CALIBRATION AND VALIDATION OF THE IBSNAT/CERES RICE MODEL

A DISSERTATION SUBMITTED TO THE GRADUATE DIVISION OF THE
UNIVERSITY OF HAWAII IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN AGRONOMY AND SOIL SCIENCE

AUGUST 1987

By

Li-Ling Lin Jang

Dissertation committee:

Goro Uehara, Chairman
Haruyoshi Ikawa
Kent D. Kobayashi
Tung Liang
James A. Silva

We certify that we have read this dissertation and that, in our opinion, it is satisfactory in scope and quality as a dissertation for the degree of Doctor of Philosophy in Agronomy and Soil Science.

DISSERTATION COMMITTEE

_____
Chairman

_____

_____

_____

_____

ABSTRACT

Two rice varieties were subjected to two nitrogen rates and three temperature regimes in the greenhouse and growth chambers to study the effects of temperature, variety and N fertilization on N uptake, development and growth of rice. Nitrogen fertilization had a significant effect on grain and straw yields for both varieties. High nitrogen application resulted in high grain yield and N stress reduced biomass production but had no effect on the timing of phenological events of variety Starbonnet, but delayed panicle initiation in variety K-C-A. Temperature affected grain yield and nitrogen uptake during the grain filling stage. High day and night temperature hastened maturation and resulted in lower filled grain percentage, lower 1,000-grain weight and lower overall grain yield. Nitrogen concentration and N uptake were higher in the higher temperature. However, the persistence of green color and a low ratio of grain N to straw N indicate that nitrogen translocation from straw to grain was diminished by the high temperature.

The IBSNAT/CERES Rice Model was calibrated and validated with data collected from field experiments under a wide range of agroenvironments. The model was able to adequately predict phenological development for a wide range of agroenvironments. Model prediction of final

biomass was also acceptable. The model is sensitive to seasonal variation and altitudinal difference and is able to mimic the high sensitivity of rice to temperature and solar radiation.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

CHAPTER I

INTRODUCTION

Rice is one of the most important and widely cultivated crops in the world. Grain yields generally decline with increasing proximity to the equator and this decline has been partly attributed to differences in climate. Temperature and daylength are two major factors that affect the growth and development of the rice plant. Widespread cultivation of short-statured, photoperiod insensitive cultivars resistant to pests and lodging and responsive to nitrogen fertilizers has enabled many importing nations to become self-sufficient in rice. In some nations, the goal of achieving self-sufficiency has been surpassed and are now faced with a new problem of over production. This situation calls for a reassessment of national goals and research priorities. For major rice consuming nations that have achieved self-sufficiency and are now faced with surplus grain, the new goal is to achieve a stable rice production system which minimizes over production while preserving self-sufficiency. The means to maintain self-sufficiency must make economic, social, environmental and political sense. There is no over production if surplus grain can be profitably marketed elsewhere, and self-sufficiency is not a sensible goal if the social cost to attain it is too high.

The research priorities must be responsive to these problems and conditions. The situation now calls for producing the desired quantity of rice, at the proper time and place in a way that is both profitable and sustainable. Profitability goes hand-in-hand with efficiency, and the latter in turn, often results in releasing excess land for other crops and uses.

What crops can be profitably grown on land that was formerly dedicated to rice? Is it possible to predict the performance of a crop cultivar in locations where the crop has never been grown? If so what is the minimum amount of information one must have to make such predictions? These are the questions researchers are now being asked to consider.

The purpose of agricultural research is to (1) obtain an understanding of processes that occur in the production system, (2) apply this understanding to predict the behavior and performance of various components and (3) use this predictive capability to control production outcomes. With the advent of high-speed computers, researchers have begun to organize their understanding of the processes governing photosynthesis, respiration, translocation, and accumulation of assimilates to produce models that simulate the growth and development of crops under a wide range of environmental conditions. A model is simply a mathematical

representation of the processes that occur in a system. The system of concern in this study consists of the soil-plant-atmosphere continuum. To be useful to policy makers and farmers, crop models must be designed to simulate and therefore, predict the performance of crop cultivars growing on any soil and under any reasonable climatic condition. Examples of existing models include those for wheat, maize, cotton and soybean. Such models offer an alternative to costly and time consuming trial and error experimentation for assessing crop suitability in locations where the crop or a crop cultivar has never been grown. Crop suitability is assessed by using long term historical weather to simulate crop performance over 20 or more years. The simulations may be repeated with different management strategies so that optimal strategies under situations of uncertainty and risk may be prescribed.

With the obove in mind, this study was designed to attain the following objectives:

1. Measure the effect of temperature on the growth and development of rice under controlled conditions for different nitrogen application and uptake rates during grain filling.
2. Calibrate an existing rice model with growth and development data collected under field conditions

using five rice cultivars of very different maturity types.

3. Validate the calibrated rice model with data collected from new experiments conducted specifically for this purpose.

Attainment of these objectives will help rice farmers and rice producing nations make reliable decisions about what cultivars to grow, when, where and under what management strategies. The principles learned from this study can be applied to other crops and may be used as the bases to begin to examine the agronomy of whole farm systems.

CHAPTER II

LITERATURE REVIEW

2.1 Effects of Climatic Factors on Rice growth and Development

The growth and development of rice is, in part, a function of its environment. The effect of climate on the performance of the rice crop is critical, and temperature, solar radiation, photoperiod, rainfall, and relative humidity are major elements of climate which influence rice yield by directly affecting the physiological processes involved in grain production, and indirectly through diseases and insects (Yodhida 1981).

2.1.1 Temperature

Rice is grown over a wide range of latitudes from the Equator to 53° N (northeastern China) and 35° S (New South Wales), within which the daily and seasonal regimes of temperature and day length vary widely (Yoshida 1981), resulting in different yields. Temperature affects not only the growth duration, but also the growth pattern of the rice plant. The three main growth phases of the rice plant consist of vegetative growth, floral development and grain filling. During growth, the influences of temperature and other factors establish mutual

interrelationships between plant morphology and the patterns of physiological response which make it difficult to consider any yield attribute or growth phase separately (Owen 1971).

Rice plants have optimal temperature ranges and critical low and high temperatures for their growth and development. Both overly high and low temperatures are unfavorable for rice production. The critical low and high temperatures vary from one growth stage to another and differ according to variety, duration of the critical temperature, diurnal changes, and physiological status of the plant. Critical temperatures for germination, tillering, panicle initiation, and ripening of rice have been identified (De Datta 1981). Minimun germination temperatures of 7 to 18 °C (Owen 1971) and 10 °C (Yoshida 1981) have been reported. Tropical varieties show higher minimum temperatures than temperate varieties and Indica varieties show higher minimum temperatures than Japonica varieties (Nishiyama 1976). Maximum germination temperatures of 40 to 45 °C (Owen 1971) and 45 °C (Yoshida 1981) have been reported.. The optimal temperature range for germination is 20 to 35 °C (Yoshida 1981).

According to Nishiyama (1976), the optimal temperature for the rooting of rice seedings is 25 to 28 °C; and it is severely inhibited by temperature below 16 °C and above

35 °C. In a review of the effects of temperature on the growth of rice, Owen (1971) indicated that maximum root numbers were produced at 31 °C. Water temperatures exerted more influence on root growth than air temperature at 16 to 21 °C. Yoshida (1981) also showed that the optimal tmeperature for rooting was 25 to 28 °C, and the critical low and high temperatures were 16 °C and 35 °C respectively.

The rate of tiller production and the length of the tillering period are affected by temperature, but there is disagreement among the reported data. There are also marked differences to tillering among plant types in their response to temperature. Some researchers obtained increased tillering with rising temperature between 15 to 33 °C, but others found the opposite in the same temperature range. Yoshida (1973) re-examined the effect of temperature on tillering in a controlled environment and found that in the range of 22 to 31 °C, higher temperatures favored faster tillering in both IR 8 and Jinheung varieties. Yoshida (1973) proposed that rice tillering should be studied in terms of interaction among light intensity, temperature, and carbohydrate metabolism. When light is adequate, higher temperatures increase tiller number and the optimal temperature for tillering is 25 to 31 °C.

Panicle initiation occurs favorably between a temperature range of approximately 18 to 30 °C, but is delayed or inhibited above 30 °C or under 15 °C (Owen 1971; Nishiyama 1976). Yoshida (1981) suggested that for panicle initiation the low critical temperature was 15 to 20 °C and high critical temperature was 38 °C. After panicle initiation, the next most sensitive stage is the anthesis stage. Severe spikelet sterility is caused by low temperatures (<12 °C). High temperatures (>30 °C) inhibit fertilization (Nishiyama 1976). Yoshida (1981) on the other hand suggested that the optimal temperature for anthesis was 30 to 35 °C. Owen (1971) reported that successful anthesis was dependent upon a favourable combination of air temperature, humidity, and light intensity.

The number of spikelets plays an important role in determining the grain yield through its effect on the total sink size. The total sink size is the product of number of spikelets and the size of each spikelet. Yoshida (1973) reported that within a temperature range from 22 to 31 °C, spikelet number increased as temperature dropped. The optimal temperature appeared to shift from high to low as growth stage advanced from the vegetative to the reproductive stage with 21 °C being optimal for producing the maximum number of spikelets per plant.

During the ripening stage, the major effects of air temperature on grain yield largely depend on the duration of the grain filling period and on the maximum weight per grain achieved. Yoshida (1976) showed that the optimum daily mean temperature for grain filling was found to range from 19 to 25 °C for variety IR 20 and from 16 to 22 °C for variety Fujisaka 5. Night temperature also affects the grain weight and grain quality. Yoshida (1976) showed that undesirable, chalky grains were mainly formed at the low (14 °C) and high nigh (32 °C) temperatures. Large temperature differences between day and night was responsible for the high incidence of chalky grains. Owen (1971) indicated that rice yield was negatively correlated with mean daily air temperature during the ripening period. In experiments conducted by Sato (1971), he found that the rate of ripening progressively increased, but ripening itself ceased earlier as temperature increased, resulting in a lower grain weight and lower panicle to straw ratio.

Temperature also affects the growth duration of rice plants. In general, high temperatures shorten the growth duration of rice.

2.1.2 Solar radiation

Solar radiation is the energy source for photosynthesis and evaporation. The solar radiation requirements of rice differ from one growth stage to

another. Solar radiation has the greatest effect on grain yield during the reproductive stage, an intermediate effect during the ripening stage, and an extremely small effect during the vegetative stage (Yoshida 1981).

In the tropics, the correlation between grain yield and solar radiation measured between panicle initiation and crop maturity was highly significant (De Datta 1981). Hence, when the grain filling period is lengthened, the opportunity to utilize more solar energy for grain filling increases and grain yield increases.

Most paddy fields in Taiwan produce two rice crops per year. The first crop is planted in February and harvested in June. The second crop is planted in July and harvested in October. On an average, the first crop's yield is 25 to 30% higher than the second crop. The major cause of this yield difference is ~~climatic~~ climate. During the first crop, temperature and daylength progressively increases, whereas, the reverse is ~~just~~ true for the second crop. The lower yield of the second crop is primarily due to the extremely low solar radiation during the reproductive and ripening stages (Lin, 1976; Chang, 1985).

Three Japanese authors have used the expression

$$Y = S [a - b (t - c)^2]$$

to estimate grain yield, where Y is grain yield, S is incident solar radiation, t is average daily mean

temperature during the ripening period, and a, b. c, are constants (Yoshida, 1976). The equation implies that high solar radiation during ripening increases the grain yield.

2.1.3 Photoperiod

Rice is basically considered to be a short-day plant and is sensitive to photoperiod. Panicle primordia may be initiated late or may fail to develop when the plants are subjected to long photoperiods. Rice cultivars are classified into photoperiod-sensitive and photoperiod-insensitive types according to the way they respond to photoperiod (Vergara and Chang, 1976). The photoperiod-insensitive rice varieties show a low response or only a slight delay in flowering when photoperiod is increased. The response of a rice variety to photoperiod may be measured by the length of photoperiod-sensitive phase (PSP), which in turn is determined by both the critical and optimum photoperiods for the variety. The plant enters the PSP during which panicle initiation can be triggered by short days. The PSP of photoperiod-insensitive varieties ranges from 0 to 30 days while that of the sensitive varieties last from 31 days to much longer periods (Vergara and Chang, 1976). The optimum photoperiod differs slightly among varieties, but in general, the optimum photoperiod of most varieties is about 9 to 10 hours. The optimum photoperiod is defined as the daylength at which the

duration from sowing to flowering is at a minimum. A longer photoperiod delays flowering. There are also indications the optimum photoperiod is influenced by temperature (Vergara and Chang, 1976). Photoperiod-insensitive varieties have the advantage of being able to flower and ripen throughout the year provided nutrient and water are not limiting. Thus, the present tendency is to select photoperiod-insensitive varieties to that make the planning of rice cultivation more flexible and more suitable to multiple cropping systems.

2.1.4 Rainfall

Understanding rainfall patterns and distribution is a prerequisite for successful rice planting. Under rainfed rice culture, and where temperatures are within the critical limits, rainfall pattern is the most limiting factor in rice cultivation. When irrigation is provided, however, growth and yield are determined largely by temperature and solar radiation. According to da Mota (1980), 1000 mm of annual rainfall, with 200 mm monthly rainfall during the growing season, is adequate for growing dryland rice in Latin America, and average daily rainfall is more meaningful than monthly or annual rainfall. Currently, rainfed rice cultivation is restricted to areas where the annual rainfall exceeds 1000 mm.

2.1.5 Relative humidity

Rice require fairly high humidity for proper growth. Flowering is best at 70 to 80% and will not occur below 40% relative humidity. Periods of high humidity may trigger diseases and cause postharvest germination problems (Sarker 1980).

2.2 Nitrogen Fertilizer and Rice

2.2.1 Enviromental factors and nitrogen uptake

Yoshida (1981) has indicated that nitrogen use efficiency for spikelet production was higher in northern than in southern Japan. He suggested that cool climates favored higher nitrogen efficiency, and temperature appeared to be a major climatic factors affecting nitrogen use efficiency for spikelet production. Temperature also affects the metabolic nitrogen absorption (Okajima 1965), leading to higher nitrogen uptake under higher temperature. Ta et al. (1981) studied the effects of various environmental and root media conditions on the growth and nitrogen uptake of Indica and Japonic rice plants and found that at low temperature (17 ^{o}C), Indica rice plants performed poorly and became chlorotic. The uptake of NH_4^+ or NO_3^- was markedly affected by temperature. Light intensity also affected nitrogen uptake

and assimilation of nitrogen was greatly inhibited at low temperature and low light intensity (Ta et al., 1982). An increase in nitrogen concentration with increasing temperature has also been reported by Chowdhury et al.(1978).

2.2.2 Amount and method of N application

Rice plants have high nitrogen requirement during the early and mid-tillering stages to maximize panicle number (De Datta 1981). However, heavy application of N fertilizer does not always give higher yield. Excessive N application tends to cause yield reduction through plant lodging, heavy mutual shading of leaves, and insect damage (Murayma, 1968).

The N requirement of rice varies with variety, area, agricultural management system, and other field constraints affecting crop response to N fertilizer such as inefficient methods of applying N, and control of weeds and pests. Stangel (1979) cited reports indicating that the leading Japonica varieties in Japan require 120 to 150 kg N/ha to achieve high yields, whereas the N requirement ranged from 90 to 120 kg/ha for Malaysian conditions, depending on variety and soils involved. The climatic condition also affects the N requirements. Russel et al. (1970) summarized the results of experiment with modern rice varieties from many parts of the world, and concluded that

the optimum N rate for modern varieties was 120 kg/ha for the dry season and about 70 kg/ha for the wet season.

Timing and method of N fertilizer application may greatly influence N fertilizer efficiency and grain yield. The capacity of soil to retain applied nitrogen is an important consideration in determining the efficiency of basal versus split applications of N fertilizer. For soils with low nitrogen-holding capacity, split applications of fertilizer should result in a higher yield than basal applications. On the other hand, split applications may be no better than basal applications in soils with high cation exchange capacity (Yoshida 1981). There are many studies on the effect of timing on nitrogen use efficiency for grain production. The results vary and generally fall in one of the following five groups (Matsushima 1965).

(1) A single application as a base application is most efficient for grain production.

(2) Top-dressing at the tillering stage is best for grain production.

(3) Top-dressing at the panicle initiation stage or at the panicle development stage is best for grain production.

(4) Split application is best for grain production. In this group, the nitrogen application is split into more than two applications, including a base dressing.

(5) Top-dressing just after the heading time is effective for increasing yield.

Chaudry et al. (1963) and Wada (1969) found that nitrogen application at tillering time gave significantly higher grain yield than the same quantity of N applied all at seeding time. Yoshida (1981) recommended that top-dressing at panicle initiation was most effective for increasing yield because absorbed nitrogen during this stage is efficiently used to increase spikelet number and panicle size and helps to keep leaves green after heading and thereby contributing to active photosynthesis for grain production. More recent studies suggest that two to three applications of nitrogen per crop give highest nitrogen use efficiency and that more split application are needed for long-duration varieties (De Datta 1981). The highly variable results that continue to be obtained suggest that nitrogen dynamics under flooded conditions can benefit from mechanistic models that take into account the important factors that affect nitrogen transformation and its uptake by plants.

2.2.3 Sources of N fertilizer

Rice plants absorb most of their nitrogen in the NH_4^+ and NO_3^- forms. The efficiency of ammonium versus nitrate forms of N in increasing rice yields has been studied by

many researchers. Some report that ammonia-N is more effective than nitrate-N, some indicate that nitrate is as effective as ammonium (Patnaik and Rao 1979). The responses of rice to ammonium and nitrate were different under different environmental cinditions and varieties. Ta et al. (1982) suggest that under conditions of high temperature and high light intensity, the Indica rice varieties are more effective than the Japonica varieties in nitrate absorption and that the Indica rice varieties are more sensitive to environmental condition than the Japonica. However, at low temperatures, the percentage of absorbed nitrogen from NH_4^+ or NO_3^- in the shoots was similar for both rice varieties. Fernandes (1984) indicated that NH_4^+ and NO_3^- were used with about equal effectiveness under low light and high temperature conditions. When under stress (low light, low temperature), NO_3^- was shown to b a better source of N than NH_4^+.

There are numerous research reports which indicate effectiveness of fertilizer nitrogen source under flooded condition. De Datta (1981) cited results of experiments to evaluate six nitrogen sources for flooded rice in the U.S.A., Sri Lanka, India, Japan, and Taiwan which indicate that ammonium sulfate is as effective as ammonium chloride, followed by urea, and that nitrate-containing fertilizers,

such as ammonium nitrate are least effective. Urea is now the major form of N fertilizer used in most rice-growing countries (Byrnes, 1983).

2.2.4 Varietal response to nitrogen

The level of N fertilization required for maximum yield is different for modern and traditional rice varieties. Much of the difference can be attributed to varietal differences in photosynthetic responses to nitrogen fertilization (De Datta 1981). The older varieties may response to N fertilization by producing more grain but much of this grain may not be harvestable because of their susceptibility to lodging. However, there may also be differences in the ability of varieties to take up and utilize nitrogen. More modern varieties tend to have more total nitrogen and more nitrogen per gram dry tissue at the 150 lb N/acre level (Nowick and Hoffpanir, 1984).

2.3 Rice Models

With the advent of high-speed computers, researchers have begun to organize their understanding of the processes governing photoysnthesis, respiration, translocation, and accumulation of assimilates to produce models that simulate the growth and development of crops under a wide range of environmental condition. Crop models are simplified representations of the complex relationships between variables that comprise crop environment and crop performance using established mathematical or statistical techniques or both (Baier, 1977). These models can be relatively simple or complicated. The rice models that have been developed in recent years can be divided into two types--one is empirical (regression) and the other is simulation models.

2.3.1 Empirical models

In the empirical approach, one or several independent variables are related to crop responses such as yield. The independent variables are often climatic factors such as temperature, precipitation and solar radiation. The weighting coefficients in these equations are obtained by using statistical procedures, such as multivariable regression analysis. Empirical crop-weather models have been used extensively for identifying, zoning and mapping

of areas in terms of their suitability for growing crops and their yield potential (Baier, 1977).

Murata (1975) reviewed some studies about the effect of climatic factors on rice yield in Japan. Correlation studies carried out in the past 50 years showed that the most important, limiting climatic factor for rice yield was solar radiation during the grain filling stage in middle and southern regions, whereas mean air temperature was the limiting factor during the same period in the northern regions. Several regression models were postulated to express these relations.

da Mota and da Silva (1980) developed an empirical-statistical rice yield-weather-technology model for Pelotas county in the irrigated rice rgeion of southern Brazil, with 15 years data on county yields, rice crop phenology, and monthly weather. They showed that temperature, solar radiation, sowing day, and technological change were correlated to rice yields.

Agrawal et al. (1980), using 25 years yield data and weekly weather variables, viz. maximum temperature, relative humidity, total rainfall and number of rainy days, developed a statistical model for forecasting the yield of rice in Raipur district, Madhya Pradesh, India.

Based on the grain yield data from irrigated rice variety trials conducted in 40 environments during 1976 to

1981, regression models were developed by Seshu and Cady (1984) and tested for predicting rice yield from total solar radiation and temperature data. Among the models evaluated, a prediction equation based on radiation and minimum temperature during the ripening stage of 30 days after flowering demonstrated predictive ability.

These empirical models can only be applied to the particular range of conditions of soil, climate under which experiments were conducted. The results cannot be extrapolated beyond this range with certainty, unless a site-specific parameter is included into the model.

2.3.2 Simulation models

In the mechanistic approach it is assumed that everything observed in a complex agrosystem can be described base on a basic biophysical postulate or laws. The simulation model can be constructed by looking at the structure of the system, by dividing the system into components, and by trying to understand the behavior of the whole system in terms of the behavior of the individual system components, and their interactions one with another (Thornely, 1976). Simulation can be useful if the model accounts for most relevant phenomena and contains no false assumptions (Baier, 1977). As part of systems analysis and simulation research, several rice simulation models have been developed in recent years.

GRORYZ (Keulen, 1976) model simulated the time course of dry matter production and the partitioning of this material among the roots, shoots (stems and leaves) and grains of the rice corp. The model was executed with time steps of one day and used temperature as driving force. The rate of development is a linear function of temperature for a given variety, but the base temperature and photoperiod were not introduced in the model.

Iwaki (1977) using a simulation language called DYNAMO, developed a growth model which simulated the growth of paddy rice over the whole growing period. The model involved the basic processes of plant growth such as photosynthesis, respiration and distribution of photosynthate into the component organs in relation to light, temperature and age of plants.

Angus and Zandstra (1980) described a growth and development model (IRRIMOD) for wetland rice that accounted for the effects of radiation, temperature, water supply, and nitrogen nutrition. The growth of crop biomass was calculated by Gompertz equation.

$$dW/dt = aWc^{-bt}$$

Where, W is biomass, t is time, and a and b are constants. A growth index (GI) was related to radiation, temperature, moisture and nitrogen status using the multiplicative equation:

$$GI = RI * TI * MI * NI$$

where, RI, TI, MI, and NI are radiation index, temperature index, moisture index, and nitrogen index respectively. Each of four indices is scaled between 0 and 1. When each is nonlimiting, GI is 1. Tests showed that this model could quantitatively account for the dependence of yield on the interaction between radiation and nitrogen supply in a flooded environment, and of drought and nitrogen response in rainfed rice. However, the water balance and rice yield of sloping fields could not be accurately simulated because the contribution of lateral water flow was not considered.

Based on the water balance concept, Bolton and Zandstra (1981) developed a simulation model (PADIWATER) to predict the yields of the drough-prone second rainfed wetland rice crop in Iloilo Province, Philippines. They found that groundwater contribution and pan evaporation rate were important factors affecting rice yield.

RICEMOD (McMennamy and O'Toole, 1983) is a rice crop simulation model which uses daily weather parameters including maximum and minimum temperature, and daylength to predict the growth of the rice variety IR-36 planted in the International Rice Research Institute (IRRI) experimental farm. The model assumes that there is no water stress and no nutrients stress on crop growth. The effect of

temperature on photosynthesis was not considered in RICEMOD. A partitioning rules table was applied to determined the partitioning of total biomass among leaf, stem, panicle, and root during each growth stage.

Some of the models mentioned above could not predict the phenological stage during the growth period. However, effect of climatic factors on rice growth was varied with the development stage. Some of them are variety- and site-specific. These kinds of model could not be utilized under any agroclimatic condition without caution.

