soil test P and other soil properties in Andisols.

<table>
<thead>
<tr>
<th>Soil property</th>
<th>Number of observation</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total N (%)</td>
<td>19</td>
<td>0.73</td>
<td>0.23</td>
<td>1.81</td>
<td>0.3</td>
</tr>
<tr>
<td>CEC (cmol(+)kg(^{-1}))</td>
<td>17</td>
<td>25.9</td>
<td>2.4</td>
<td>99.7</td>
<td>21.1</td>
</tr>
<tr>
<td>Base Saturation (%)</td>
<td>17</td>
<td>32.6</td>
<td>5.0</td>
<td>76.0</td>
<td>23.8</td>
</tr>
<tr>
<td>Exchangeable bases (cmol(+) kg(^{-1}))</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>21</td>
<td>14.8</td>
<td>1.6</td>
<td>36.3</td>
<td>14.8</td>
</tr>
<tr>
<td>Mg</td>
<td>21</td>
<td>3.8</td>
<td>0.30</td>
<td>8.6</td>
<td>3.0</td>
</tr>
<tr>
<td>K</td>
<td>21</td>
<td>0.73</td>
<td>0.0</td>
<td>4.2</td>
<td>0.9</td>
</tr>
<tr>
<td>Na</td>
<td>21</td>
<td>0.39</td>
<td>0.10</td>
<td>1.51</td>
<td>0.7</td>
</tr>
<tr>
<td>Ex. Al (cmol (+) kg (^{-1}))</td>
<td>21</td>
<td>0.35</td>
<td>0.0</td>
<td>1.9</td>
<td>0.08</td>
</tr>
<tr>
<td>ECEC (cmol (+) kg(^{-1}))</td>
<td>21</td>
<td>25.1</td>
<td>2.4</td>
<td>44.8</td>
<td>17.3</td>
</tr>
<tr>
<td>Al Saturation (%)</td>
<td>21</td>
<td>6.7</td>
<td>0</td>
<td>34.5</td>
<td>12.0</td>
</tr>
<tr>
<td>Dith. Cit. extr. Fe (%)</td>
<td>17</td>
<td>9.6</td>
<td>89.0</td>
<td>100.0</td>
<td>5.1</td>
</tr>
<tr>
<td>Oxalate extr. Fe (%)</td>
<td>11</td>
<td>3.4</td>
<td>1.8</td>
<td>5.7</td>
<td>1.3</td>
</tr>
<tr>
<td>Phosphate retention (%)</td>
<td>12</td>
<td>96.2</td>
<td>89.0</td>
<td>100.0</td>
<td>4.5</td>
</tr>
<tr>
<td>Lime required (kg ha(^{-1}))</td>
<td>21</td>
<td>0.4</td>
<td>0</td>
<td>2.1</td>
<td>0.7</td>
</tr>
</tbody>
</table>

\(^a\) 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.

<table>
<thead>
<tr>
<th>Soil property</th>
<th>Number of observations</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil P methods (mg/kg⁻¹)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mod. Truog P</td>
<td>22</td>
<td>77.4</td>
<td>11.0</td>
<td>294.1</td>
<td>74.7</td>
</tr>
<tr>
<td>Bray I P</td>
<td>22</td>
<td>1.8</td>
<td>0.02</td>
<td>9.6</td>
<td>3.0</td>
</tr>
<tr>
<td>Olsen P</td>
<td>22</td>
<td>3.4</td>
<td>0.42</td>
<td>10.4</td>
<td>2.8</td>
</tr>
<tr>
<td>Double Acid P</td>
<td>22</td>
<td>1.3</td>
<td>0.05</td>
<td>5.84</td>
<td>1.4</td>
</tr>
<tr>
<td>Hydroxide Carbonate P</td>
<td>22</td>
<td>40.9</td>
<td>2.4</td>
<td>549.1</td>
<td>114</td>
</tr>
<tr>
<td>Chloride-sulfate resin P</td>
<td>22</td>
<td>5.1</td>
<td>0.20</td>
<td>29.2</td>
<td>7.3</td>
</tr>
<tr>
<td>Isotope carrier P</td>
<td>7</td>
<td>3.7</td>
<td>1.20</td>
<td>6.8</td>
<td>1.7</td>
</tr>
<tr>
<td>Solution P</td>
<td>10</td>
<td>0.92</td>
<td>0.21</td>
<td>4.7</td>
<td>1.4</td>
</tr>
<tr>
<td>0.5 N H₂SO₄ P</td>
<td>22</td>
<td>110.4</td>
<td>1.4</td>
<td>239.7</td>
<td>76.0</td>
</tr>
<tr>
<td>P Availability (kg/l⁻¹)</td>
<td>9</td>
<td>0.0033</td>
<td>0.00089</td>
<td>0.0125</td>
<td>0.003</td>
</tr>
<tr>
<td>P Buffering Capacity (1 kg⁻¹)</td>
<td>9</td>
<td>548</td>
<td>80</td>
<td>1123</td>
<td>334</td>
</tr>
<tr>
<td>P sorption (mg kg⁻¹) at:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.02 mg P l⁻¹</td>
<td>9</td>
<td>17.8</td>
<td>5</td>
<td>45</td>
<td>12.5</td>
</tr>
<tr>
<td>0.10 mg P l⁻¹</td>
<td>9</td>
<td>68.3</td>
<td>45.0</td>
<td>90.0</td>
<td>18</td>
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<tr>
<td>pH</td>
<td>22</td>
<td>8.1</td>
<td>7.4</td>
<td>9.3</td>
<td>0.57</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>22</td>
<td>38.5</td>
<td>21.4</td>
<td>77.4</td>
<td>30.9</td>
</tr>
<tr>
<td>CaCO₃ (%)</td>
<td>22</td>
<td>25.0</td>
<td>0</td>
<td>61.0</td>
<td>23.2</td>
</tr>
<tr>
<td>Organic C (%)</td>
<td>22</td>
<td>0.64</td>
<td>0.16</td>
<td>1.99</td>
<td>0.40</td>
</tr>
</tbody>
</table>
Appendix 5.5 (continued) Number of observations, mean, range and standard deviation for soil test P and other soil properties in calcareous soils.

<table>
<thead>
<tr>
<th>Soil Property</th>
<th>Number of Observation</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total N (%)</td>
<td>22</td>
<td>0.05</td>
<td>0.01</td>
<td>0.16</td>
<td>0.04</td>
</tr>
<tr>
<td>CEC (cmol(+) kg⁻¹)</td>
<td>22</td>
<td>41.8</td>
<td>3.9</td>
<td>100.6</td>
<td>38.6</td>
</tr>
<tr>
<td>CEC (cmol (+) kg clay⁻¹)</td>
<td>22</td>
<td>84.6</td>
<td>13.2</td>
<td>196.1</td>
<td>62.1</td>
</tr>
<tr>
<td>Exchangeable bases (cmol(+) kg⁻¹)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mg</td>
<td>22</td>
<td>16.1</td>
<td>2.9</td>
<td>38.0</td>
<td>12.4</td>
</tr>
<tr>
<td>K</td>
<td>22</td>
<td>1.02</td>
<td>0.10</td>
<td>2.8</td>
<td>1.00</td>
</tr>
<tr>
<td>Na</td>
<td>22</td>
<td>9.8</td>
<td>0.30</td>
<td>23.6</td>
<td>7.4</td>
</tr>
<tr>
<td>Dith. Cit. extr. Fe (%)</td>
<td>9</td>
<td>1.4</td>
<td>0.0</td>
<td>1.7</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Note: Log transformed mean and standard deviation re-expressed in terms of the original data using Equations (5.4 and 5.5) (Haan, 1977).