The IBSNAT/CERES Rice model, a component of the Decision Support System for Agrotechnology Transfer (DSSAT) was developed by collaborators at Michigan State University, the International Fertilizer Development Center and the University of Hawaii. The model simulates the growth, phenological development, soil water balance, and soil and plant nitrogen budget of different rice varieties under any agroclimatic condition (Ritchie et al., 1986). The model assumes complete control of limiting factors such as weeds, insects, diseases and other management variables (phosphorus, potassium, liming, etc.). Climate, nitrogen, and water are the main factors driving the IBSNAT/CERES Rice model.

The simulation models must be adequately validated in order for users to have confidence in their predictive

ability at new sites. Such model evaluation requires that experiments be conducted and that in each experiment, a set of soil, crop, weather, and management data be recorded. A data base management system (DBMS) developed by the IBSNAT Project stores these data and provides easy-to-use procedures for entering and retrieving site and experimental data for subsequent analyses and crop simulation (IBSNAT Project 1986).

CHAPTER III

THE EFFECTS OF TEMPERATURE, VARIETY, AND NITROGEN RATE ON NITROGEN UPTAKE AND PARTITIONS IN RICE

3.1 Introduction

The growth and development of rice are influenced by many factors including (1) plant factors, (2) environmental factors, and (3) management factors. The environmental factors, especially climate, are the most difficult to control. Temperature is one of the major factors affecting rice production. Although rice shows high adaptability to wide climatic ranges, each cultivar has an optimal temperature range for its growth and development. Overly high or low temperatures are unfavorable for rice production.

Nitrogen is often the most limiting nutrient for rice, and nitrogen deficiency almost always occurs unless it is applied as a fertilizer. The plant must be supplied with appropriate amount of nitrogen to produce high yields.

It has always been difficult to raise the nitrogen utilization by the rice plant, and to increase its nitrogen use efficiency for grain production. Because of the high nitrogen requirement of rice and the strong genotype by environment interaction involved in nitrogen uptake and partitioning, a realistic assessment of the amount and cost

of nitrogen required to meet rice production targets is important for improving efficiency of rice production.

This phase of the research was conducted to better understand the absorption of nitrogen by rice at different growth stages under different temperatures. The results would be used to test and refine the IBSANT/CERES Rice Model for subsequent field calibration validation.

3.2 Materials and Methods

3.2.1 Experimental description and assignment of treatments

The pot experiment was conducted in the greenhouse and growth chambers of the Department of Agronomy and Soil Science, University of Hawaii between February and July, 1986, to study the effects of temperature, variety and N fertilization on N uptake, development and growth of rice.

A split split-plot design with two replicates was used with temperature as main plots, nitrogen rate as subplots and variety as sub-subplots. The Hanalei silty clay soil, a member of the very-fine, oxidic, nonacid, isohyperthermic family of Tropic Fluvaquents was collected from the Kauai Rice Experimental Field. Some important physico-chemical properties of the soil are shown in Tabel 3.1.

The soil was air dried, ground and screened through a 5-mm sieve. Plastic pots 30 cm in diameter and 30 cm deep were filled with 10 kg of air dried soil. Th two N levels selected for treatment were 0, 1.88 g N/pot. All treatments received 0.56 g P/pot as triple superphosphate, 1.04 g K/pot as KCl, 0.36 g Si/pot as slag, 0.12 g Mg/pot as $MgSO_4.7H_2O$, 0.16 g Zn/pot as $ZnSO_4$ and 0.02 g B/pot as Borax. Two rice varieties, Kwang-Chang-Ai (K-C-A) and Starbonnet, representing two extreme maturity types were selected for this experiment.

Table 3.1

Physico-chemical properties of soil used in pot experiment

Properties	Values
Sand (%)	7.8
Silt (%)	37.8
Clay (%)	54.4
pH (H_2O)	4.71
pH (KCl)	4.03
Organic Carbon (%)	5.92
NH_4-N (ppm)	3.41
NO_3-N (ppm)	5.46
MTRP* (ppm)	11.37
Ca (meq/100g)	5.92
Mg (meq/100g)	8.47
Na (meq/100g)	2.75
K (meq/100g)	0.48

* Modified Truog P

One third of nitrogen fertilizer was dissolved in water along with the other nutrients and mixed with the soil in order to facilitate uniform distribution. Three seeds were planted in each pot and placed in the greenhouse. After seed emergence, the plants were thinned to one plant per pot. A thin layer of water was maintained on the soil surface for two weeks after emergence. Following that, five cm of standing water were maintained until a few days prior to maturity. During the third tillering and panicle initiation stages, the pots were surface drained and kept dry for 3 days. The remaining nitrogen fertilizer was split and applied at 3rd tillering stage and panicle initiation stage respectively. At flowering time, two third of the pots were transferred to the growth chambers. Table 3.2 shows the controlled climatic conditions maintained in the growth chambers during the grain filling stage. The positions of pots were change at regular interval to minimize light intensity differences.

Table 3.2

Controlled climatic conditions in the growth chambers

Climatic factors	Chamber 1	Chamber 2
Temperature (degree C day/night)	25/20	35/30
Photoperiod (hours/day)	12	12
Light intensity (uE/m^2 s)	1,000	1,000
Relative humidity (%)	80	80

3.2.2 Plant observations and sampling

During the course of crop growth, dates of phenological events were recorded for each treatment. The events recorded were germination, emergence, panicle initiation, heading, flowering, milk grain, dough grain and physiological maturity. The event was considered to have occurred when at least 50% of plants had reached the phenological stage.

Determination of panicle initiation required destructive sampling and is usually examined in the following way. Starting at about 30 days before the estimated heading date, several large tillers from 2 to 3 plants are cut from the plants base each day. A sewing needle is used to split and strip the sheaths one at a time. The flag leaf, recognized as a little white cone, should be stripped of carefully as the panicle resides inside it. At the panicle initiation stage, the young panicle has white hairs and is easily distinguished from a leaf. A microscope makes the examination easier.

Leaf tip appearance on the main culm was also determined by using the Haun index. After the 50% emergence date had been determined, certain plant were selected for leaf appearance study. The first leaf (oldest) was leaf number one (1). The Haun index is obtained in the following way. For example, if 10 days

after planting (DAP) the second leaf is 6 cm long, the value tentatively recorded at 10 DAP is 2.6. The second leaf is measured again when it is fully expanded, i.e., when the collar has appeared. If its maximum leaf length is 12 cm, the Haun index at 10 DAP is 2.5 (2 and 6/12).

Two plants (pots) were sampled from each treatment six times during the course of the experiment. These samplings were at the 3rd tillering stage, panicle initiation stage, flowering stage, and three times during the grain filling stage. Each plant was partitioned to determine tiller number, leaf area, leaves weight, sheathes weight, panicle number, panicles weight and grains weight. Each partitioned part was ground and submitted for tissue analyses.

The above ground samples were analyzed for N, P, K, Ca, Mg, S, Mn and Fe. The concentration of N in the dry matter was determined by the Kjeldahl method while the other elements were measured with a multichannel, x-ray fluorencence quantometer.

Grains from each plant were categorized as filled or unfilled grain and weighted seperately. The weight of 1000 grains was also determined for each pot.

3.3 Results and Discussion

3.3.1 The phenology of two rice varieties in the greenhouse

The seeds of both rice variety were soaked in water for 24 hours before sowing. The sowing date for both varieties was February 7, 1986. The occurrence of phenological events shown in Table 3.3 show that Starbonnet has a longer growth duration than K-C-A. Starbonnet has a long vegetative stage and long grain filling stage. However, the duration from panicle initiation to flowering was nearly the same for the two varieties.

The effect of nitrogen rate on phenological events were not the same for both varieties. Nitrogen stress did not delay the timing of phenological events of Starbonnet, but delayed panicle initiation by seven days in K-C-A and this effect was reflected in the timing of physiological maturity.

3.3.2 The rate of leaf tip appearance

Leaf tip appearance rate was determined from the slope of the linear regression of leaf tip data over time (Figure 3.1). Under greenhouse condition, K-C-A developed 14 leaves and Starbonnet developed 17 leaves on the main culm. Before the initiation of panicle primodia, the leaf number was linearly related to the days after planting.

Table 3.3

Phenological events for K-C-A and Starbonnet

Phenological events	Nitrogen application (g/pot)	Days after planting	
		K-C-A	Starbonnet
Germination	1.88	3	4
	0	3	4
Emergemce	1.88	4	5
	0	4	5
Panicle initiation	1.88	48	72
	0	55	72
Flowering	1.88	75	98
	0	81	98
Milk grain	1.88	81	113
	0	88	113
Dough grain	1.88	92	126
	0	99	126
Physiological maturity	1.88	112	143
	0	119	143

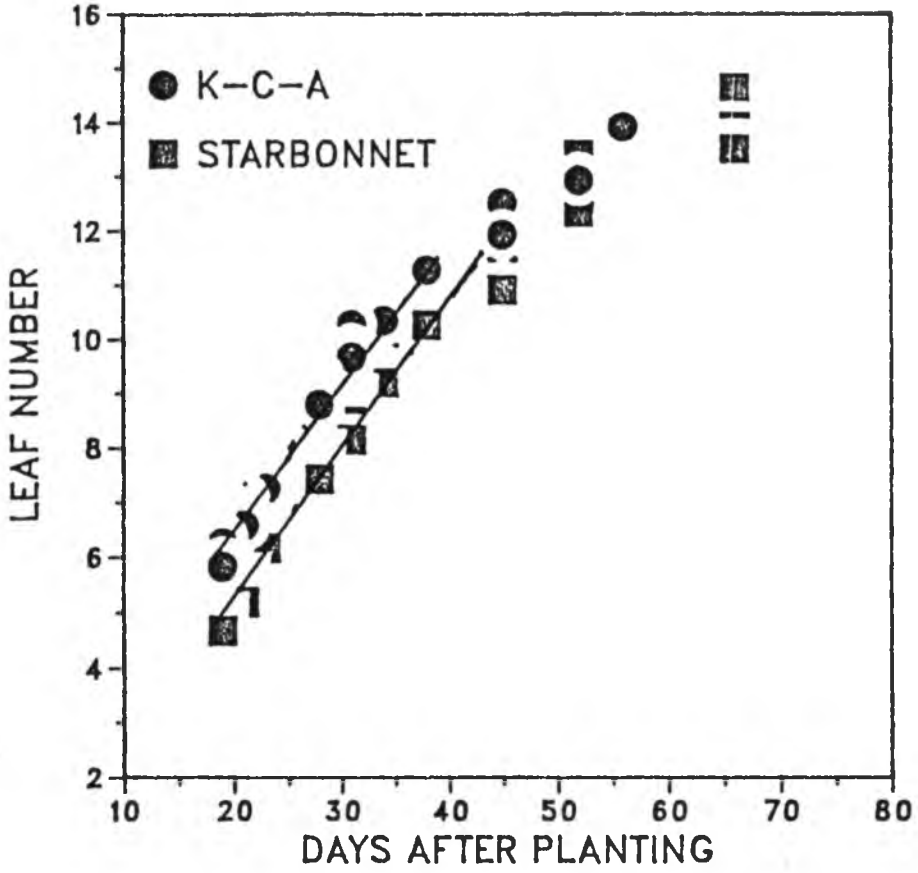

Figure 3.1 Leaf tip appearance rates of K-C-A and Starbonnet in the greenhouse

The linear regressions of leaf tip data over time for both varieties are:

$Y = 0.938 + 0.28X$ for K-C-A $R^2 = 0.98$

$Y = 0.056 + 0.27x$ for Starbonnet $R^2 = 0.97$

where X is days after planting (DAP) and Y is leaf number on main culm.

The leaf production rates (slope of the linear regression) were 0.28 leaves/day for K-C-A and 0.27 leaves/day for Starbonnet, respectively. The leaf emergence rate was not significantly different for two rice varieties. However, Starbonnet is a long duration variety, and took longer to produce the same number of leaf tip than K-C-A did. After panicle initiation, the rates of tip emergence declined.

3.3.3 Effect of N rate on leaf area index, tillering capacity and partitioning weights during the course of crop growth

The leaf area indices (LAI) obtained in this study are presented in Figure 3.2. The maximum LAI occurred near flowering time for both varieties. Nitrogen application had a highly significant effect on LAI. Plants that received N (1.88 g N/pot) attained maximum LAI 4.8 and 4.5 for K-C-A and Starbonnet respectively.

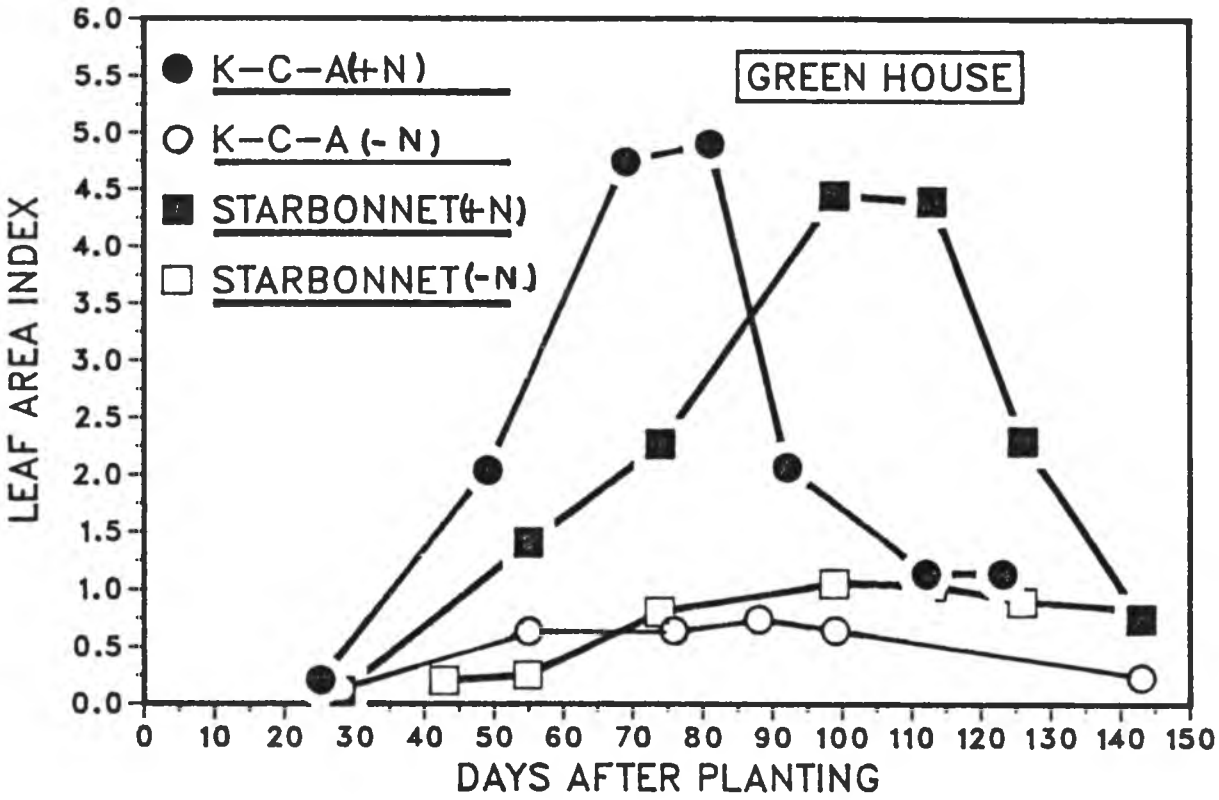

Figure 3.2 Effect of nitrogen on LAI on two rice cultivars in the greenhouse

Nitrogen application also markedly increased tillering of the two rice varieties (Figure 3.3). The results show that variety K-C-A has higher tillering capacity than starbonnet. These results were used to modify the genetic coefficients of the two varieties in the rice model.

The weights of leaves, sheaths, stems, and grains during the course of the experiment also show similar response to N (Figures 3.4, 3.5, 3.6 and 3.7).

Nitrogen fertility level had a direct influence on grain and straw yields at harvest (Figures 3.8 and 3.9). Mean separation of the grain yields using Duncan's multiple range test indicated that there was significant difference between the means for two nitrogen levels at 5% level. Mean separation of Straw yields gave similar results. Plants that were grown in high N rate obtain 71.5 g/pot and 62.4 g/pot of grain, 60.7 g/pot and 99.65 g/pot of straw for K-C-A and Starbonnet, respectively. Plants that were grown under N stress only obtained 29.9 g/pot and 16.7 g/pot of grain and 18.7 g/pot and 29.0 g/pot of straw for K-C-A and Starbonnet.

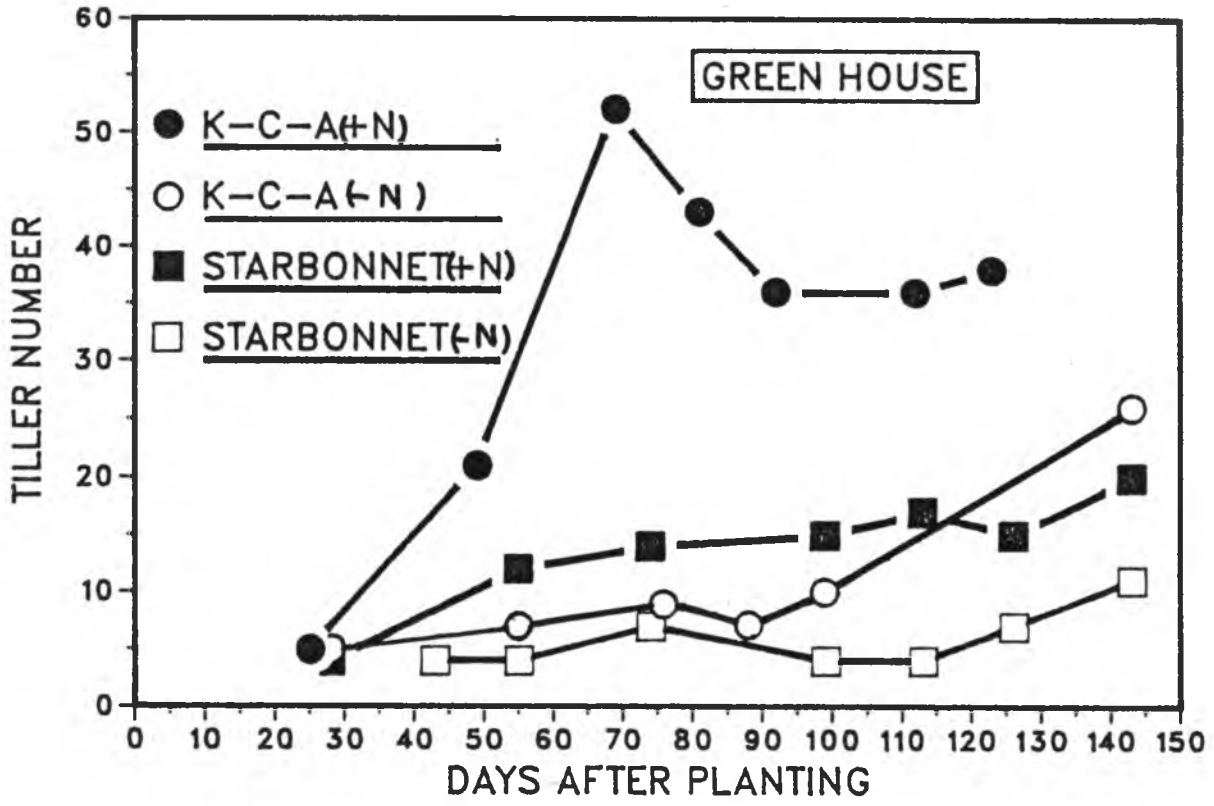

Figure 3.3 Effect of nitrogen fertilization on tiller number for two rice cultivars under greenhouse condition

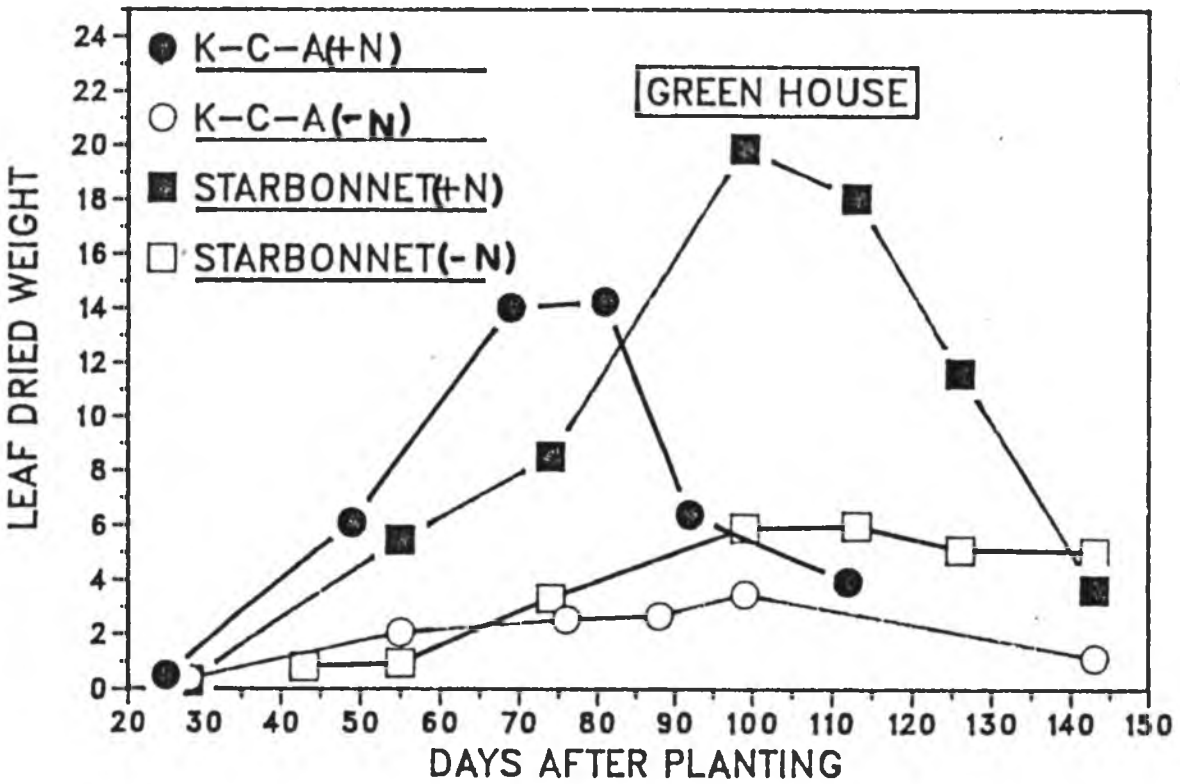

Figure 3.4 Effect of nitrogen fertilization on leaf dry-weight for two rice cultivars under under greenhouse condition

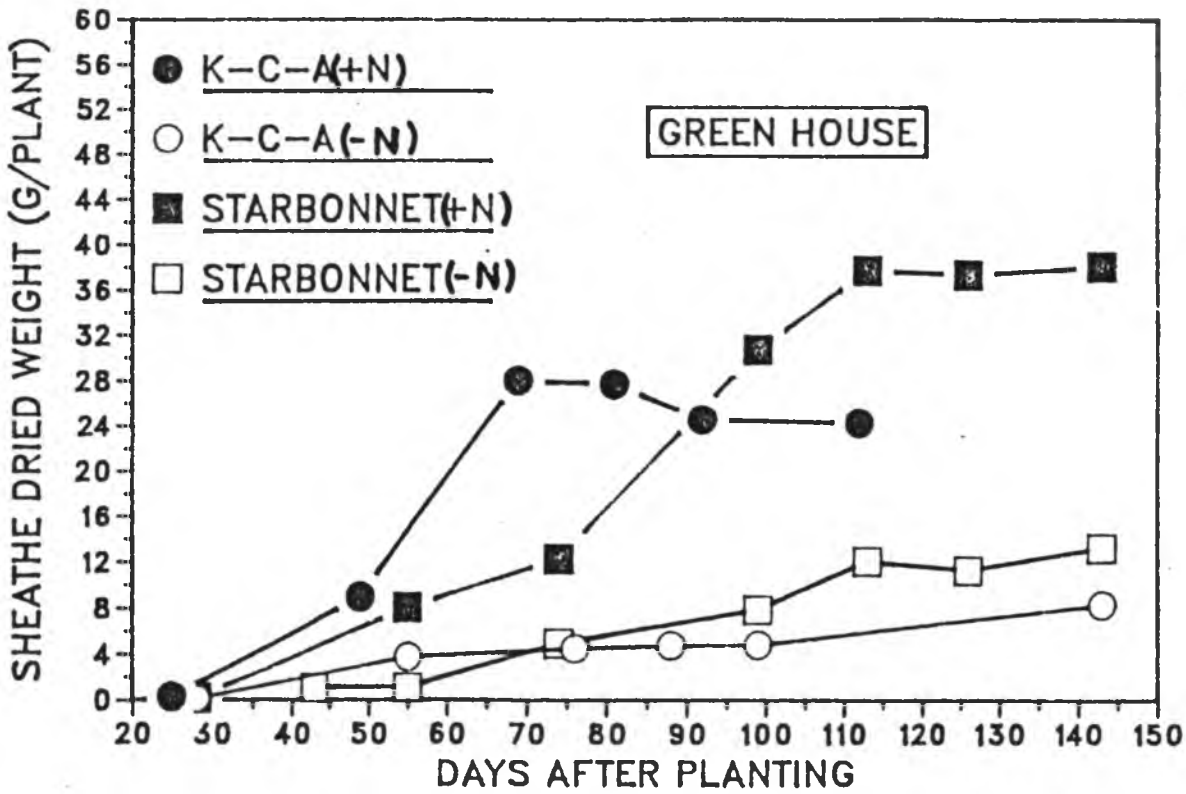

Figure 3.5 Effect of nitrogen fertilization on sheath dry-weight of two rice cultivars under greenhouse condition

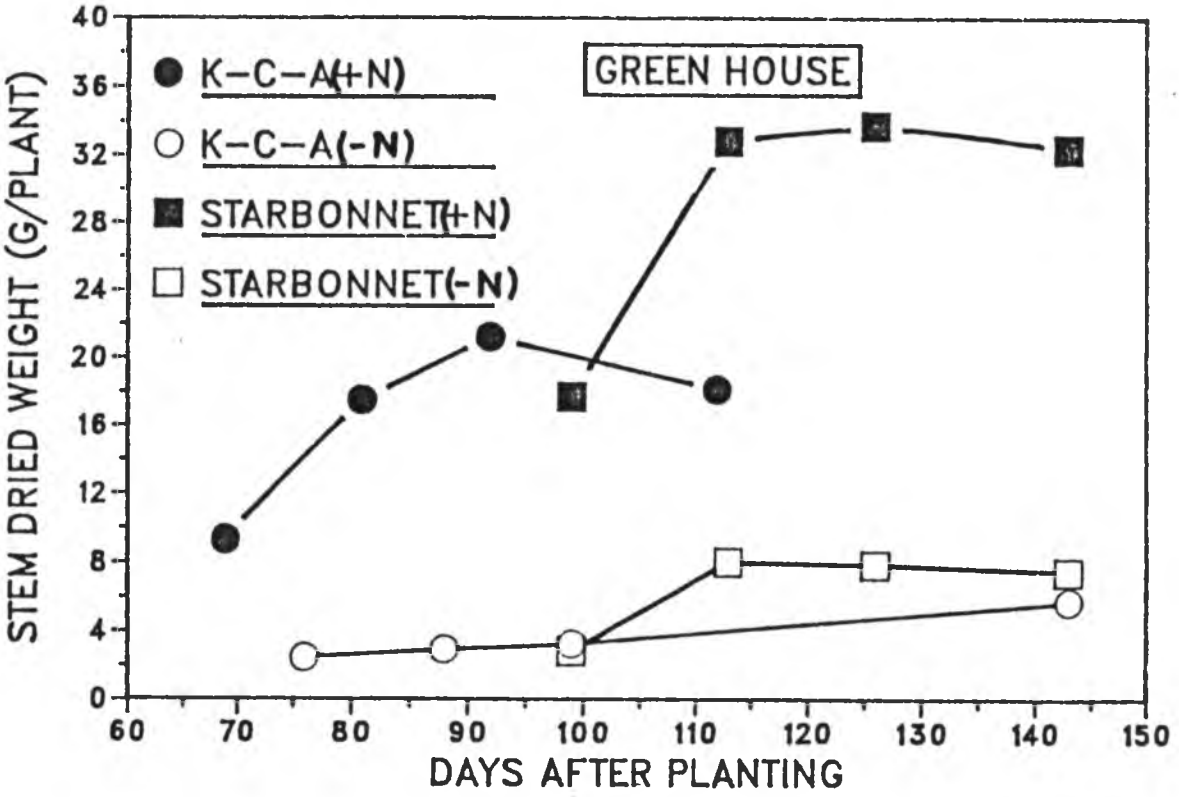

Figure 3.6 Effect of nitrogen fertilization on stem dry-weight of two rice cultivars under greenhouse condition

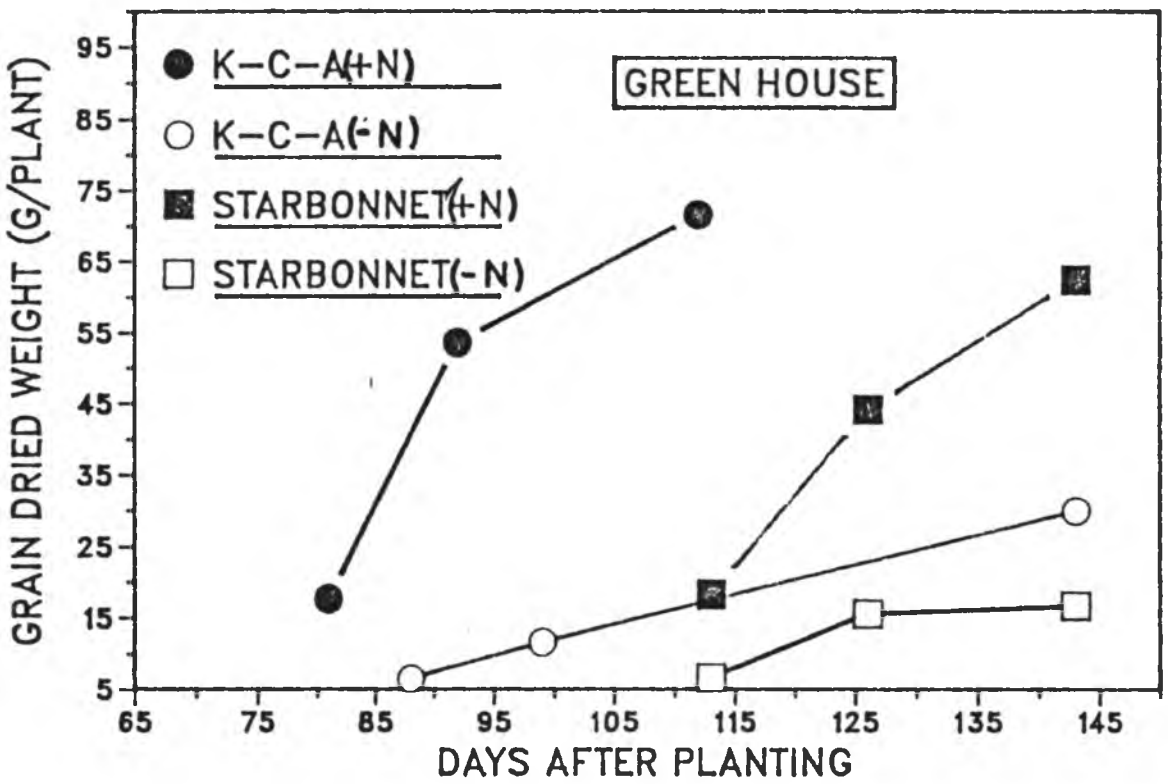

Figure 3.7 Effect of nitrogen fertilization on grain dry-weight of two rice cultivars under greenhouse condition

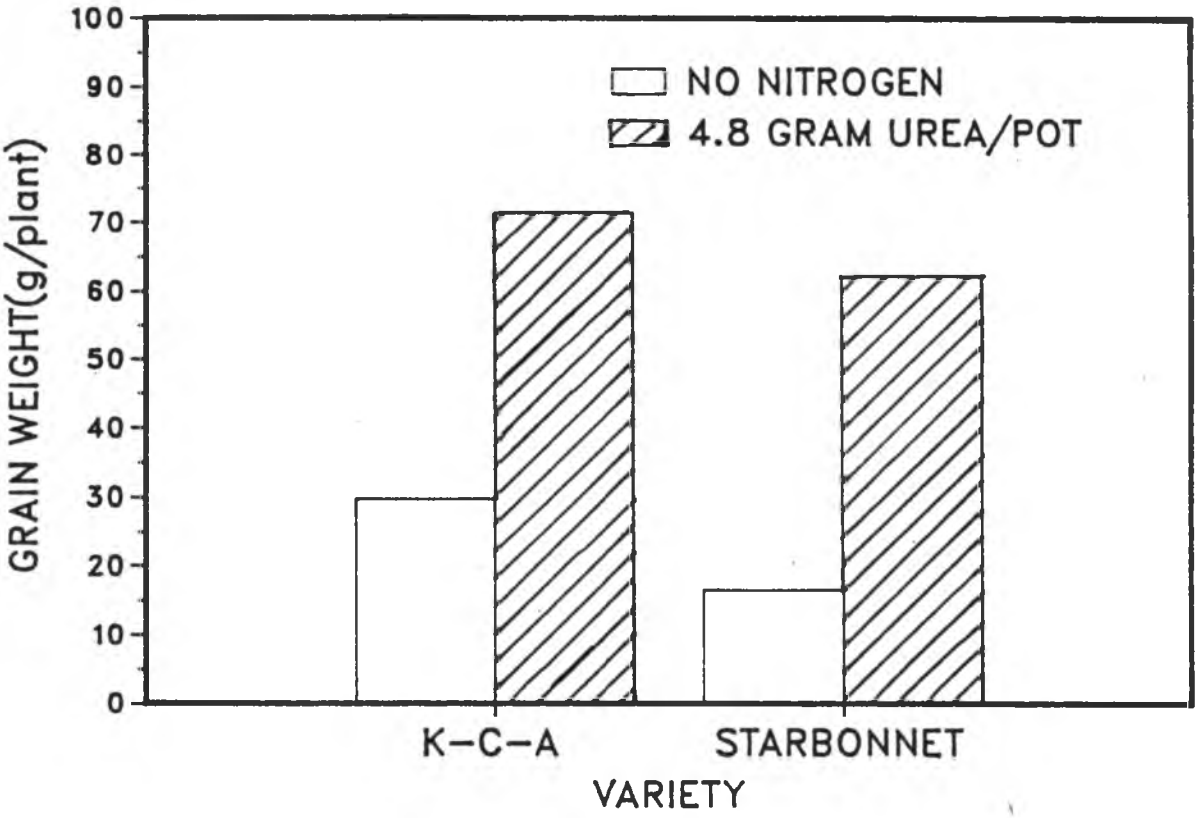

Figure 3.8 Effect of nitrogen fertilization on grain weight of two rice cultivars under greenhouse condition

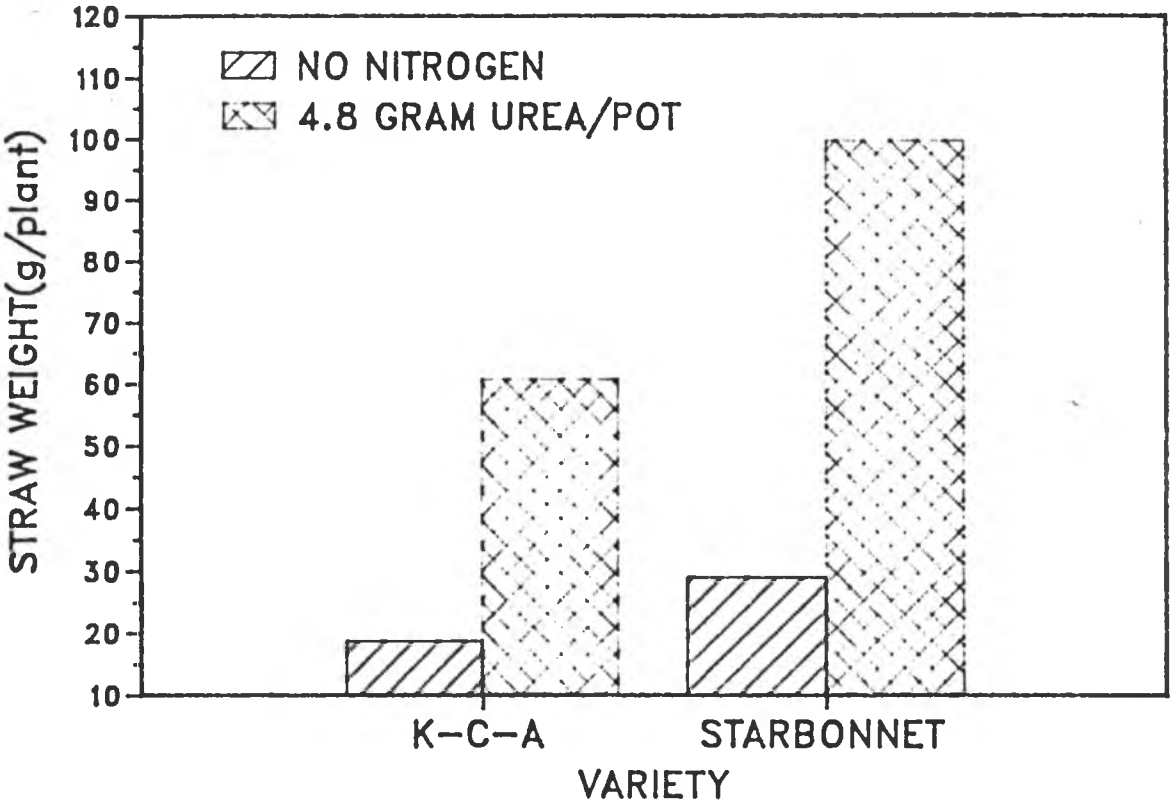

Figure 3.9 Effect of nitrogen fertilization on straw weight of two rice cultivars under greenhouse condition

3.3.4 Nutrient content at different growth stages

Changes in the nutrient content of the rice plant at different growth stages under the greenhouse weather condition were showed in Figure 3.10, 3.11, 3.12 and 3.13. The results demonstrated that the changes in the nutrient content at various stages among four treatments were similar, whereas the concentration of plant nutrients varied considerably among the various parts of the plant.

The nitrogen, phosphorus, and sulfur contents in the vegetative parts (leaf, sheath, and stem) were generally high at early growth stages and declined with maturity. In contrast, the calcium and magnesium cntents were initially low but increased with maturity.

The phosphorus content in the grains increased with maturity, however the nitrogen content decreased during the grain filling stage. Nitrogen and phosphorus contents were higher in the grain than in the straw (leaf + stem + sheath), while those of potassium, calcium, magnesium were higher in the straw. The results confirmed those obtained by Yosida (1981).

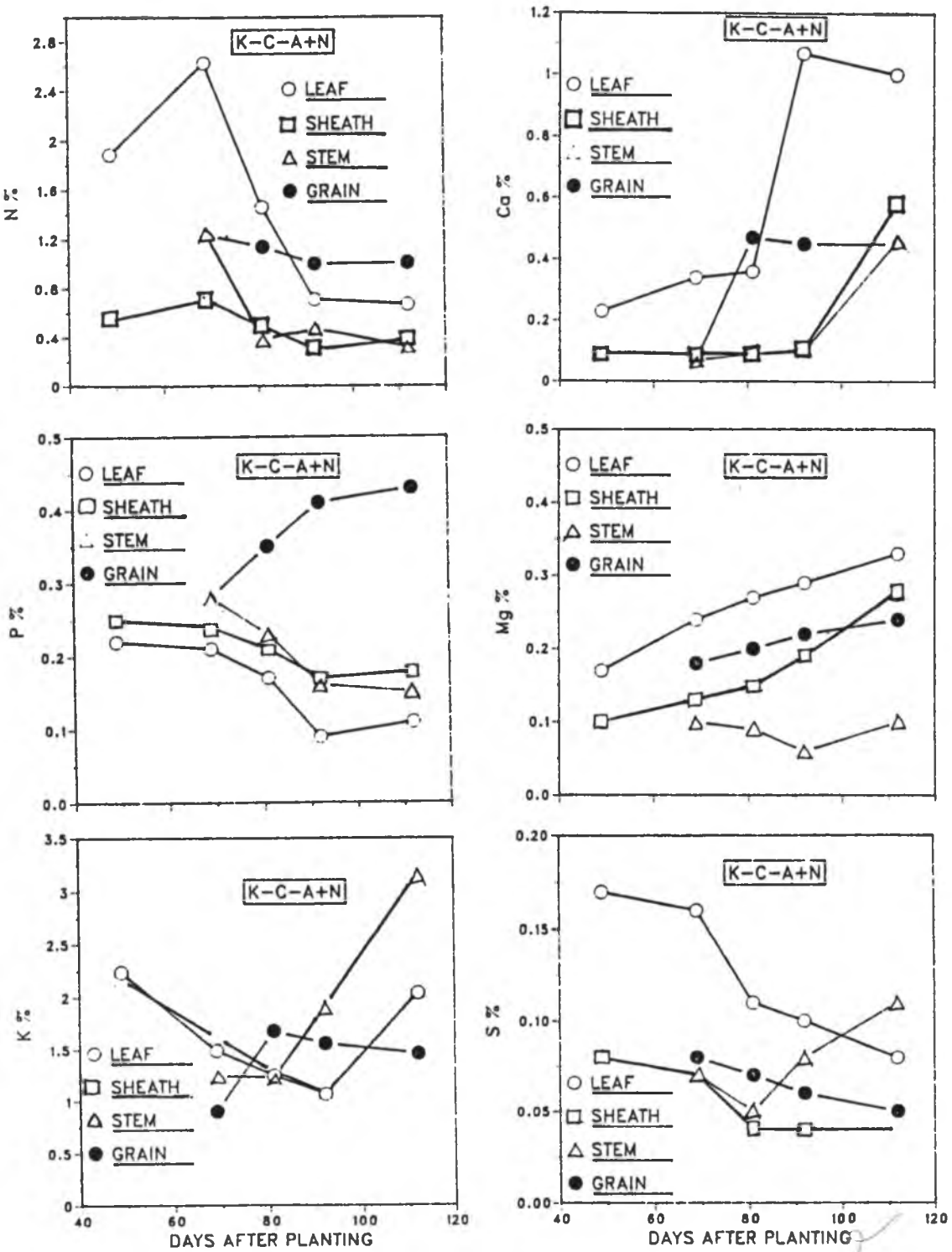

Figure 3.10 Nutrient concentrations for various plants parts measured over time for rice cultivar K-C-A supplied with N

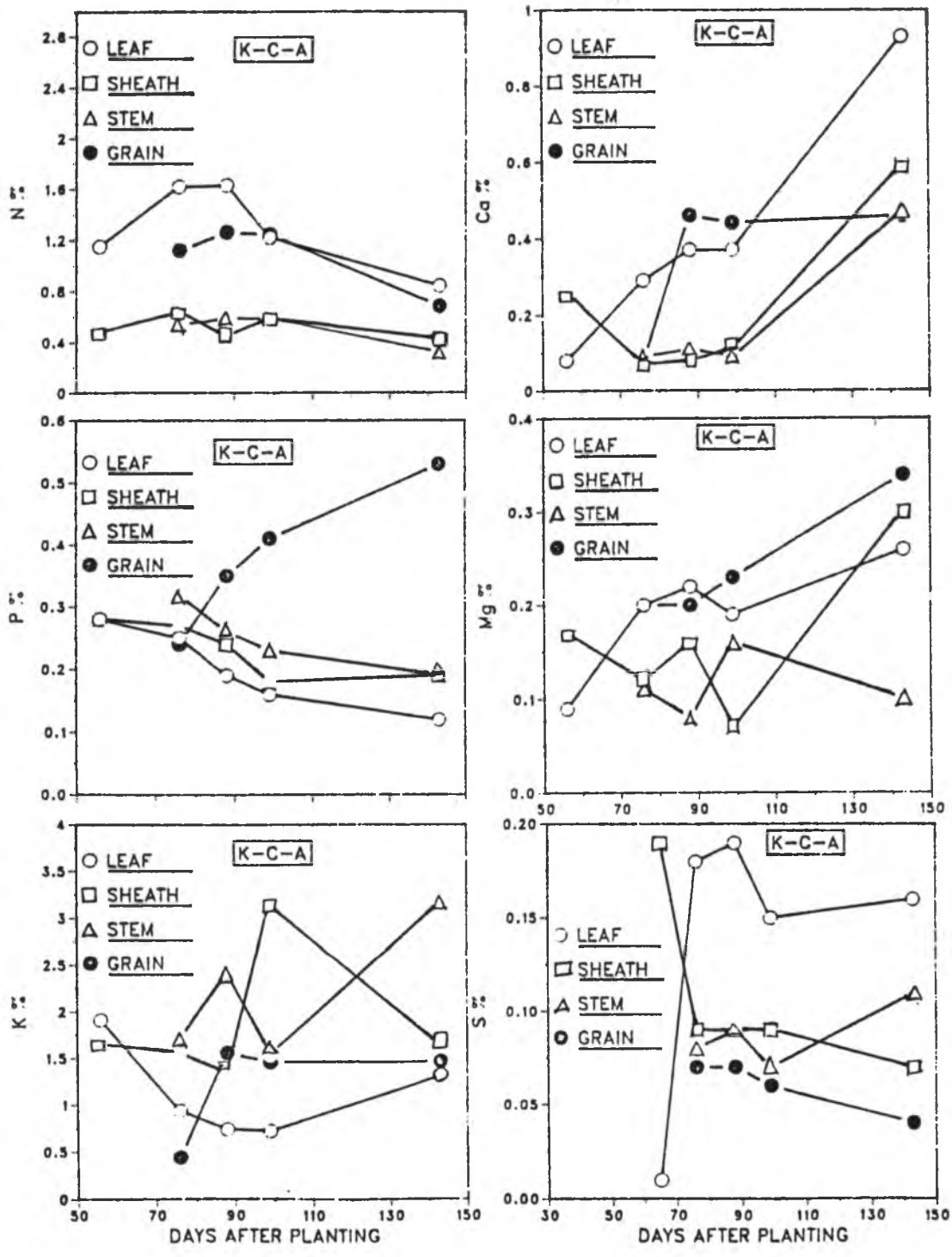

Figure 3.11 Nutrient concentrations for various plant parts measured over time for rice cultivar K-C-A not supplied with N

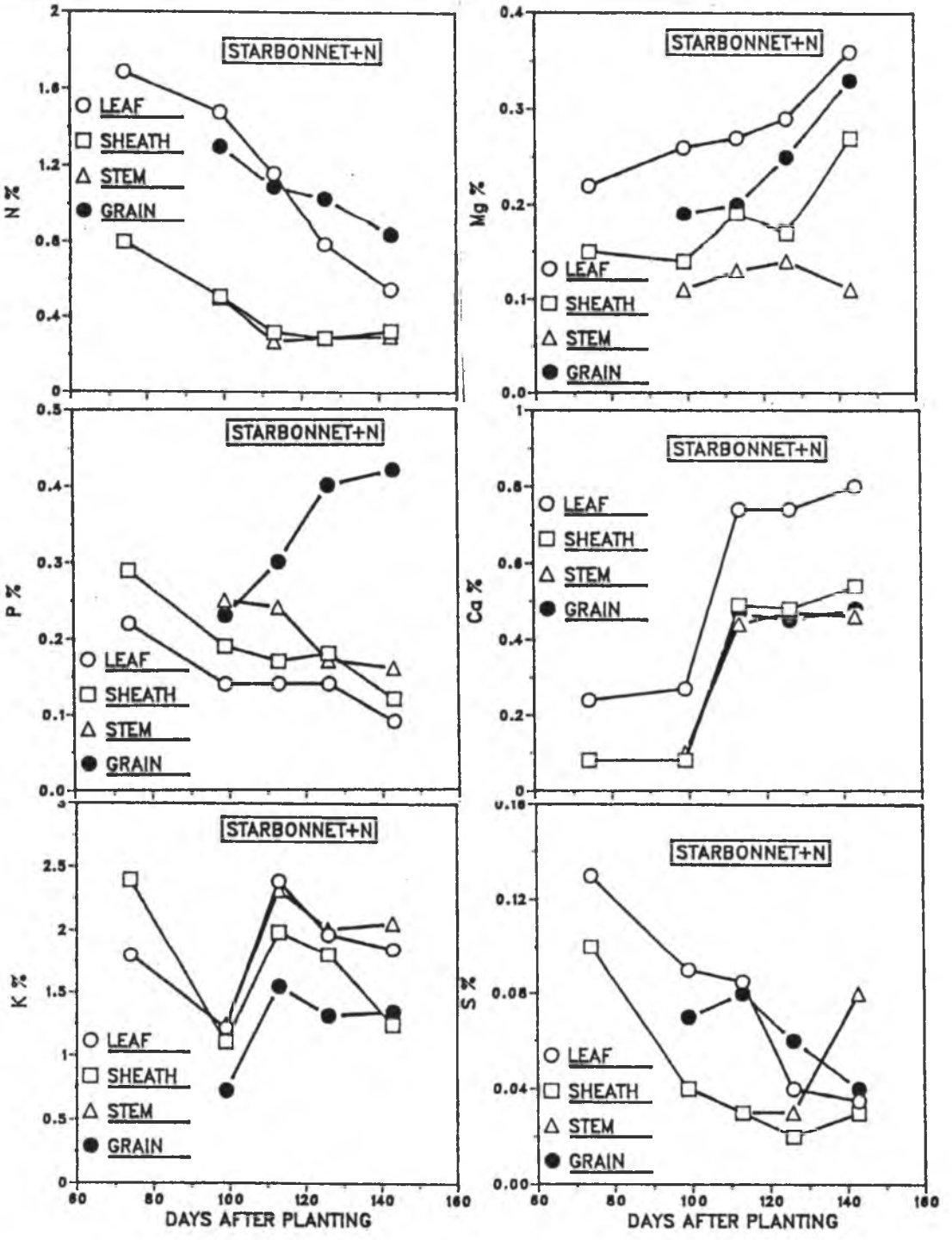

Figure 3.12 Nutrient concentrations for various plant parts measured over time for rice cultivar Starbonnet supplied with N

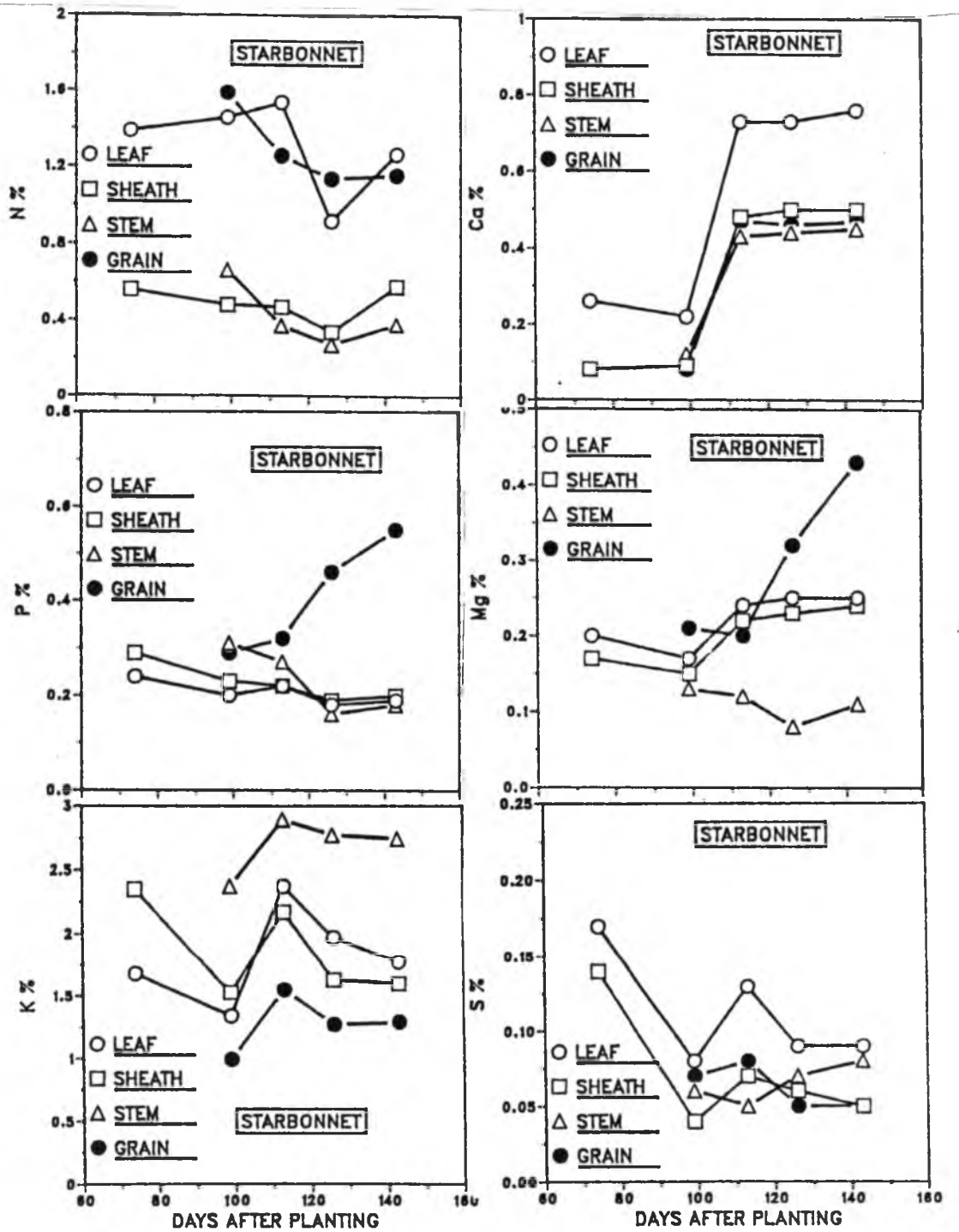

Figure 3.13 Nutrient concentrations for various plant parts measured over time for rice cultivar Starbonnet not supplied with N

3.3.5 Nutrient uptake at maturity

The total nutrient uptake reported as the product of nutrient concentration and dry matter are presented in Table 3.4. Nitrogen application markedly increased the total nitrogen uptake values largely because of higher dry matter production. Nitrogen application also increased other nutrients uptake. Nutrient uptake was not significantly different between two varieties.

3.3.6 Effects of temperature on growth and nitrogen uptake during grain filling

From observations of rice plants in the growth chambers it was evident that temperature had a marked effect on their growth and development. One week after transferring the plants into the chambers, the contrast in leaf color in the chambers became evident. The leaves remained green and vigorous in the high temperature (35/30 °C) chamber (Figure 3.14, 3.15, 3.16, and 3.17) but became yellowish in the low temperature (25/20 °C) chamber. This was accompanied by faster panicle exsertion in the high temperature than in the low temperature chamber and many more green tillers developed (Figure 3.18, 3.19, 3.20, and 3.21).

Table 3.4

Nutrient concentration and total nutrient uptake in 2 rice varieties and 2 nitrogen rate at maturity

Nutrient	Nutrient concentrations (%)				Nutrient uptake (g/plant)				
	Leaf	Sheath	Stem	Grain	Leaf	Sheath	Stem	Grain	Total
				K-C-A (+N)					
N	0.67	0.39	0.32	1.01	0.12	0.09	0.06	0.72	0.99
P	0.11	0.18	0.15	0.43	0.02	0.04	0.03	0.31	0.40
K	2.04	2.06	3.15	1.46	0.37	0.50	0.57	1.04	2.48
Ca	1.00	0.58	0.46	0.45	0.18	0.14	0.08	0.32	0.72
Mg	0.33	0.28	0.10	0.24	0.06	0.07	0.02	0.17	0.32
S	0.08	0.04	0.11	0.05	0.01	0.01	0.02	0.04	0.08
				K-C-A (-N)					
N	0.84	0.42	0.32	0.68	0.03	0.04	0.02	0.21	0.30
P	0.12	0.19	0.19	0.53	0.01	0.02	0.01	0.16	0.20
K	1.32	1.64	3.17	1.47	0.06	0.14	0.18	0.44	0.82
Ca	0.93	0.59	0.47	0.44	0.04	0.05	0.03	0.13	0.25
Mg	0.26	0.30	0.10	0.34	0.01	0.03	0.01	0.10	0.15
S	0.16	0.07	0.11	0.04	0.01	0.01	0.01	0.01	0.04

Table 3.4 (Continued)

Nutrient concentration and total nutrient uptake in 2 rice varieties and 2 nitrogen rate at maturity

Nutrient	Nutrient concentration				Nutrient uptake				
	Leaf	Sheath	Stem	Grain	Leaf	Sheath	Stem	Grain	Total
	-----%-----				---(g/plant)---				
	Starbonnet (+N)								
N	0.55	0.33	0.30	0.84	0.16	0.12	0.09	0.53	0.90
P	0.09	0.12	0.16	0.42	0.03	0.05	0.05	0.26	0.39
K	1.85	1.25	2.06	1.35	0.54	0.48	0.67	0.84	2.53
Ca	0.80	0.54	0.46	0.48	0.23	0.21	0.15	0.30	0.89
Mg	0.36	0.27	0.11	0.33	0.11	0.10	0.04	0.21	0.46
S	0.03	0.03	0.08	0.04	0.01	0.01	0.03	0.02	0.07
	Starbonnet (-N)								
N	1.27	0.58	0.38	1.16	0.11	0.08	0.03	0.19	0.41
P	0.19	0.20	0.18	0.55	0.02	0.03	0.01	0.09	0.15
K	1.77	1.60	2.74	1.29	0.15	0.21	0.20	0.21	0.77
Ca	0.76	0.50	0.45	0.47	0.06	0.07	0.03	0.08	0.24
Mg	0.25	0.24	0.11	0.43	0.02	0.03	0.01	0.07	0.13
S	0.09	0.05	0.08	0.05	0.01	0.01	0.01	0.01	0.01

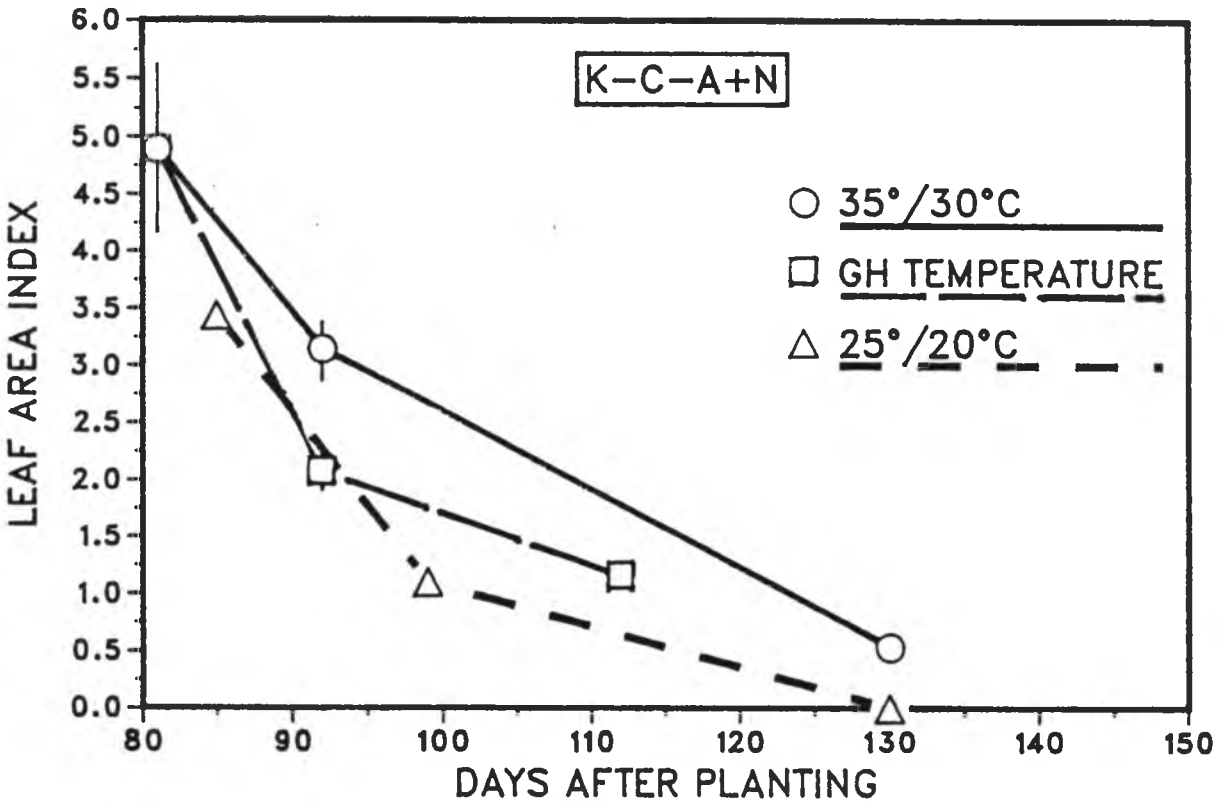

Figure 3.14 Leaf area index of rice cultivar K-C-A adequately supplied with nitrogen as a function of time and temperature in growth chambers and greenhouse (GH)

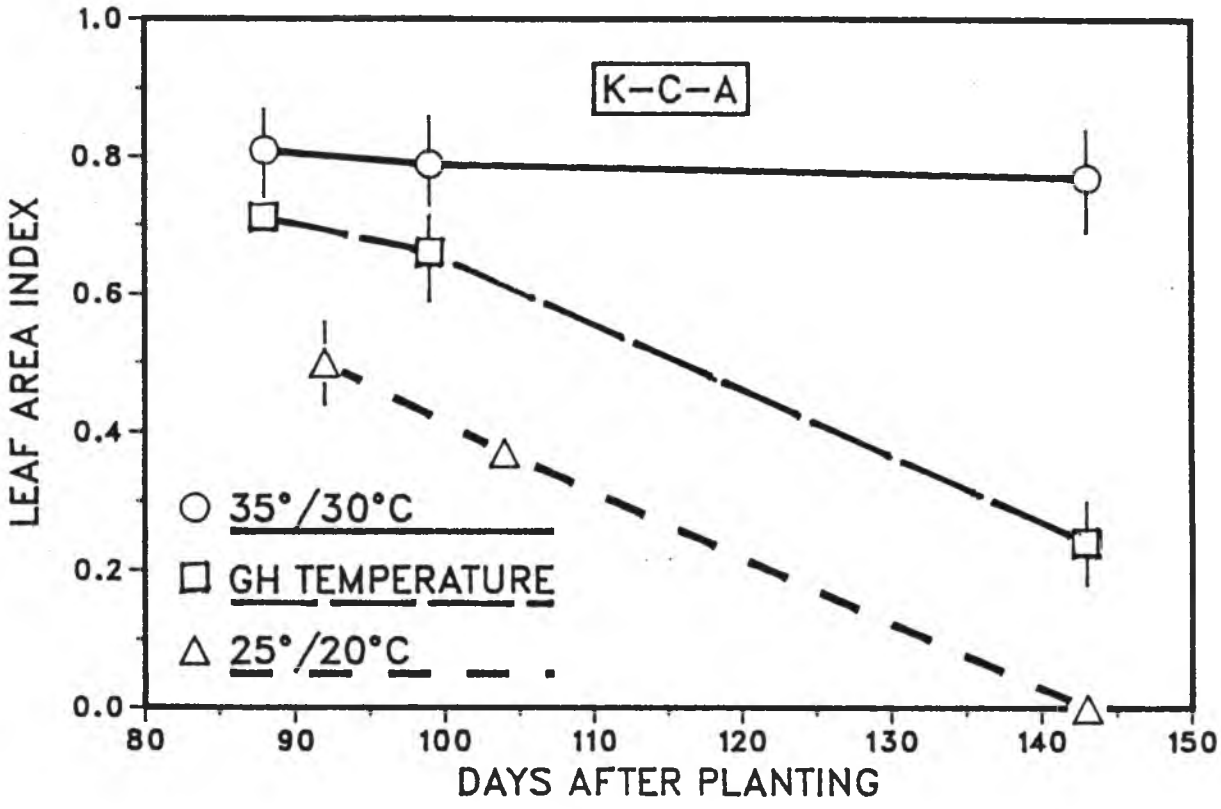

Figure 3.15 Leaf area index of rice cultivar K-C-A without nitrogen fertilization as a function of time and temperature in growth chambers and greenhouse (GH)

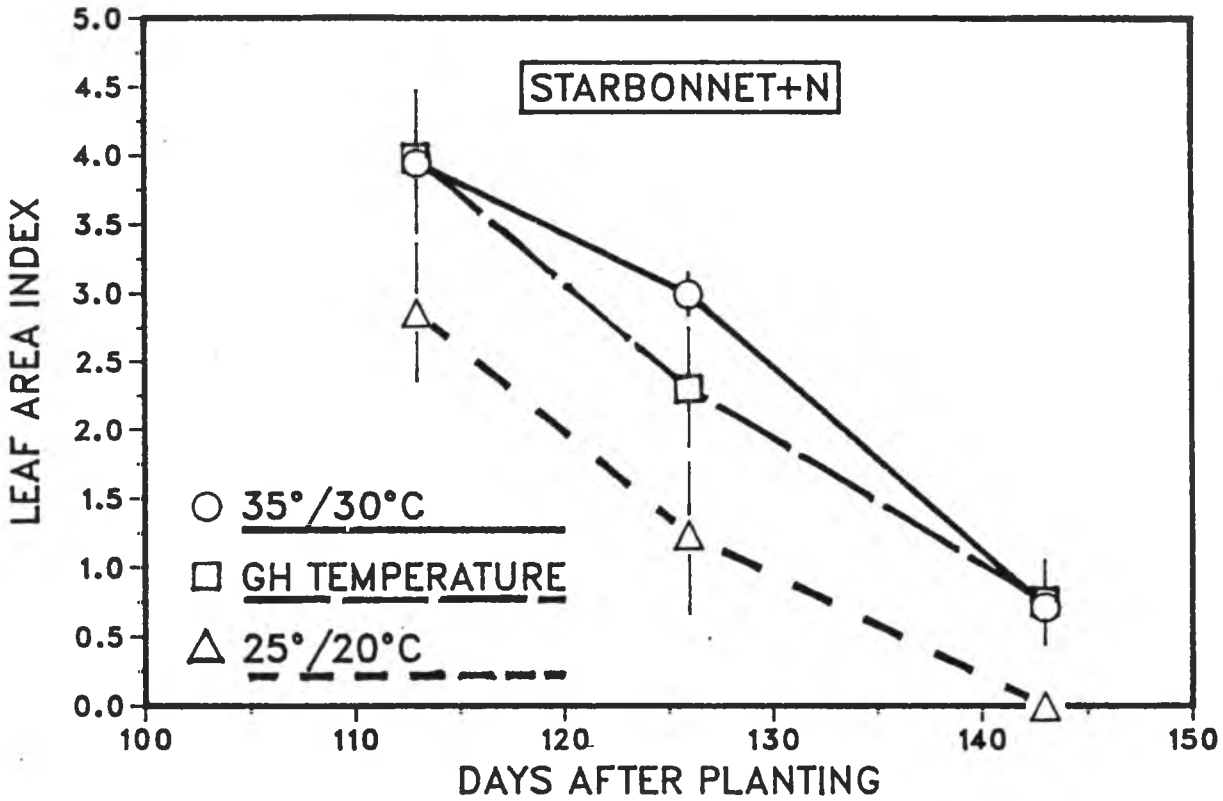

Figure 3.16 Leaf area index of rice cultivar Starbonnet adequately supplied with nitrogen as a function of time and temperature in growth chambers and greenhouse (GH)

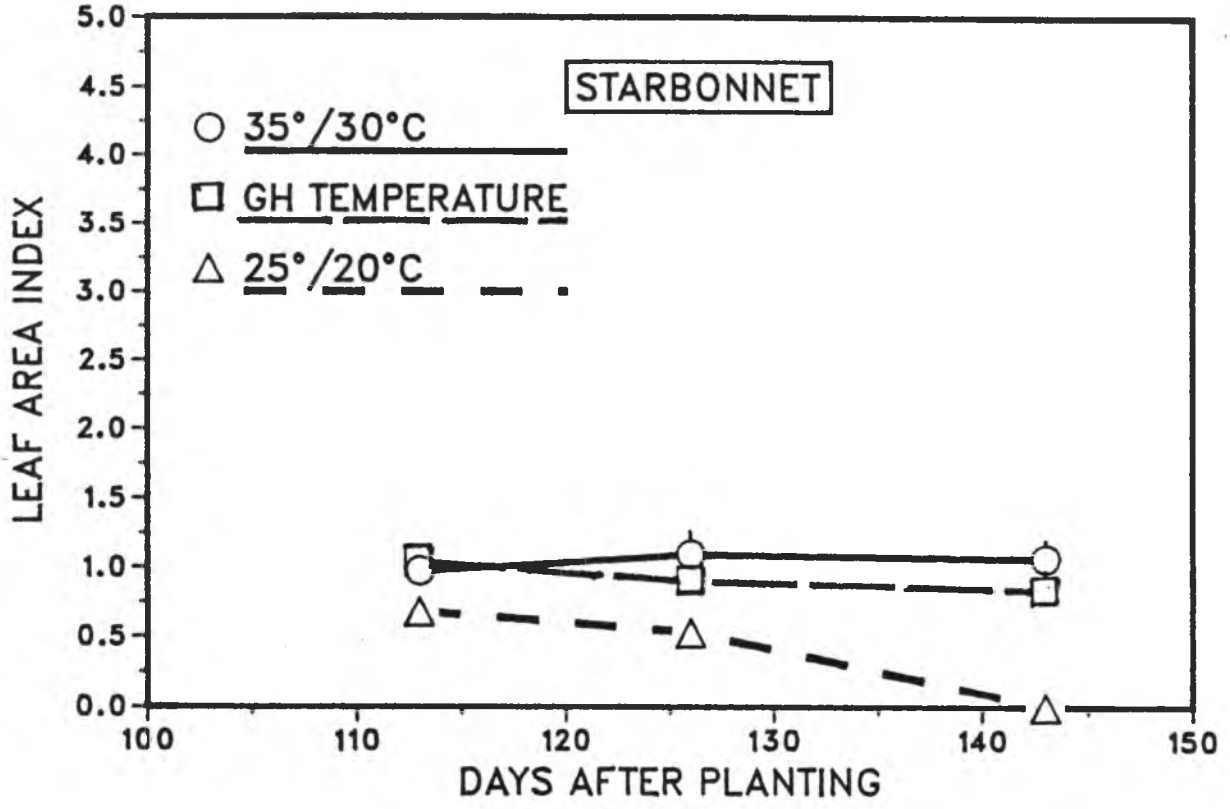

Figure 3.17 Leaf area index of rice cultivar Starbonnet without nitrogen fertilization as a function of time and temperature in growth chambers and greenhouse (GH)

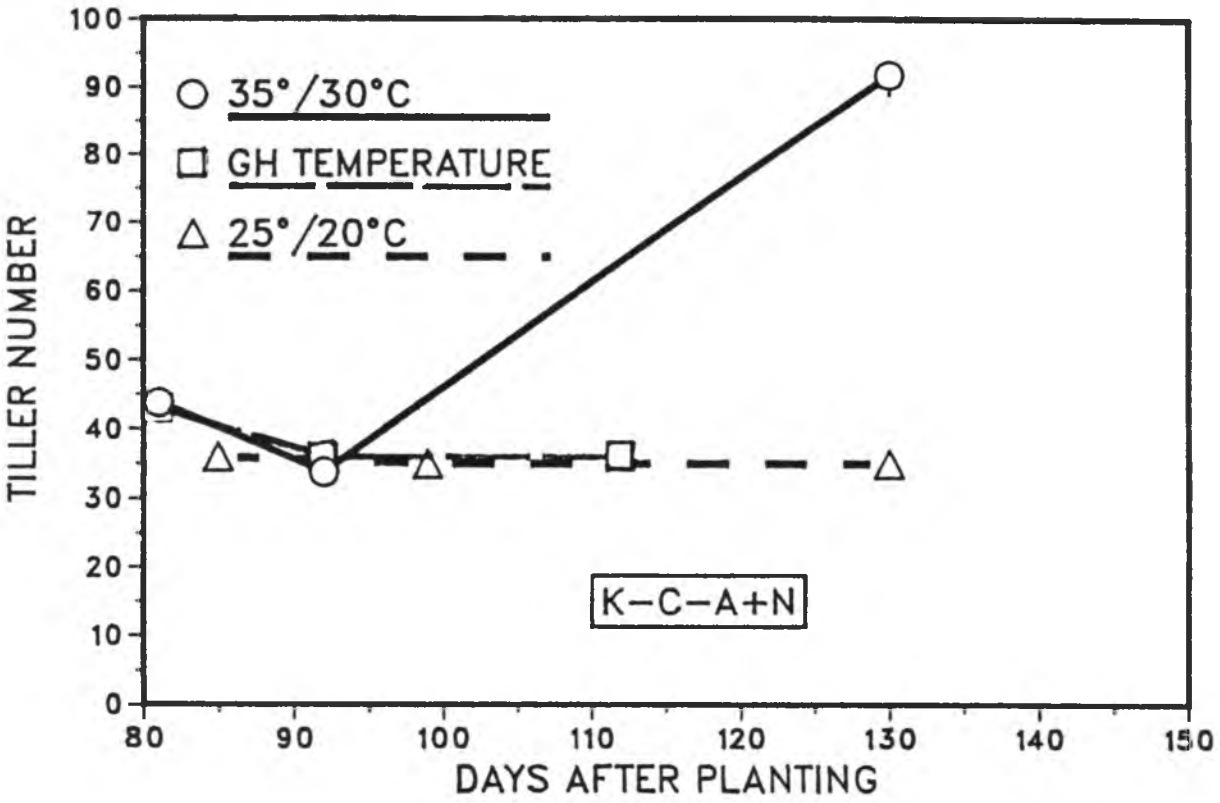

Figure 3.18 Effect of growth chambers and greenhouse (GH) temperature and time after planting on tiller number of rice cultivar K-C-A supplied with adequate nitrogen

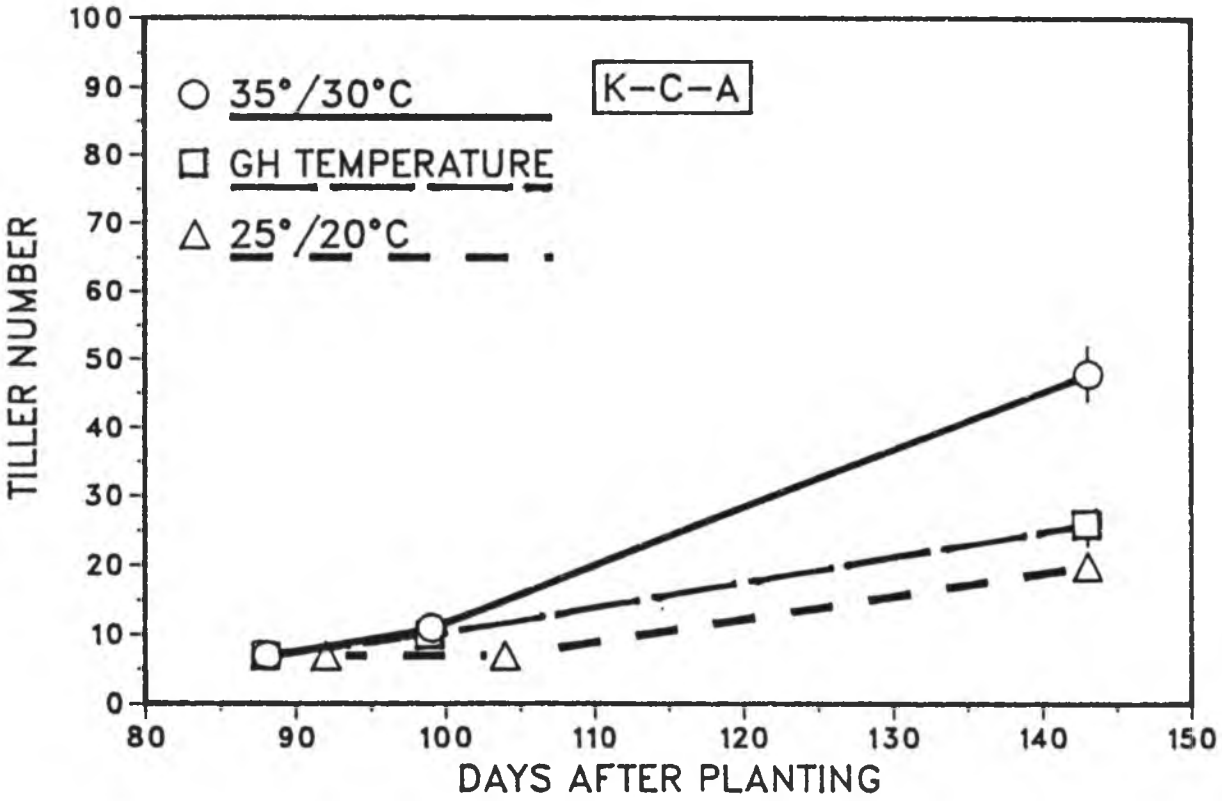

Figure 3.19 Effect of growth chambers and greenhouse (GH) temperature and time after planting on tiller number of rice cultivar K-C-A with no nitrogen fertilization

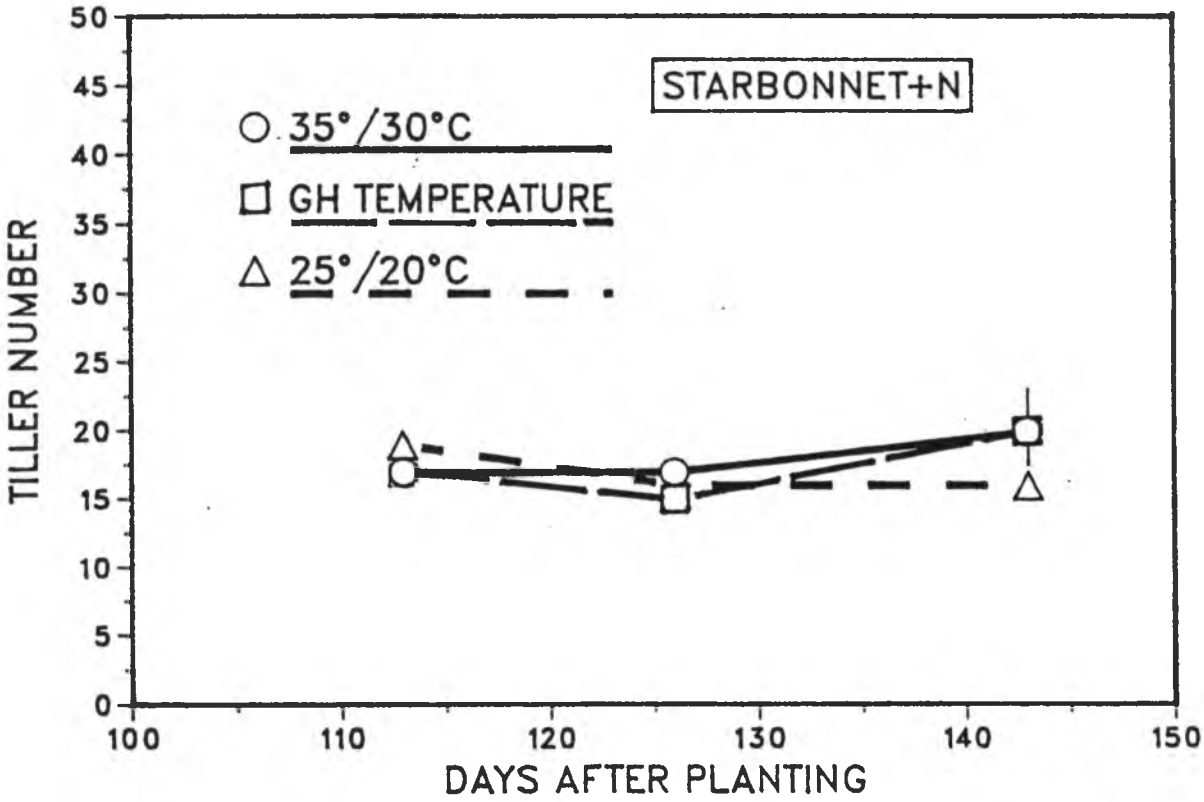

Figure 3.20 Effect of growth chambers and greenhouse (GH) temperature and time after planting on tiller number of rice cultivar Starbonnet supplied with adequate nitrogen

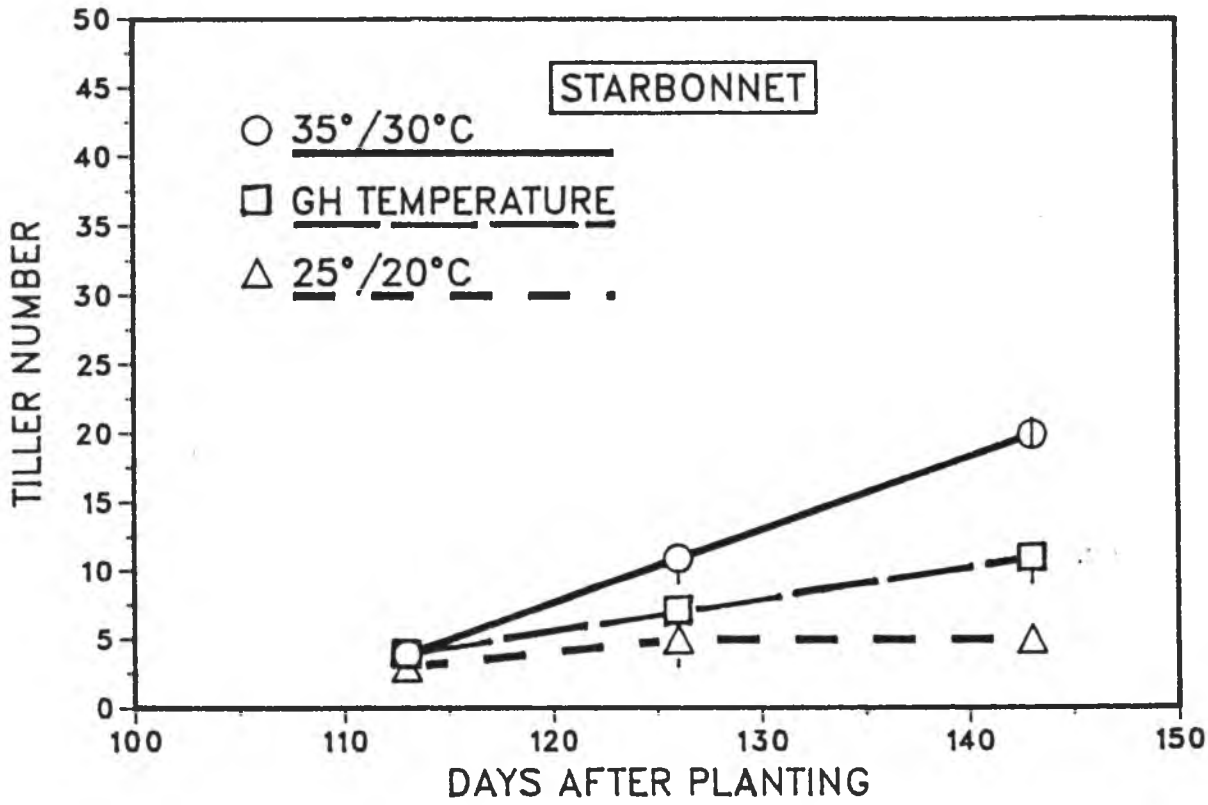

Figure 3.21 Effect of growth chambers and greenhouse (GH) temperature and time after planting on tiller number of rice cultivar Starbonnet with no nitrogen fertilization

The grain filling period was shorter at the higher temperature. Total above ground biomass was not significantly different (Figure 3.22) among three temperature regimes, but the grain yield was higher in the low temperature treatment (Figure 3.23). In contrast, the straw weight was higher in the high temperature treatment (Figure 3.24).

Under the higher temperature (35/30 °C), maturation was hastened and duration of grain filling period was shortened resulting in lower filled grain percentage, lighter 1000-grain weight and lower overall grain yield (Table 3.5). At the lower temperature (25/20 °C) grain filling continued for a longer period resulting in higher filled grain percentage and 1000-grain weight.

Chowdhury et al. (1978) and Sato (1979) attributed low grain weight at high temperature to high maintenance respiration which consumes substrate normally used for growth, and a low ratio of grain to straw (Table 3.5) caused by profuse tillering.

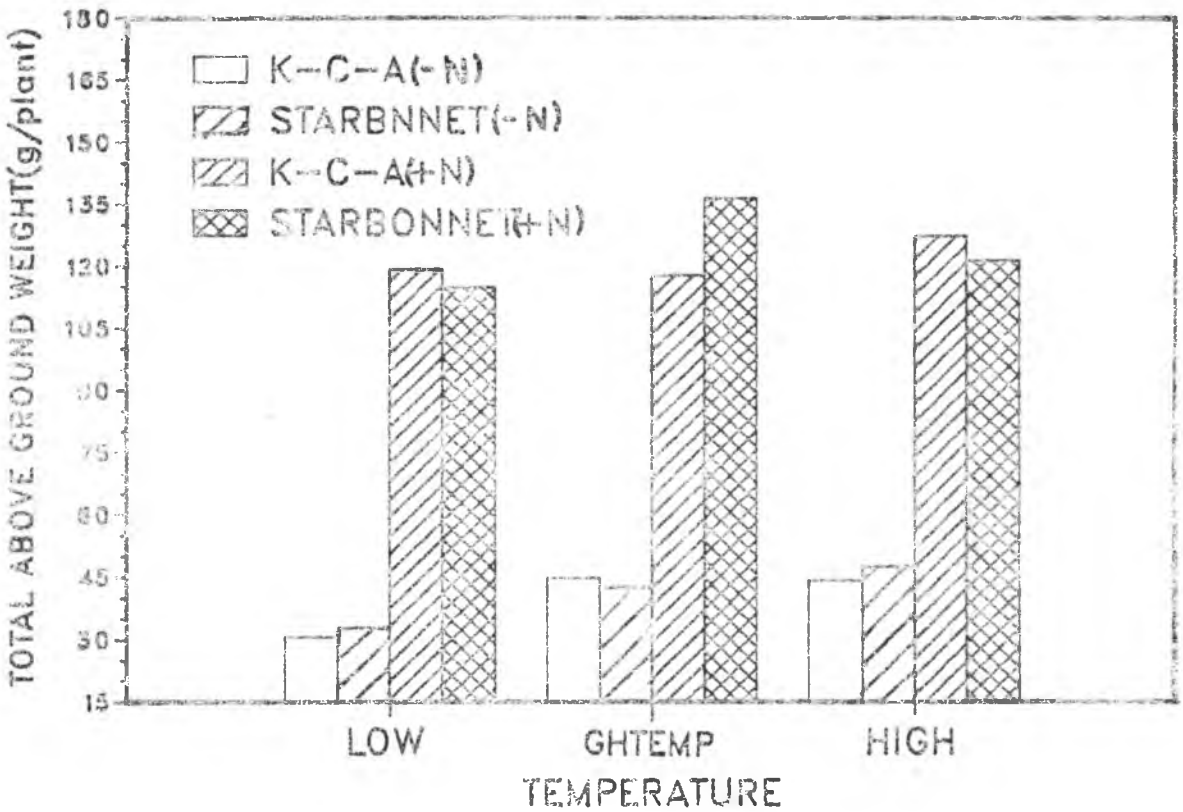

Figure 3.22 Effect of nitrogen fertilization on total above ground biomass of two rice cultivars under low and high growth chamber and intermediate greenhouse (GH) temperatures

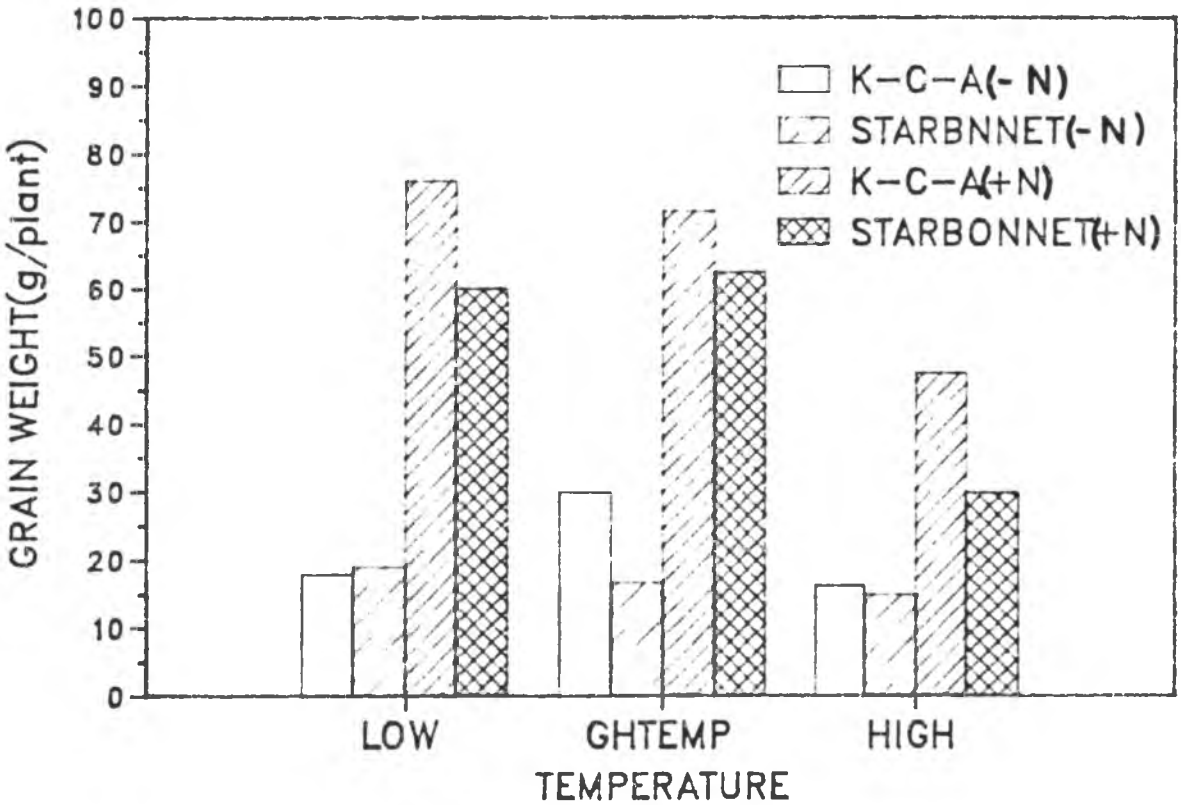

Figure 3.23 Effect of nitrogen fertilization on grain weight of two rice cultivars under low and high growth chamber and intermediate greenhouse (GH) temperatures

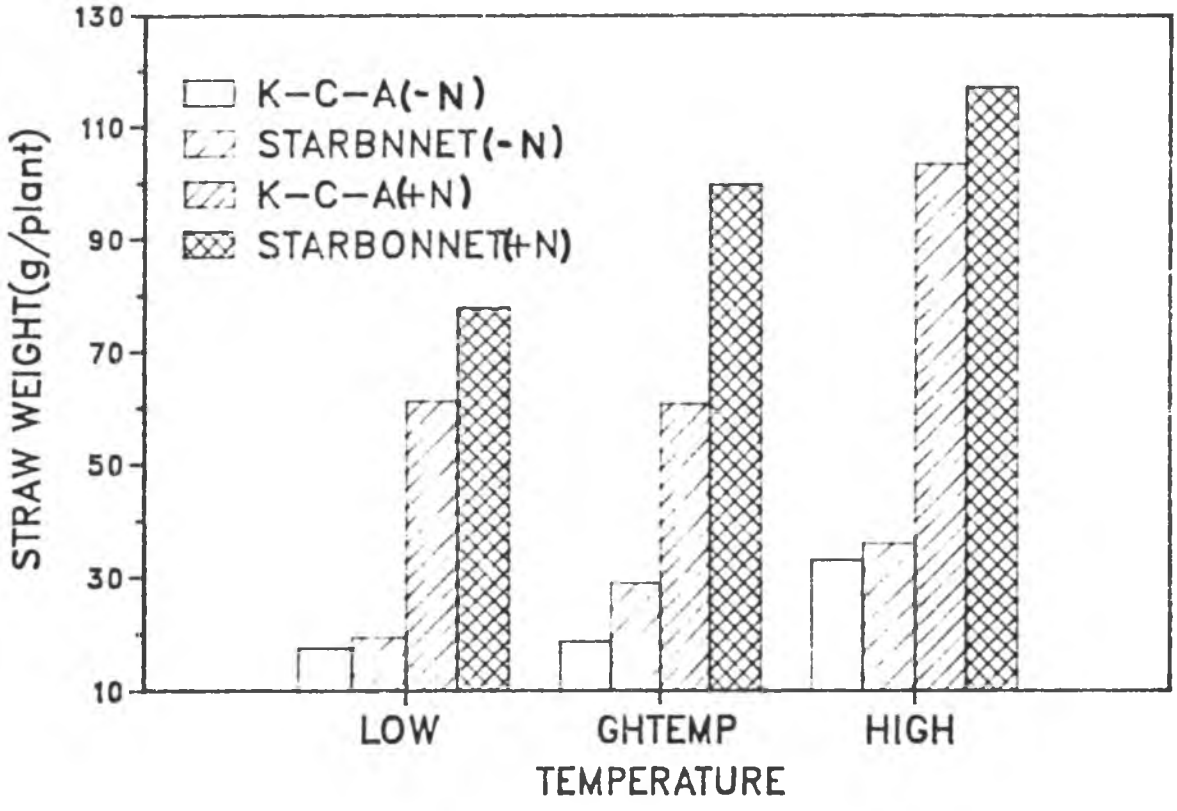

Figure 3.24 Effect of nitrogen fertilization on straw weight of two rice cultivars under low and high growth chamber and intermediate greenhous (GH) temperature

Table 3.5

Grain weight, straw weight, 1000-grain weight and grain/straw ratio under three temperature regimes

Temperature regime (°C) Day/Night	Filled grain Weight (g/plant)	%	Unfilled grain Weight (g/plant)	%	1000-grain (g)	Straw weight (g/plant)	Grain straw ratio
			K-C-A (+N)				
35/30	34.00	71	13.39	29	19.47	103.40	0.46
GHT*	69.37	97	2.14	3	23.14	60.69	1.18
25/20	75.43	99	0.58	1	22.35	61.21	1.24
			K-C-A (-N)				
35/30	10.64	65	5.74	35	16.83	33.08	0.48
GHT	27.67	92	2.27	8	23.55	18.70	1.60
25/20	15.84	89	2.04	11	22.26	17.51	1.02
			Starbonnet (+N)				
35/30	17.73	60	12.06	40	19.85	116.95	0.25
GHT	58.80	94	3.57	6	18.58	99.65	0.63
25/20	57.45	96	2.54	4	20.55	77.75	0.77
			Starbonnet (-N)				
35/30	9.84	66	5.05	34	19.58	36.04	0.41
GHT	15.08	90	1.60	10	19.29	28.97	0.57
25/20	18.18	96	0.80	4	21.47	19.43	0.98

* Greenhouse temperature

The maximum daily temperature in the greenhouse was occasionally higher than 35 °C, and the minimum daily temperature was also frequently lower than 30 °C, and the mean daily temperature was between 25 and 35 °C. Although the maximum temperature in the greenhouse was sometime higher than 35 °C, the grain yield was higher than in the high temperature chamber. Light intensity was also higher in the greenhouse than in the growth chambers. Low light intensity combined with high temperature is unfavorable for grain development (Sato 1971) and low light intensity during the ripening period affects grain yield by decreasing the percentage of filled grains (Yoshida et al. 1977).

The the effects of the two temperatures treatment on nitrogen uptake and partitioning are shown in Tabel 3.6. Temperature significantly increased the nitrogen concentration of both varieties in the leaf, sheath, stem, and grain. Total nitrogen uptake was also higher under the high temperature treatment, but nitrogen uptake by the grains was relatively low. After the plants entered the reproductive stage, a large amount of nitrogen was translocated from the vegetative to the reproductive tissues (Moore et al. 1981). This effect is illustrated in Figure 3.25 where grain nitrogen uptake is plotted against straw nitrogen uptake.

Table 3.6

Nitrogen concentration and total nitrogen uptake by rice plants at maturity under two temperature regimes

Temperature (day/night) °C	N concentration (%)				N uptake (g/plant)		
	Leaf	Sheath	Stem	Grain	Straw	Grain	Total
K-C-A (+N)							
35/30	0.85	0.59	0.43	1.02	0.63	0.49	1.12
25/20	0.47	0.33	0.26	0.79	0.21	0.60	0.81
K-C-A (-N)							
35/30	1.59	0.80	0.60	1.27	0.32	0.20	0.52
25/20	0.97	0.52	0.42	1.15	0.10	0.21	0.31
Starbonnet (+N)							
35/30	0.74	0.42	0.35	0.85	0.54	0.25	0.79
25/20	0.34	0.35	0.29	0.94	0.25	0.57	0.82
Starbonnet (-N)							
35/30	1.13	0.57	0.51	1.18	0.25	0.18	0.43
25/20	0.72	0.39	0.34	1.12	0.09	0.21	0.30

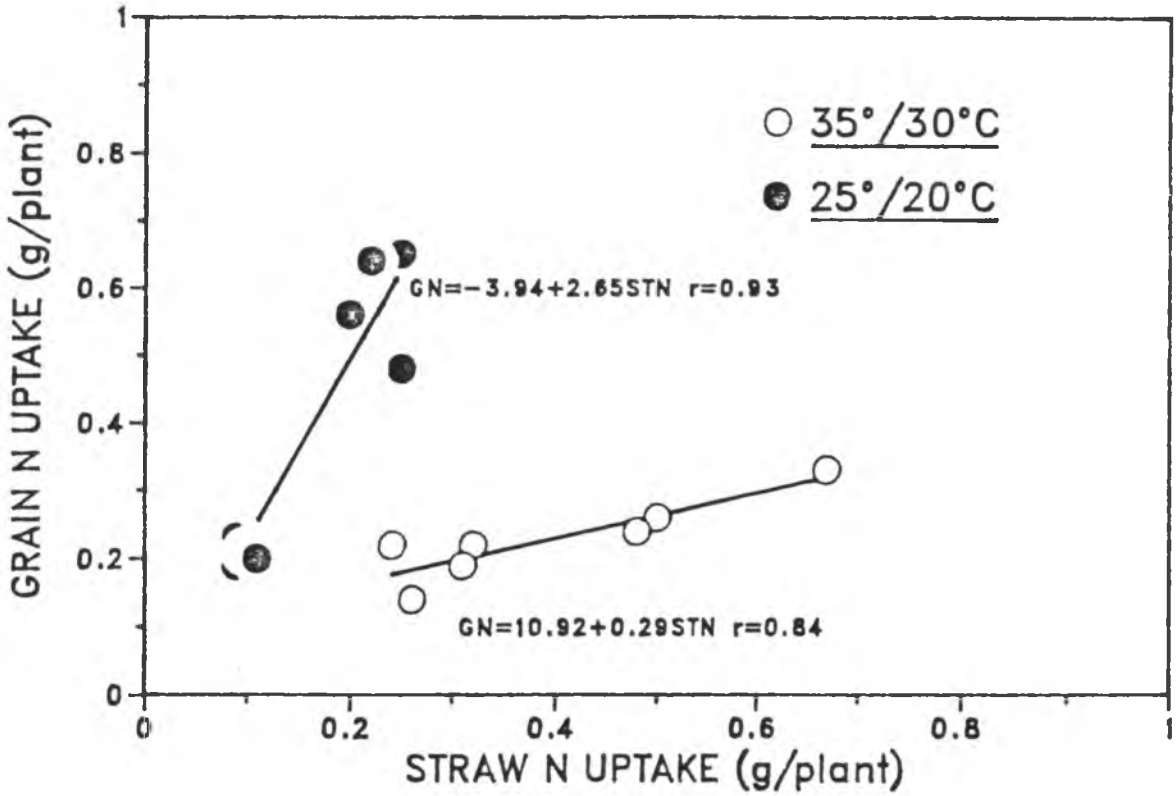

Figure 3.25 Effect of temperature on the relationship between N uptake by grain and straw

The slopes of the two lines probably represents early termination of grain filling under high temperature.

3.4 Conclusions

This experiment was designed to obtain data on the growth and development of two rice varieties differing in growth duration under different temperature regimes and different nitrogen rate.

Nitrogen fertility had a direct influence on grain and straw yields at final harvest. Nitrogen application increased the yield by increasing tiller numbers and maximum LAI during the early development stages. Nitrogen fertilization had no effect on the timing of phenological events in variety Starbonnet but delayed panicle initiation by about a week in variety K-C-A. Nitrogen rate also affected other nutrients uptake.

Temperature affected the yield and nitrogen uptake during the grain filling stage of both rice varieties. Under high temperature, maturation was hastened and duration of grain filling period was shortened resulting in lower filled grain percentage, lower 1000-grain weight and lower overal grain yield. The nitrogen concentration and N uptake were higher in the high temperature regime. However, the persistence green color of the straw and a low ratio of grain N to straw N, indicated that nitrogen translocation from straw to grain was diminished by the high temperature.

CHAPTER IV

CALIBRATION AND VALIDATION OF IBSNAT/CERES RICE MODEL

4.1 Introduction

The IBSNAT/CERES Rice Model, a component of the Decision Support System for Agrotechnology Transfer (DSSAT), is currently in the early stage of development by a multidisciplinary team of soil scientists, agronomists, and crop physiologists at Michigan State University, the International Fertilizer Development Center and the University of Hawaii.

The model simulates the growth, phenological development, soil water balance and nitrogen dynamics of different rice varieties under any agroclimatic condition. The present version of the model works for upland rice and has been primarily an adapation of the CERES-Maize and CERES-Wheat model structures. The model has not yet been calibrated and tested because complete minimum data sets on rice experiments are not yet available. A major constraint is the unavailability of weather and soil information to fully evaluate the IBSNAT/CERES Rice Model.

In order to collect minimum data sets on rice, field experiments were conducted on Islands of Kauai and Maui to quantify model coefficients. The overall objective is to

collect reliable data sets from field experiments and to calibrate and validate the IBSNAT/CERES Rice Model with these data sets.

4.2 Materials and Methods

4.2.1 Field description and assignment of treatments

The experiments designed to calibrate and validate the phasic and growth subroutines of the IBSNAT/CERES Rice Model were conducted in September 1985 to November 1986. These experiments enable the effects of temperature, photoperiod, and solar radiation on the growth and phasic development for the five rice varieties at different seasons and elevations to be studied.

The experimental sites were located in Wailua, Island of Kauai, and Kuiaha, Haleakala and Olinda on the Island of Maui. The description of the sites is presented in Table 4.1 and soil profile properties are shown in Appendix A.

The rice varieties used in the experiments were:

Kwang-Chang-Ai - a highly photoperiod sensitive variety;

Bellemont - a very low photoperiod sensitive variety;

Labelle - a short juvenile phase variety;

Starbonnet - a long juvenile phase variety; and

IR-36 - a high tillering capacity and intermediate juvenile phase variety.

The daily weather data of air temperature (maximum and minimum), and solar radiation were recorded automatically with CR-21 Microloggers. The model RG-2501 Sierra Tipping Bucket Raingages were used to record daily rainfall.

A randomized complete block design with five varieties and three replications was used in the Wailua upland rice experiment. The field layout is shown in Figure 4.1. A randomized complete block design with two varieties and three replications was used in Kuiaha, Haleakala, and Olinda upland rice experiments. The field layouts are shown in Figure 4.2, 4.3, and 4.4. The equivalent of 50 kg N ha^{-1} as urea, 50 kg P ha^{-1} as triple superphosphate, 150 kg K ha^{-1} as KCl, 50 kg Mg ha^{-1} as $MgSO_4$, 15 kg Zn ha^{-1} as $ZnSO_4$, and 2 kg B ha^{-1} was broadcasted and incorporated to a soil depth of 20cm to all plots before sowing. Two doses of 50 kg N ha^{-1} were applied as top-dressing around the 3rd tillering stage and panicle initiation stage, respectively. The dates of fertilizer application at the different sites are presented in Table 4.2. The sowing dates, depth, row spacing and plant population are shown in Table 4.3. The crop was irrigated and assumed to be free of water stress.

A lowland (flooded) rice experiment was also conducted in Wailua with the same treatments as the upland rice experiment. Instead of direct seeding, 20-days old rice seedling was transplanted into the paddy field. Follwing

that, 5 cm of standing water was maintained in the field. Insecticides and herbicides were applied as necessary.

4.2.2 Plant observations and sampling

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

Four plants were sampled from each plot four times during the course of growth. These samples were taken at the 3rd-tillering stage, panicle initiation stage, heading stage, and physiological maturity stage. The plants surrounding the sampling sites were tagged so that they would not be sampled since they would no longer be representative of the plot/treatment. For each plant, tiller number and panicle number were counted and leaf area, and dry weights of leaves, sheaths, stems and grains were determined. The leaf area was determined with a Li-Cor Model 3100 Area Meter. A one meter square area was selected randomly in each plot to determine the final yield.

Table 4.1

Soil and environmental characteristics of the experimental sites

Characteristic	Sites			
	Wailua	Kuiaha	Haleakala	Olinda
Latitude	22° 03'30"N	20° 54'11"N	20° 54'40"N	20° 48'27"N
Longitude	159° 20'30"W	156° 18'24"W	156° 17'51"W	150° 17'07"W
Elevation(m)	6	283	640	1150
Mean annual rainfall(mm)	2815	1910	1830	1270
Temperature regime	isohyperthermic		isothermic	isomesic
Soil series	Hanalei	Haiku	Makawao	Olinda
Soil order	Entisols	Ultisols	Ultisols	Inceptisols
Soil parent material	Alluvium from high rainfall area weathered from basic igneous rock	Basic igneous rock	Basic igneous rock	Volcanic ash over basic igneous rock
Physiography	Flood plains	Nearly level upland	Gently sloping upland	Moderately steep shoulder position on knoll
Slope(%)	0	2	5	16
Drainage	Poorly drained	----------Well drained---------		
Ground water	Low	Deep	Deep	Deep
Permeability	Moderate	--------Moderately rapid-------		

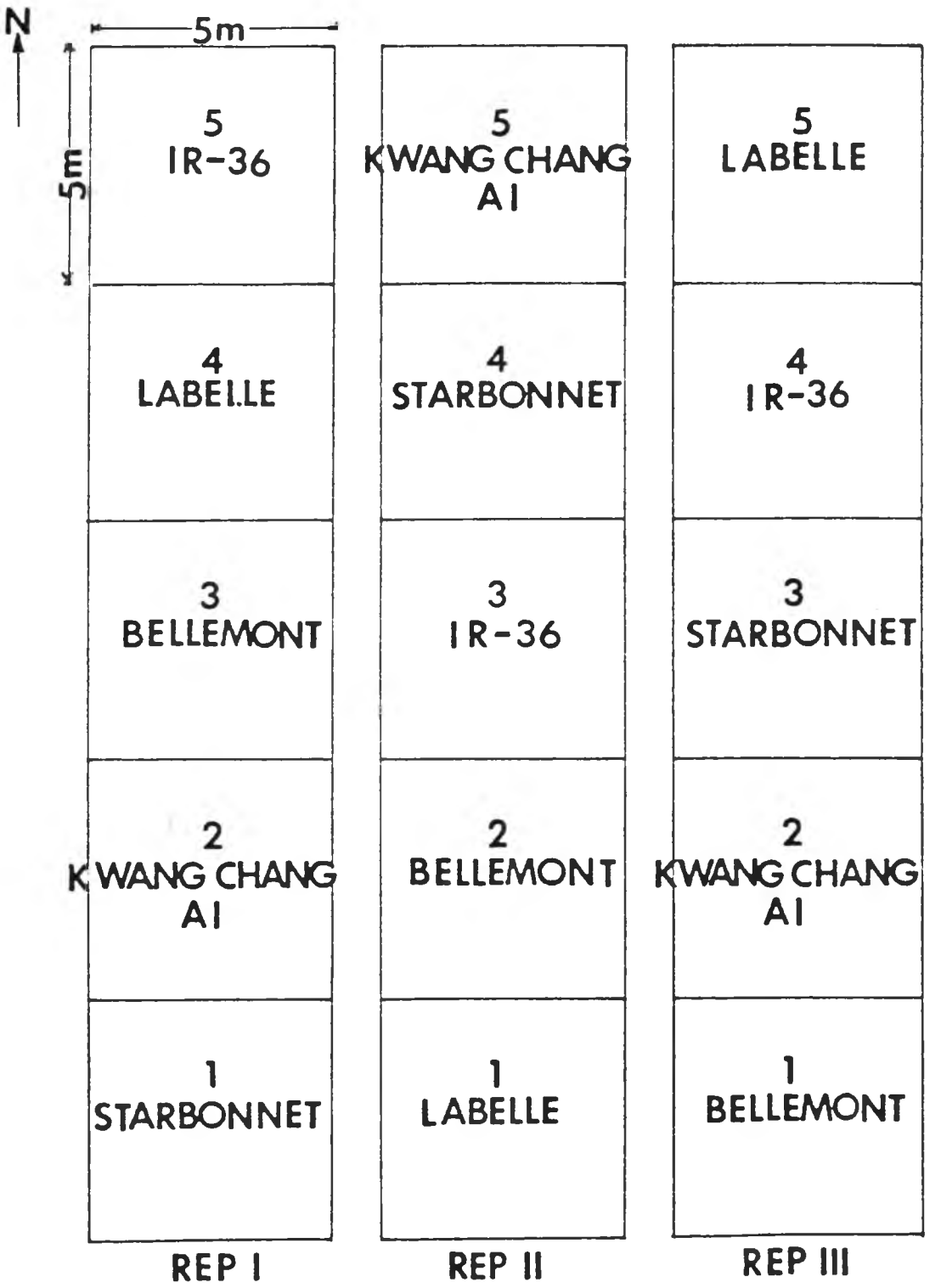

Figure 4.1 Field layout of the Wailua rice experiment

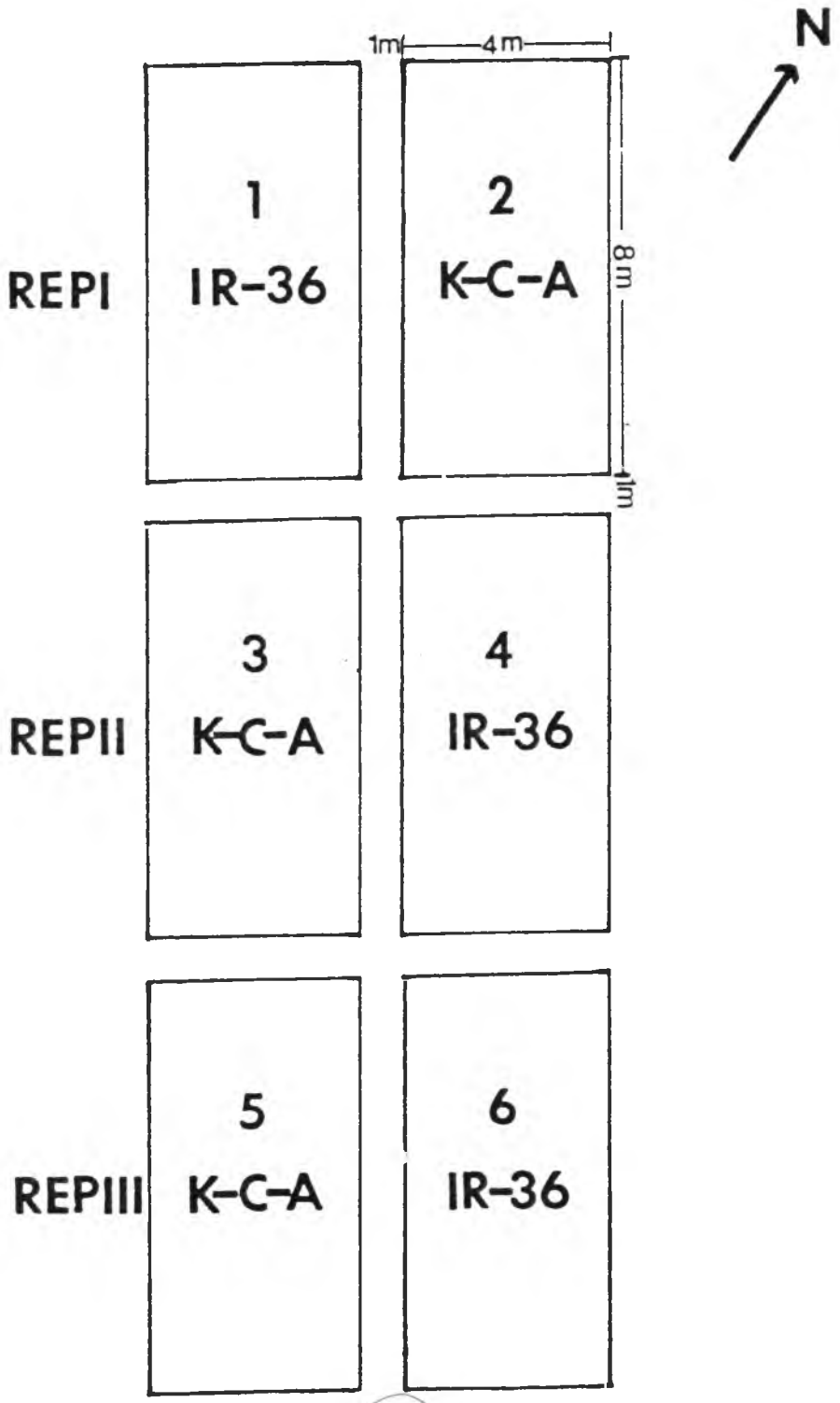

Figure 4.2 Field layout of Kauiaha rice experiment

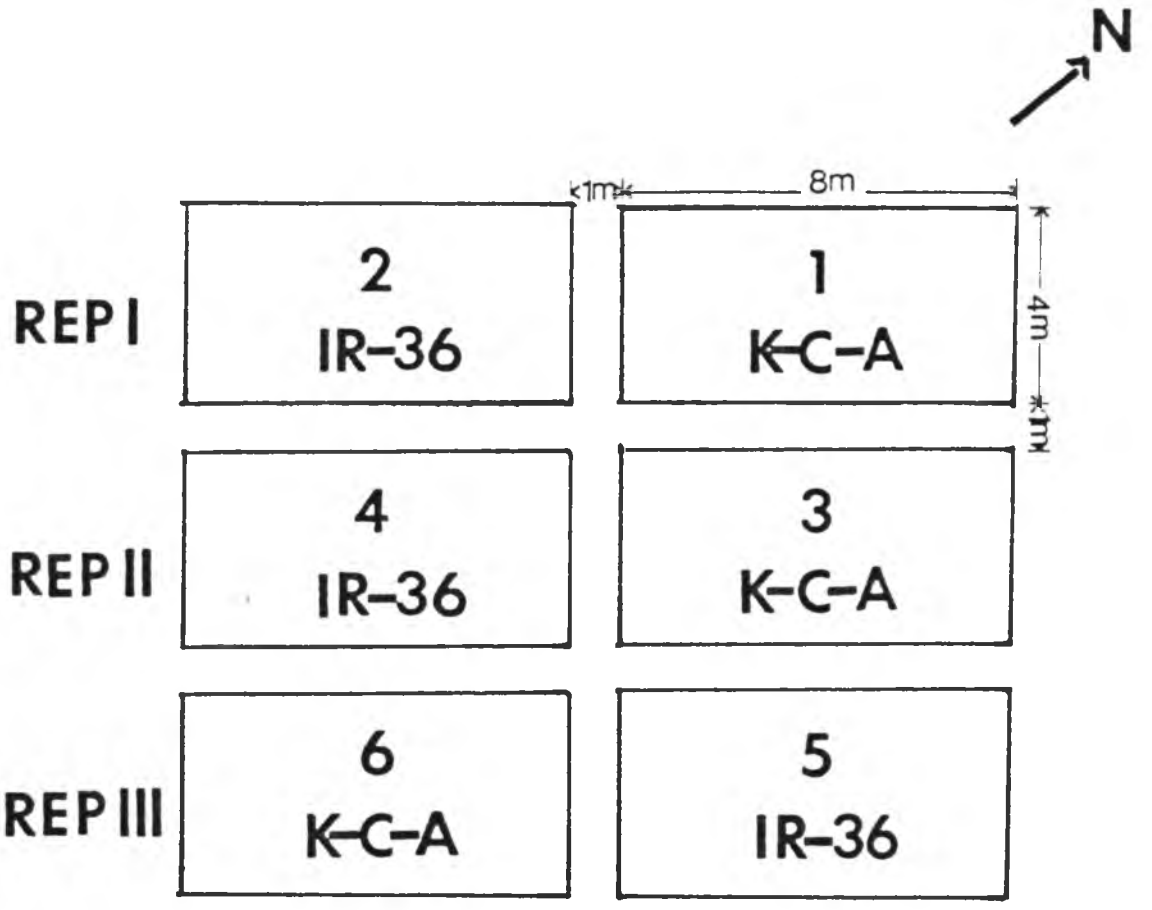

Figure 4.3 Field layout of the Haleakala rice experiment

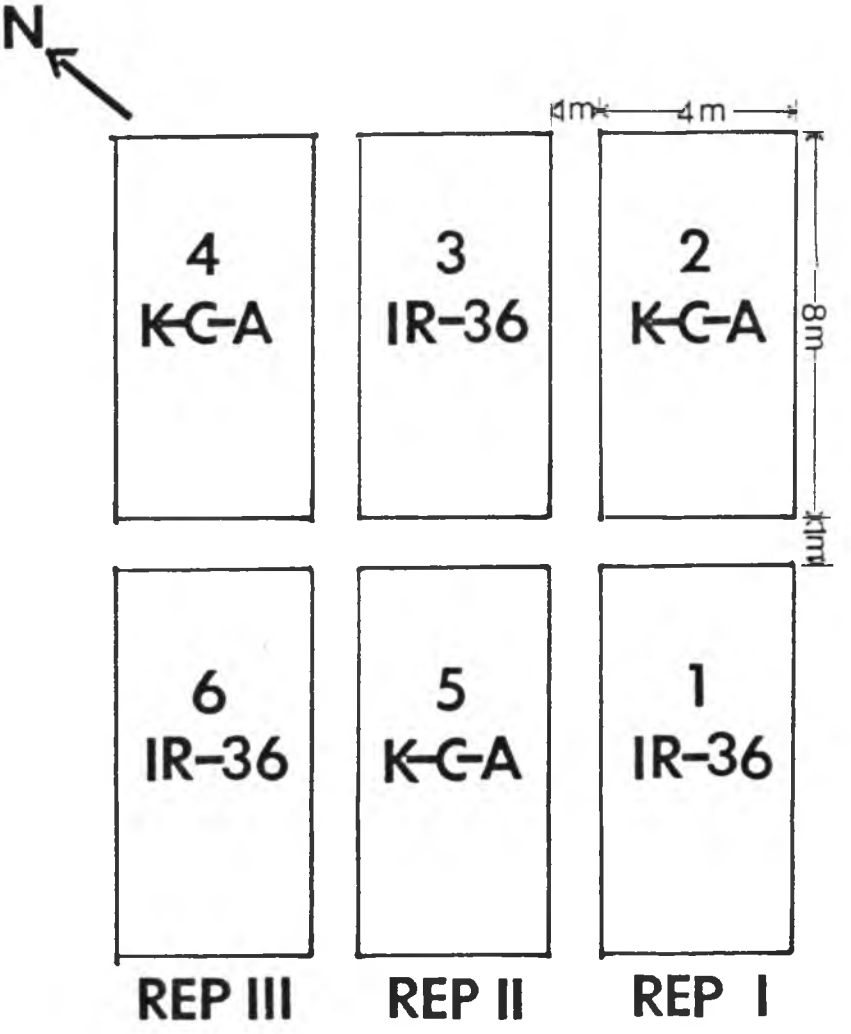

Figure 4.4 Field layout of the Olinda rice experiment

Table 4.2

Dates of fertilizer application

Sites	Fertilizer	Date*
Wailua 1985 (winter) planting	Basal application	09/04/85
	N top-dressing	09/22/85
	N top-dressing	10/22/85
Wailua 1986 (summer) planting	Basal application	06/09/86
	N top-dressing	06/24/86
	N top-dressing	07/23/86
Kuiaha	Basal application	04/17/86
	N top-dressing	05/16/86
	N top-dressing	07/03/86
Haleakala	Basal application	04/22/86
	N top-dressing	05/28/86
	N top-dressing	07/08/86
Olinda	Basal application	04/21/86
	N top-dressing	05/29/86
	N top-dressing	07/08/86

* month/day/year

Table 4.3

Planting information for each site

Site	Sowing date	Plant population (plants m^{-2})	Row spacing (m)	Sowing depth (cm)
Wailua 1985	09/05/85	25	0.20	2.5
Wailua 1986	06/10/86	25	0.20	2.5
Kuiaha	04/17/86	28	0.25	5.0
Haleakala	04/23/86	28	0.25	5.0
Olinda	04/21/86	28	0.25	5.0

4.2.3 IBSNAT/CERES Rice Model

The IBSNAT/CERES Rice Model, is one of several crop models being developed under the IBSNAT project. The model ultimately will estimate yields for rice grown under rainfed and irrigated condition. It is a relatively simple, user-oriented, yet comprehensive rice model that is designed to predict the growth and development of different varieties under any agroclimatic condition. It is programmed in FORTRAN 77 and designed to operate interactively in a microcomputer. The model operates on a daily time step and transforms input materials such as seeds, water, and fertilizers into grain and straw through the use of space, energy (solar, chemical and biological), and management practices, subject to environmental factors such as solar radiation, maximum and minimum air temperatures, precipitation, daylength and soil properties.

The model is able to simulate the following important processes;

a. phasic development or duration of growth stages as influenced by genotype and environmental factors;
b. biomass production and partitioning;
c. root systems dynamics; and
d. effect of soil water deficit and nitrogen deficiency on the photosynthesis and photosynthate partitioning in the plant systems.

The model assumes complete control of limiting factors such as weeds, insects, diseases and other management variables (phosphorus, potassium, liming, etc.). A general process diagram of the IBSNAT/CERES Rice Model is shown in Table 4.4 and the input data required for the IBSNAT/CERES Rice Model are given in Table 4.5. The formats of input files are described in IBSNAT Technical Report 5 (1986).

The main components of the IBSNAT/CERES Rice Model, consisting of phasic development, crop growth, water balance, and nitrogen dynamics are discussed in following sections.

A. Phasic development

Both genotype and environment influence the phasic development in the rice model. After seed germination, the developmental rate is controlled by temperature. The model assumes that the developmental rates are directly proportional to temperatures between 8 °C and 33 °C. When the maximum and minimum daily air temperatures are within this range, the thermal time for the day is calculated as the average between the maximum and minimum temperatures with a base temperature of 8 °C. The mean daily air temperature (TEMPM) and the daily thermal time (DTT) are computed using the relationship,

$$TEMPM = (TEMPMX + TEMPMN)/2$$

$$DTT = TEMPM - TBASE$$

where,

TEMPMX = maximum daily air temperature (°C)

TEMPMN = minimum daily air temperature (°C), and

TBASE = 8 °C

When the maximum and minimum temperatures are outside the linear range, thermal time is calculated using the relationship,

TTMP = TEMPMN+TMFAC(I)*(TEMPMX-TEMPMN)

where,

TTMP = 3-hours mean air temperature and

TMFAC(I) = eight 3-hourly correction factors for air temperature.

If TTMP is greater than 8 °C and less than or equal to 33 °C then

DTT = DTT + (TTMP - TBASE) / 8

If TTMP is greater than 33 °C and less than 42 °C then

DTT = DTT + (33-TBASE) * [1-(TTMP-33)/9]/8

Photoperiod controls the inductive stage of photoperiod-sensitive variety. A longer thermal time is required when the day length is longer than the optimum photoperiod. The coefficients associated with the thermal time (P1, P2R, P5, P2O) have been calculated from phytotron studies on some cultivars, and from field photoperiod observations (Vergara and Chang, 1976) for a large number of cultivars.

Table 4.4

General process diagram for the IBSNAT/CERES Rice Model[a]

INPUT	PROCESS	OUTPUT
CONTROLLABLE INPUTS		
variety seed	Plant growth	Grain yield
plant spacing	Phasic development	Yield components
date of sowing	Morphological development	Aboveground biomass
sowing depth	Soil water balance	Dates of phasic developmental changes
date & amount of irrigation	Soil nitrogen balance	Optimal output at user-selected frequency
date & amount of N fertilization	Plant nitrogen balance	Soil water balance components
type of fertilizer N		Soil N balance components
genetic coefficients		Root densities
type of residue		Indices of nitrogen & water stress
NONCONTROLLABLE INPUTS		
daily weather data		
day length		
soil properties & initial condition		

[a] Adapted from Ritchie et al. (1986).

Table 4.5

Input data needed for the IBSNAT/CERES Rice Model

LOCATION DATA

Latitude (deg)

CLIMATIC DATA

Daily solar radiation (MJ m^{-2} day^{-1})

Daily maximum temperature (^{o}C)

Daily minimum temperature (^{o}C)

Daily precipitation (mm)

MANAGEMENT DATA

Variety name

Planting date

Planting depth (cm)

Plant population (plants m^{-2})

Irrigation dates and amount (mm)

Fertilizer N: dates, amount (kg ha^{-1}), sources, and depth of incorporation (cm)

GENETIC COEFFICIENTS

P1 - thermal time required for the plant to develop from emergence to end of juvenile stage (^{o}C-day)

P2R - rate of photoinduction (days delay/hour increase in photoperiod)

Table 4.5 (continued) Input data needed for the IBSNAT/CERES Rice Model

---

GENETIC COEFFICIENTS

- P2O - optimum photoperiod (hr)
- P5 - thermal time for grain filling (^{o}C-day)
- G1 - conversion efficiency from sunlight to assimilates
- TR - tillering rate

SOIL DATA

- Number of layers
- Depth of layers (cm)
- Soil albedo
- Soil water by layer
  - Initial soil water content (cm^3 cm^{-3})
  - Saturated soil water content (cm^3 cm^{-3})
  - Drained upper limit of soil water (cm^3 cm^{-3})
  - Lower limit of extractable soil water (cm^3 cm^{-3})
  - Root preference factor (unitless, 0-1)

Table 4.5 (continued) Input data needed for the IBSNAT/CERES Rice Model

SOIL DATA
Runoff curve number
Upper limit of stage 1 soil evaporation (mm)
Profile drainage rate constant (1 day^{-1})
Soil Nitrogen by layer
Initial NO_3^- and NH_4^+ content (mg kg^{-1})
Organic carbon (%)
Bulk density (g cm^{-3})
pH
C:N in roots and in straw
Amount of straw incorporated (kg ha^{-1}) and depth of incorporation (cm)
Temperature amplitude for the growing period (^{o}C)
Mean temperature for the growing period (^{o}C)
N mineralization factor, DMOD
OTHER INFORMATION
Title of the data
Switch settings to initiate:
Soil water balance (ISWSWB)
Nitrogen model (ISWNIT)

The growth stages in the model are numbered as described in Table 4.6. The active aboveground growing stages are numbered 1 through 5. Stages 6 through 9 are used to describe other events occurring in the crop cycle.

Table 4.6

Phenological stages of IBSNAT/CERES Rice Model[a]

Growth Stage	Event	Growing Plant Parts
1	Juvenile Stage	Roots, Leaves
2	Floral Induction	Roots, Leaves, Stems
3	End of Leaf Growth	Roots, Leaves, Stems, Panicle
4	Anthesis and Flowering	Roots, Stems, Panicle
5	Grain Filling	Grain
6	Physiological Maturity to Harvest	
7	Fallow or Presowing	
8	Sowing to Germination	
9	Germination to Emergence	Roots, Coleoptile

[a] Adapted from Ritchie et al. (1986).

Details of growth stages

Stage 7: Presowing

This stage in the model is used to write the sowing date and other information. It then sets a day counter (NDAS) to zero, and determines the soil layer (L0) in which the seed is sown.

Stage 8: Sowing to germination

During this stage the model determines whether the soil water content in the soil layer is sufficient to allow seed germination.

SWSD=[SW(L0)-LL(L0)]*0.65+[SW(L0+1)-LL(L0+1)]*0.35

where SWSD = extractable soil water at the seeding depth ($cm^3\ cm^{-3}$)

SW(L0) = soil water content in the soil layer L0 ($cm^3\ cm^{-3}$)

LL(L0) = lower limit of plant-extractable soil water content in the soil layer L0 ($cm^3\ cm^{-3}$)

The seeds will germinate only when the soil water content of the layer in which the seed was sown is greater than the lower limit of plant-extractable soil water content.

The temperature range for germination is 16 ^{o} to 42 ^{o}C. Seed germination requires 45 degree-days for a base temperature of 8 ^{o}C.

Stage 9: Germination to seedling emergence

Before seedling emergence, root depth (RTDEP, cm) increases daily as a function of growing thermal time (DTT).

RTDEP = RTDEP + 0.15 * DTT

Seedling emergence is influenced by temperature and the depth of sowing. It occurs when the growing degree days summation variable (SUMDTT) reach P9. The magnitude of P9 is determined by the following equation:

P9 = 7.0 * SDEPTH

where SDEPTH = sowing depth (cm).

Stage 1: Seedling emergence to end of juvenile stage

Plants grow vegetatively during this stage and produce roots, leaves and tillers. Plants are not sensitive to photoperiod during this period and developmental rate is controlled primarily by temperature. The duration of this period is determined by a genetic coefficient P1 through the relationship

XSTAGE = SUMDTT/P1

where XSTAGE is 0.0 at emergence and 1.0 at the end of the juvenile stage. The juvenile stage ends when the cumulative thermal time equals the value the genetic coefficient P1.

Stage 2: End of juvenile stage to panicle initiation

The duration of this stage is photoperiod dependent. Plants still grow vegetatively. The gorwth (XSTAGE) is 1.0 at the begining of this stage and is 1.5 at the end . It is calculated from the temporary variable SIND (0-1).

XSTAGE = 1.0 + 0.5 * SIND

In the model, rate of floral induction (RATEIN) is calculated from the day length (HRLT) and genetics coefficients.

RATEIN = 1/136

If day length is longer than optimum photoperiod (P2O), then

RATEIN = 1/[136 + P2R * (HRLT - P2O)]

RATEIN is summed daily with the temporary variable SIND.

SIND = SIND + RATEIN * DTT

When SIND reaches 1.0, stage 2 is completed.

Stage 3: Panicle initiation to end of leaf growth and heading

Duration of this stage is from panicle initiation to the flag leaf expansion and is controlled by temperature. This stage is calculated from P3 and SUMDTT.

XSTAGE = 1.5 + 3.0 * SUMDTT/P3

P3 = 450 + 0.15 * SUMDTT

This stage varies from 1.5 at the begining to 4.5 at its end.

Stage 4: End of leaf growth to begining grain filling

During this stage, the anthesis is occurring, the panicles flower begining at the top, middle and lower thirds. Then the florets open and self-pollinated. Duration of this stage calculated from the genetic coefficient P5 and SUMDTT

XSTAGE = 4.5 + 1.5 * SUMDTT/(P5 * 0.95)

This stage ends when SUMDTT equals or exceeds 170 ^{o}C.

Stage 5: Effective grain filling to physiological maturity

During this stage, grains are rapidly growing from milk grains, dough grains to mature grains. Thermal time for completion of this stage is determined by genetic coefficient P5.

XSTAGE = 6.0 + 4.0 * SUMDTT/P5

The stage ends when SUMDTT equals or exceeds 0.95*P5.

Stage 6: Physiological maturity to harvest

Physiological maturity occurs when SUMDTT equals or exceeds P5.

SUMDTT = P5

B. Crop growth

Plant photosynthetic rate is significantly influenced by incident solar radiation, leaf area, and leaf canopy structure. As in many models the IBSNAT/CERES Rice Model

employs Beer's low to quantify light absorption by the plant canopy according to the relationship,

$$I/I_o = \exp(-K * LAI)$$

where I_o = light intensity incident on the leaf canopy;

I = light intensity in the plant canopy;

LAI = average total leaf area per unit of ground area; and

K = foliar absorption coefficient (dimensionless).

K is related to LAI, if LAI is less than 0.6 then

$$K = \exp(-LAI)$$

if LAI is in the range of 0.6 to 5 then

$$K = 0.58 - 0.04 * LAI$$

if LAI is greater than 5 then K = 0.36.

The photosynthetic rate is expressed as a function of photosynthetically active radiation (PAR) as in the CERES-Maize (Jones and Kiniry 1986) and CERES-Wheat models (Ritchie and Otter 1985). The value of PAR above the canopy is assumed to be a function of the incoming solar radiation.

$$PAR = 0.02092 * SOLRAD$$

Thus, mathematically, photosynthesis is expressed in the model as follows:

$$PCARB = G1 * PAR * (1 - I/I_o)$$

where PCARB = potential dry matter production, (gm^{-2} day^{-1})

PAR = photosynthetically active solar radiation, ($MJ\ m^{-2}\ day^{-1}$)

G1 = conversion factor of PAR to dry matter in grams per MJ of intercepted PAR.

The actual rate of dry matter production (CARBO) is usually less than the potential rate due to the environmental effects of non-optimal temperature, water stress or nitrogen deficiency. That is,

CARBO = PCARB*PRFT*AMIN1(SWDF1,NDEF1)

where PRFT = 0-1 stress value calculated from minimum and maximum daily air temperatures, with optimum value at 26 ^{o}C,

SWDF1 = 0-1 stress value due to water deficit, derived from a ratio of the total potential daily root water uptake and transpiration,

NDEF1 = 0-1 stress value due to nitrogen deficiency which is a function of the critical, actual and minimum N concentration of the stover (non-grain shoot).

Partition of the assimilate follows the "partition rules table" used in RICEMOD (McMennamy and O'Toole 1983) where the assimilates are partitioned among the growing parts in each stage. A complete computer program for the growth subroutine is presented in Appendix B. In the

IBSNAT/CERES Rice Model, when water stress and/or nitrogen deficiency occurs, partitioning to the top decreases in favor of the roots.

The proportion partitioned to the roots affects root density and consequently the capacity of the roots to supply water and nutrients to the shoot. The fraction of assimilates partitioned to the roots also depends on the growth stage of the crop and declines as the plant matures. However, at all growth stages except stage 5, the fraction partitioned to the roots increases with water deficits and/or nitrogen deficiency. The potential rate of downward root growth is assumed to be proportional to the rate of plant development which is influenced by temperature. The water content in each soil layer is used to determine the distribution of root growth in the profile. The preference factor for a layer is reduced when the soil water content is below a threshold value. Thus, when a particular soil layer becomes dry, root growth in that layer decreases and compensatory root growth occurs elsewhere in the profile where the water status is more favorable.

According to Yoshida (1981), the 1,000-grain weight of rice crops is a very stable varietal character. In the IBSNAT/CERES Rice Model, grain weight is the product of the grain filling rate times the grain filling duration. Grain filling rate varies among varieties and grain yield is

directly proportional to the panicles wieght. Thus the rate and duration of panicle growth, as influenced by the environment and plant size, control yield.

C. Soil water balance

The soil water balance calculates yield reduction caused by soil and plant water deficits. It can be by-passed if the soil water is assumed to be nonlimiting. The water balance component of the IBSNAT/CERES Rice Model has two principle functions; (1) to calculate redistribution and drainage of water during and after precipitation or irrigation, and (2) to calculate soil evaporation and plant transpiration. Singh (1985) presented the complete computer program for the model. The model evaluates soil water balance as:

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

Soil water (SW) can increase due to precipitation (RAIN) or irrigation (AIRR) and soil water content can decrease due to soil evaporation (ES), plant transpiration (EP), runoff (RUNOFF), and drainage (DRAIN). The field-drained upper limit (DUL), and the field-saturated water content (SAT) for each layer are the limits to which water content can decrease or increase.

D. Nitrogen model

In most soils much of the nitrogen is in the organic form, and only a small fraction occurs in the inorganic form. Depending on the type of organic matter transformation, organic nitrogen is mineralized into ammonia, or inorganic nitrogen is immobilized into organic nitrogen. The inorganic soil nitrogen is mainly present in the form of nitrate and ammonia. Ammonia may be transformed to nitrate-N by nitrification, and nitrate-N may be transformed into volatile nitrogen compounds. These microbial processes are influenced by temperature, moisture, pH and soil aeration. Because the turnover rate of the organic, ammonium, nitrate and elemental forms of nitrogen is very high and the influence of temperature and precipitation is considerable, it is virtually impossible to measure the inorganic nitrogen available to plants at any moment during the growing season on the basis of chemical and physical experiments (Beek and Frissel, 1973).

As with the soil water balance, the nitrogen component in the IBSNAT/CERES Rice Model can also be by-passed when nitrogen fertility is nonlimiting. When in use, the submodel simulates changes in nitrate and ammonium soil levels on a layer-by-layer basis. The major nitrogen transformations simulated by the model are

environmentally driven and thus have the potential to work in any location (Godwin, et al., 1984).

Included in the nitrogen subroutine is the initialization of soil N conditions and fertilizer management, as well as the transformation processes for humus and organic nitrogen into N forms usable by the plant. The process involves the mineralization of organic nitrogen and immobilization of mineral nitrogen produced from organic matter decomposition; nitrification of ammonium and denitrification. The nitrogen subroutine also calculates the demand for N by the crop, the supply of N available to the crop, and the N uptake by the crop. Singh (1985) presented the complete computer program for the nitrogen subroutine. Some important equations are described in the following section.

Soil nitrogen initialization

The model assumes uniform incorporation of straw to a given depth. Roots from the previous crop are distributed among soil layer according to the function,

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

Where WRN(I)=N contained in the root residues (kg N ha^{-1})

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

DEPMX=depth of the soil profile (cm)

The stable organic matter in a layer HUM(I), is composed of all other organic matter and is computed as:

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

Where OC(I) = organic carbon content (%)

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

DLAYER(I) = depth of layer (I).

The amount of nitrogen in the stable organic matter pool, NHUM(I) (kg ha^{-1}) is calculated by subtracting mineral nitrogen from total soil nitrogen from the expression

$$NHUM(I)=OC(I)/10*DLAYER(I)*BD(I)*1000-[SNO3(I)+SNH4(I)]$$

where SNO3(I) AND SNH4(I) are soil nitrate and ammonium levels in kg N ha^{-1}, respectively.

Mineralization and immobilization of N

The processes of N mineralization and immobilization are based on the mineralization immobilization routine in PAPRAN (Seligman and van Keulen, 1981). If fertilizer was applied on the current day, then fertilizer nitrogen is apportioned into nitrate and ammonium fractions. The model assumes instantaneous transformation of fertilizer materials into the appropriate pools. The fraction of fresh organic nitrogen FON(I), or fresh organic matter FOM(I), mineralized in a given day, DECR(I), is given by the equation

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

where,

RDECR = a rate constant which is a function of the FOM(I)/IFOM(I) ratio,

TFAC = a temperature factor, and

MF = a moisture factor.

If FOM(I)/IFOM(I) ratio is greater than 0.8,

RDECR = RDCARB.

If ratio is less than or equal to 0.8 and greater than 0.1,

RDECR = RDCELL.

Else

RDECR = RDLIGN.

Where,

RDCARB = rate constant for decomposition of carbohydrate-like fraction of the residue ($1\ day^{-1}$),

RDCELL = rate constant for decomposition of cellulose-like fraction of the residue ($1\ day^{-1}$),

RDLIGN = rate constant for decomposition of lignin-like fraction of the rssidue ($1\ day^{-1}$),

The fraction of FON(I) mineralized depends upon C:N ratio factor(CNRF). The gross amount of nitrogen which is released (GRNOM) due to mineralization of FON(I) is

GRNOM = DECR(I) * FON(I)

The rate of mineralization of nitrogen from stable organic matter (RHMIN) is computed from the equation

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

where DMINR is a soil-dependent rate constant and NHUM(I) is the amount of nitrogen in the stable organic matter.

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

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

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

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

Nitrification

Nitrification is computed immediately after mineralization and immobilization are calculated. The actual nitrification rate RNTRF(L) is calculated using a Michaelis-Menten Kinetic-type equation (Barber,and Cushmam 1981),

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

in which the A value used in the calculation is a function of the minimum of water factor, temperature factor and the nitrification capacity index.

Crop nitrogen uptake

The above-ground nitrogen demand TNDEM ($g\ N\ plant^{-1}$) is calculated as follows:

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

Where STOVWT = stover dry weight ($g\ plant^{-1}$),

TCN = 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 nitrogen demand of tops therefore depends on two factors: (1) the demand due to difference between TANC and TCNP which can be either positive or negative, and (2) the demand for nitrogen of the potential new growth.

A zero to one nitrogen factor, NFAC, is calculated:

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

This provides an index of nitrogen deficiency in the plant. When the actual above ground nitrogen 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.

4.2.4 Calibration and valiation of IBSNAT/CERES Rice Model

The IBSNAT/CERES Rice Model was calibrated with the growth and development data collected from two crops with five varieties conducted at the Wailua experimental field, on Kauai. This process involved changing the input data and then executing the model. Some coefficients in the model were adjusted untill reasonable agreement between observed and simulated results were obtained. Once the model was calibrated, the data collected from Kuiaha, Haleakala, and Olinda rice experiments on Maui Island were used to validate the calibrated IBSNAT/CERES Rice Model.

4.3 Results and Discussion

4.3.1 Effect of planting season on growth and development of five rice varieties

The final harvests of five rice varieties grown on two different season on the same field are shown in Table 4.7. Planting date had a highly significant effect on grain yield. Mean separations of the grain yields using Duncan's multiple range test show that there were significant difference between the means of grain yield, straw weight, total biomass and grain to straw ratio for two crops under upland and lowland conditions at 5% level. However, the means of yield among the five varieties are only significantly different under upland condition and are not significantly different for the lowland condition. The major causes of yield difference between the two crops were differences in temperature and solar radiation.

Rice yield is determined by four major components; (1) number of panicles per unit area, (2) number of spikelets per panicle, (3) the percentage of filled grain, and (4) 1000-grain weight. These components which develop during different stages of crop growth are affected by temperature and solar radiation in different ways. The heading stage is most sensitive to low temperature. When the rice plant is subjected to low temperature for several days during heading stage , high spikelet sterility will occur.

Table 4.7

Final harvest of five rice varieties planted in Wailua, Kauai

Variety	Year	Grain yield (g m-2)		Straw weight (g m-2)		Total Above Biomass (g m-2)		Grain straw Ratio	
		Upland	Lowland	Upland	Lowland	Upland	Lowland	Upland	Lowland
Bellemont	1985	351.3	301.3	568.8	794.4	920.1	1098.7	0.6	0.4
	1986	360.0	835.9	471.9	728.0	832.0	1563.9	0.8	1.2
Labelle	1985	174.2	128.9	743.3	995.9	917.4	1124.8	0.2	0.1
	1986	315.3	1048.7	532.2	1389.2	847.5	2438.0	0.6	0.8
IR-36	1985	325.5	159.5	1073.8	1269.9	1399.4	1429.5	0.3	0.1
	1986	546.6	1006.3	635.2	1111.2	1181.8	2117.5	0.9	0.9
K-C-A	1985	496.3	306.8	904.8	892.6	1401.1	1199.4	0.6	0.3
	1986	667.0	1351.9	693.4	1312.7	1360.4	2664.6	1.0	1.0
Starbonnet	1985	11.5	11.4	1530.9	1975.1	1542.4	1986.5	0.0	0.0
	1986	227.2	1070.4	721.5	1301.5	948.7	2371.9	0.3	0.8

The heading stage of the 1985 planting was occurred during December resulting in a high percentages of unfilled grain (Table 4.8 and 4.9). On the other hand, the heading stage of 1986 planting occurred in August and sterility from cool temperature was avoided. This was one of the principal reasons for the yield difference between two crops.

The number of panicles at harvesting time for the two crops are shown in Table 4.10. The results indicate that the number of panicles for the 1986 planting were less than those for the 1985 planting, except the Labelle variety, for both upland and lowland conditions. The lower panicle number of the 1986 crop was the result of a shortened panicle formation period cause by higher temperatures during the reproductive stage. Although the panicle number decreased, the yield increased. Most of panicles for the 1986 crop were mature at harvesting time.

Solar radiation is the other factor which affects grain weight and filled grain percentage. The 1985 crop was planted during the wet season, whereas the 1986 crop was planted during the dry season. The solar radiation was higher during 1986 planting than the 1985 planting. Higher solar radiation resulted in higher 1000-grain weight and higher yield (Table 4.11).

Table 4.8

Grain weight per plant of five rice varieties

Variety	Grain Weight per plant (gm)							
	Filled				Unfilled			
	Upland		Lowland		Upland		Lowland	
	1985	1986	1985	1986	1985	1986	1985	1986
Bellemont	15.24	25.49	14.77	47.56	1.29	1.56	2.32	3.05
Labelle	5.83	22.99	5.50	57.50	1.91	1.37	2.42	6.17
IR-36	18.65	29.40	8.43	51.45	4.32	2.19	2.60	7.03
K-C-A	23.61	29.44	14.31	48.60	2.02	2.14	2.11	3.89
Starbonnet	0.53	18.34	0.51	46.23	2.63	0.85	1.27	6.16

Table 4.9

Percentage of filled grain per plant of five rice varieties

Variety	Upland		Lowland	
	1985	1986	1985	1986
	----------	%	----------	
Bellemont	92.2	94.3	86.5	94.0
Labelle	75.4	94.4	69.5	90.3
IR-36	81.2	93.1	76.4	88.0
K-C-A	92.1	93.2	87.2	92.6
Starbonnet	16.6	95.6	28.8	88.3

Table 4.10

Panicle number per plant of five rice varieties at harvesting time

Variety	Panicle Numbers Per Plant			
	Upland		Lowland	
	1985	1986	1985	1986
Bellemont	10.0	8.3	15.6	13.5
Labelle	7.6	11.0	15.3	16.7
IR-36	35.5	22.7	43.7	27.5
K-C-A	26.8	15.8	25.5	18.0
Starbonnet	13.3	10.5	18.0	15.5

Table 4.11

1,000 grains weight of five rice varieties

Variety	1,000 Grains Weight (g)			
	Upland		Lowland	
	1985	1986	1985	1986
Bellemont	20.775	20.896	19.484	21.306
Labelle	18.426	18.448	16.392	18.549
IR-36	18.591	20.570	19.124	21.121
K-C-A	22.492	24.048	19.973	23.855
Starbonnet	18.312	19.067	17.861	18.856

The maximum leaf area index (LAI) was obtained at heading stage for all varieties (Table 4.12). There was no significant difference in LAI between the two crops. However, there was a significant difference between crops planted to upland and lowland condition.

In general, the yield of lowland land rice was higher than upland rice. However, in the 1985 planting, the lowland rice yield was lower. This low yield can be attributed to low water temperature during the reproductive stage.

The above results were used to calibrate the IBSNAT/CERES Rice Model in a manner described in the following sections.

Table 4.12

Maximum LAI at heading stage of two crops grown in Wailua, Kauai

Variety	Upland		Lowland	
	1985	1986	1985	1986
Bellemont	2.50	3.16	6.11	6.75
Labelle	3.76	2.43	6.16	9.32
IR-36	6.78	7.39	8.08	10.79
K-C-A	6.89	6.89	10.22	12.86
Starbonnet	6.62	5.02	8.98	9.72

4.3.2 Model calibration

Rice genotypes

The genotype specific coefficients (P1, P2R, P2O, and P5) were adjusted until reasonable agreement between simulated and observed dates of panicle initiation, heading and physiological maturity were obtained. As expected the five rice varieties have different genetic coefficients (Table 4.13).

The conversion efficiency of sunlight to produce assimilates (G1) and to control tillering rate (TR) were adjusted until there was reasonable agreement between the measured and predicted values. The highest value of G1 for variety K-C-A corresponds to this variety's high observed yields. The highest value of TR for IR-36 also reflects the high tiller number for this variety.

Rice growth

The measured values of growth and yield components were different for the two planting dates. The 1985 yield was very low and attributable to some bird damages and cold weather. If it is assumed that there were no nutrient deficiency and water stress under the upland condition, the 1986 yields for the upland and lowland rice should have been similar. A comparison of nitrogen concentration of the 1986 rice plants for the upland and lowland conditions

is shown in Table 4.14. The results indicate that the nitrogen concentrations of the lowland rice plants were higher than in the upland. Based on these results, the yield difference between the upland and lowland plantings was attributed to nutrient deficiency and water stress in the upland rice. For this reason the data from the 1986 lowland experiment were used to calibrate the growth subroutine of IBSNAT/CERES Rice Model.

From the growth chamber experiment described in Chapter III it was found that the optimum temperature for grain filling was 22.5 ^{o}C. Based on this information the critical temperatures for the model were changed from 17 and 35 ^{o}C to 22 and 33 ^{o}C (lines 3410-3440)* for the grain filling stage. In addition the critical low temperature for the heading stage was increased from 21 to 22 ^{o}C (lines 3090-3110) to improve agreement between observed and simulated results. Finally, the grain filling rate (GRN) was change from 0.000083 gDTT^{-1} to 0.000063 gDTT^{-1} (line 0460) and panicle growth rate was changed from 0.00095 gDTT^{-1} to 0.00115 gDTT^{-1} (line 0450). Prior to the above changes the model overpredicted the 1000-grain weight and panicle number.

---

* Reference to the line numbers in the program listing (Appendix B)

Table 4.13

Comparison of calibrated genetic coefficients of five rice varieties grown under upland condition

Genetic coefficient		Bellemont	Labelle	IR-36	K-C-A	Starbonnet
P1	A	520	508	600	550	840
	B	-	318	550	-	880
P2R	A	50	50	100	80	50
	B	-	189	149	-	164
P2O	A	12.8	12.8	11.7	11.7	13.0
	B	-	12.8	11.7	-	13.0
P5	A	550	550	550	490	550
	B	-	550	550	-	550
G1	A	3.65	4.05	4.00	4.50	3.80
	B	-	2.00	2.70	-	2.00
TR	A	0.60	0.60	0.64	0.64	0.60
	B	-	0.60	0.66	-	0.60

A = After calibration

B = Before calibration

Table 4.14

Nitrogen concentration of rice components during the 1986 planting in Wailua site

DAP	Nitrogen concentration (%)					
	Leaf		Stem		Grain	
	Upland	Lowand	Upland	Lowand	Upland	Lowand
			Bellemont			
29	4.09	-	1.85	-	-	-
43	3.52	4.84	1.48	2.28	-	-
63	2.92	3.81	1.06	1.62	-	-
79	2.36	3.43	0.54	1.10	1.17	-
99	0.78	2.75	0.38	0.76	1.14	1.15
115	-	1.35	-	0.62	-	1.13
			IR-36			
29	4.69	-	2.36	-	-	-
43	-	4.92	-	2.34	-	-
63	2.60	3.92	1.01	2.07	-	-
79	2.20	-	0.60	-	1.03	-
99	-	2.65	-	0.82	-	1.18
105	0.42	-	0.51	-	1.08	-
129	-	1.20	-	0.71	-	1.36
			K-C-A			
29	4.12	-	2.12	-	-	-
43	-	5.13	-	2.27	-	-
63	2.40	3.58	0.95	1.52	-	-
79	2.33	3.20	0.60	1.22	1.00	-
99	-	2.66	-	0.69	-	1.26
108	0.59	-	0.17	-	1.18	-
115	-	1.21	-	0.47	-	1.15
			Labelle			
29	3.73	-	1.95	-	-	-
43	3.19	5.02	1.38	2.51	-	-
63	2.28	3.79	0.84	1.68	-	-
79	1.72	3.30	0.52	1.30	1.05	1.23
99	0.82	2.33	0.37	0.63	1.20	1.22
115	-	1.32	-	0.65	-	1.31
			Starbonnet			
29	4.17	-	2.23	-	-	-
43	-	5.26	-	2.59	-	-
63	2.41	3.67	1.00	1.89	-	-
79	2.11	2.98	0.62	1.12	-	-
99	-	2.33	-	0.71	-	1.11
115	0.60	-	0.39	-	1.07	-
129	-	1.28	-	0.51	-	1.28

4.3.3. Prediction rice performance of Wailua rice experiments

The calibrated model was used to simulate rice performance at Wailua, Kauai. The observed and simulated dates of phenological events for the upland condition are presented in Appendex C. IR-36 and K-C-A took much longer to reach panicle initiation during the 1986 planting. This is because IR-36 and K-C-A are photoperiod-sensitive varieties and require more time to accumulate the heat units for panicle initiation during summer than in winter or fall. The duration of grain filling was longer for the 1985 planting due to the lower temperature during the grain filling stage. In general, the results tend to indicate that the phenology component of IBSNAT/CERES Rice Model can be calibrated for the Wailua data (Figure 4.5 and 4.6). However, the model is not designed to account for the delay caused by transplanting under lowland management. The phenological events of lowland rice were delayed by about 2 to 10 days for both crops and varied with the vraiety (Table 4.15).

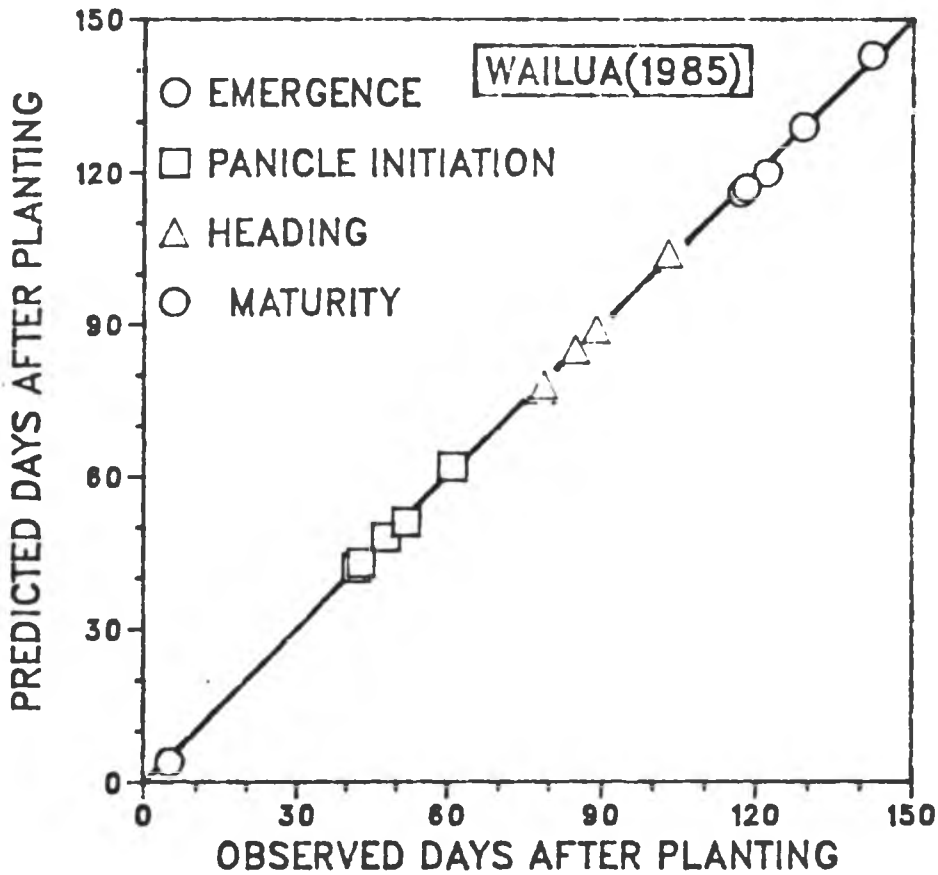

Figure 4.5 Comparison of observed phenological events of five rice varieties with simulated results obtained with calibrated model

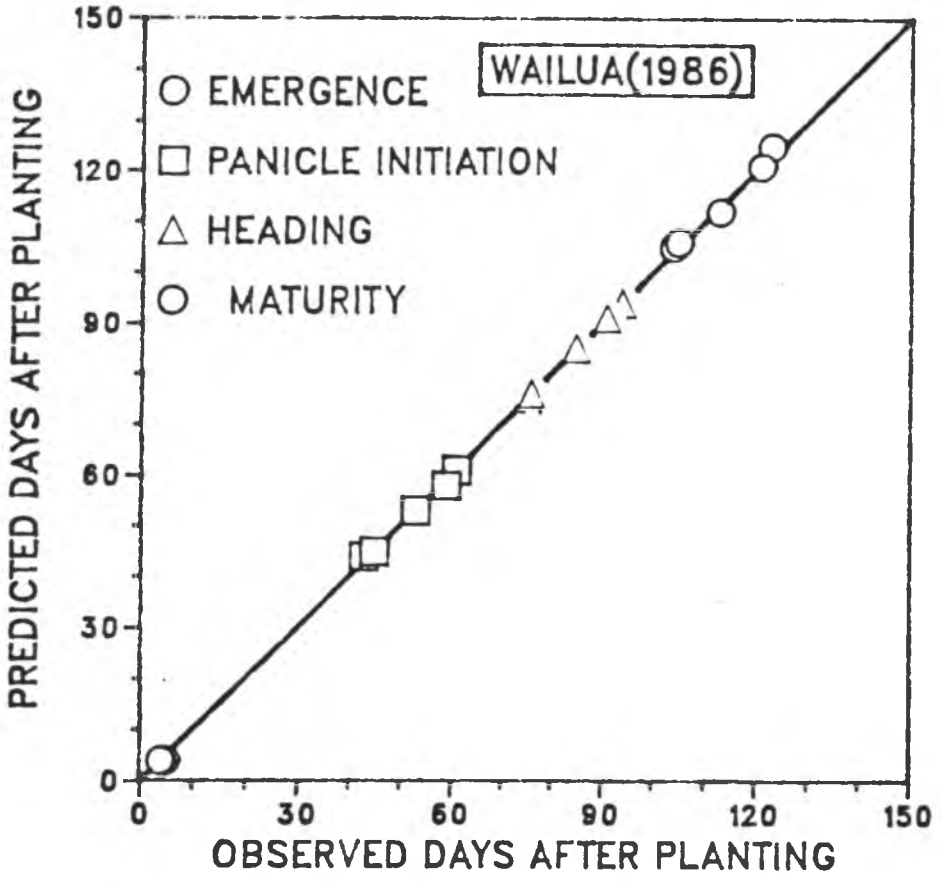

Figure 4.6 Comparison of observed phenological events of five rice varieties with simulated results obtained with calibrated model

Table 4.15

Observed phenological events of lowland rice in Wailua, Kauai

Variety	Transplanting	Days After Planting: Panicle Initiation	Heading	Physiological maturity
		Wailua (1985 winter)		
Bellemont	20	52	85	-
IR-36	20	54	94	-
K-C-A	20	50	90	-
Labelle	20	51	88	-
Starbonnet	20	69	105	-
		Wailua (1986 summer)		
Bellemont	14	54	85	115
IR-36	14	61	93	126
K-C-A	14	53	88	119
Labelle	14	51	81	113
Starbonnet	14	67	96	132

Comparison of measured and simulated growth components

Leaf area was determined five times for each variety during the course of the experiment. As expected the maximum leaf area index (LAI) was obtained near the heading stage for all varieties. The measured and simulated LAI are shown in Table 4.16. LAI predictions were overestimated during the vegetative stage and later stages of crop growth for all varieties. However the model predicts LAI at heading stage within 10% of the measured values for short duration varieties e.g. Bellemont and Labelle (Figure 4.7 and 4.8).

Comparisons of measured and simulated above ground biomass are presented in Table 4.17. The model overestimated the above ground biomass during the early stage of plant growth. However, the simulated values at harvest time were within 15% of the measured values. Considering the plant to plant variability in the field, the model predictions seem acceptable.

Comparisons of measured and simulated leaf and stem weights are shown in Table 4.18 and Table 4.19. The results indicate that there are still problems with biomass partitioning in the model.

Table 4.16

Comparison of measured and simulated leaf area indices for the 1986 lowland planting

Days After Planting	Leaf Area Index	
	Measured	Simulated
	Belloment	
43	0.40	2.33
63	3.70	6.14
79	6.80	6.29
99	6.70	5.54
106	4.00	5.00
	Labelle	
43	0.40	3.80
63	3.20	8.84
79	9.30	8.58
99	6.30	7.51
105	4.00	7.20
	IR-36	
43	1.13	4.42
63	6.54	10.77
99	10.79	11.95
121	6.00	10.83
	K-C-A	
43	1.51	6.45
63	6.06	14.21
79	12.90	15.03
99	9.60	14.53
112	5.00	13.80
	Starbonnet	
43	0.40	3.04
63	3.50	10.21
79	9.70	13.74
99	7.30	14.11
125	4.00	12.90

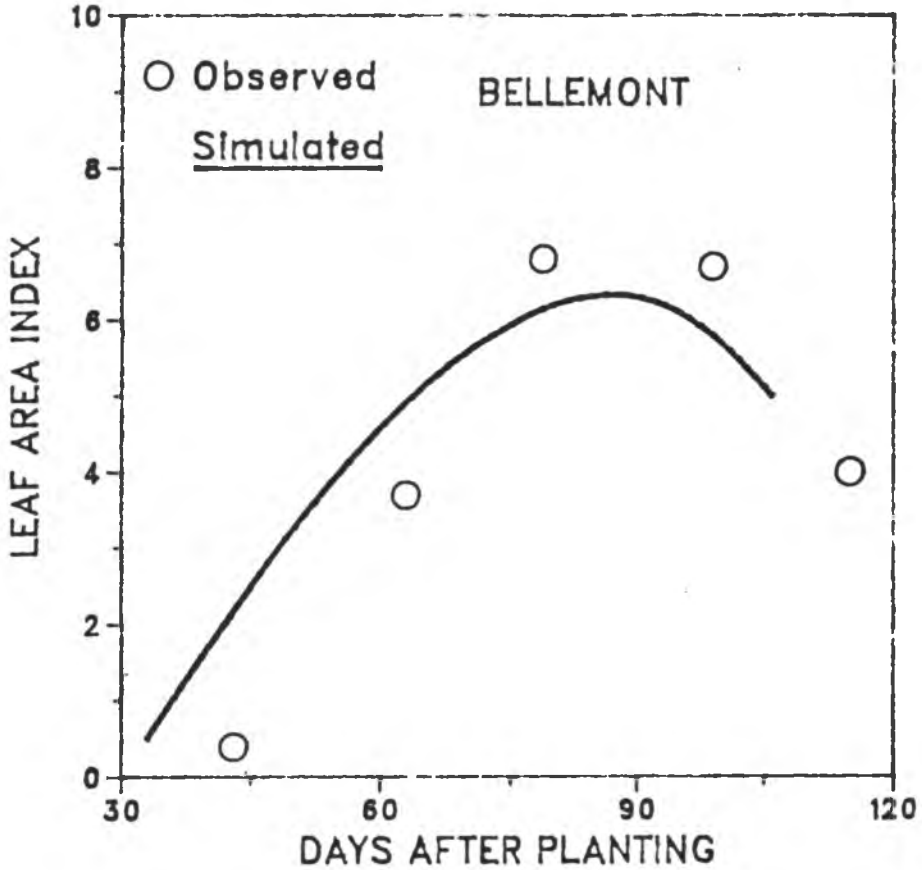

Figure 4.7 Comparison of measured and simulated LAI for Bellemont

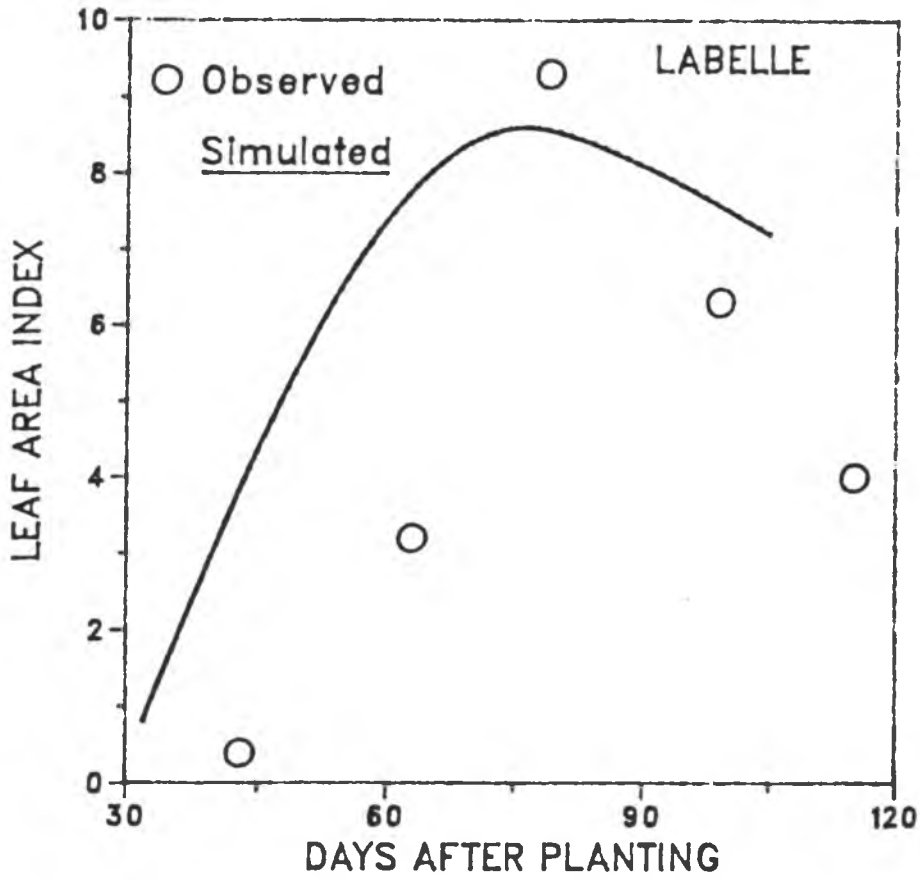

Figure 4.8 Comparison of measured and simulated LAI for Labelle

Table 4.17

Comparison of measured and simulated above ground biomass for the 1986 lowland planting

Days After Planting	Above Ground Biomass ($g\ m^{-2}$)	
	Measured	Simulated
	Belloment	
43	41.8	165
63	472.3	647
79	905.8	1093
99	-	1645
106	1563.9	1751
	Labelle	
43	55.5	266
63	503.0	840
79	1236.0	1364
99	2124.8	2026
105	2438.0	2128
	IR-36	
43	80.3	272
63	620.3	828
99	-	1997
121	2117.5	2459
	K-C-A	
43	118.3	369
63	560.7	1044
79	1393.8	1650
99	2215.6	2381
112	2664.6	2639
	Starbonnet	
43	47.3	201
63	395.8	714
79	1072.0	1224
99	1481.3	1831
125	2371.9	2414

Table 4.18

Comparison of measured and simulated leaf weight for the 1986 lowland planting

Days After Planting	Leaf Weight (g plant^{-1})	
	Measured*	Simulated
	Belloment	
43	0.75+/-0.48	5.85
63	8.48+/-1.27	14.43
79	13.70+/-2.17	14.57
99	15.31+/-2.04	10.91
106	13.32+/-1.24	9.56
	Labelle	
43	0.94+/-0.64	9.24
63	9.44+/-1.40	18.78
79	17.87+/-1.83	18.72
99	17.13+/-2.85	14.00
105	19.25+/-1.64	12.66
	IR-36	
43	1.65+/-0.86	10.44
63	12.48+/-1.78	24.64
99	25.42+/-3.19	26.37
121	16.81+/-2.04	21.52
	K-C-A	
43	2.48+/-0.92	13.67
63	10.91+/-2.28	28.54
79	21.35+/-1.89	29.80
99	22.31+/-2.94	27.67
112	15.95+/-1.76	24.93
	Starbonnet	
43	0.82+/-0.76	7.93
63	7.66+/-1.61	26.45
79	19.36+/-2.03	34.51
99	19.28+/-2.21	34.83
125	21.47+/-1.35	28.97

* Mean weight +/- one standard deviation.

Table 4.19

Comparison of measured and simulated stem weight for the 1986 lowland planting

Days After Planting	Stem Weight (g plant^{-1}) Measured*	Simulated
	Belloment	
43	0.92+/-0.49	0.78
63	10.41+/-1.51	8.09
79	22.52+/-3.10	19.31
99	24.87+/-2.54	21.33
106	23.14+/-1.80	20.81
	Labelle	
43	1.28+/-0.80	1.39
63	10.68+/-1.53	10.47
79	31.58+/-2.29	23.69
99	30.86+/-4.60	25.13
105	39.35+/-2.08	24.61
	IR-36	
43	1.56+/-0.76	0.45
63	12.33+/-1.60	8.08
99	32.50+/-3.73	41.77
121	32.66+/-3.02	40.00
	K-C-A	
43	2.26+/-0.98	1.08
63	11.52+/-2.36	11.48
79	34.40+/-2.46	27.58
99	31.51+/-3.91	43.52
112	23.62+/-1.85	42.25
	Starbonnet	
43	1.07+/-0.69	0.10
63	8.17+/-1.62	2.00
79	23.25+/-2.31	9.93
99	31.09+/-2.62	24.63
125	42.19+/-2.03	24.43

* Mean weight +/- one standard deviation.

Comparison of measured and simulated straw yields, grain yields, and grain components

Comparison of measured and simulated straw and grain yields for five varieties of the 1986 lowland planting are shown in Figure 4.9 and Figure 4.10. The model overpredicted the straw yields but underestimated the grain yields of K-C-A and IR-36. K-C-A and IR-36 are more sensitive to photoperiod than the other varieties. During the 1986 planting, K-C-A and IR-36 took longer to reach panicle initiation due to the longer photoperiod. The partitioning into straw was higher owing to an extended vegetative stage which resulted in smaller fraction going into grain. However, the partitioning fractions may remain the same for certain variety in spite of duration change in the field.

The weather condition during the 1986 planting was more favorable for rice growth and development. This condition resulted in higher yield in the 1986 planting than in the 1985 planting and the model was able to simulate the yield difference between the two crop (Table 4.20). The simulated grain yields of 1986 planting was higher than the 1985 planting for photoperiod-insensitive varieties (Bellemont, Labelle, and Starbonnet). The model overpredicted the grain yield of upland rice and lowland rice in 1985 planting (Figure 4.11). The overestimation by

the model may be attributed to water stress and nitrogen shortage in the upland rice and low water temperature of the lowland rice of the 1985 planting. The IBSNAT/CERES Rice Model does not simulate the effect of water temperature on crop performance.

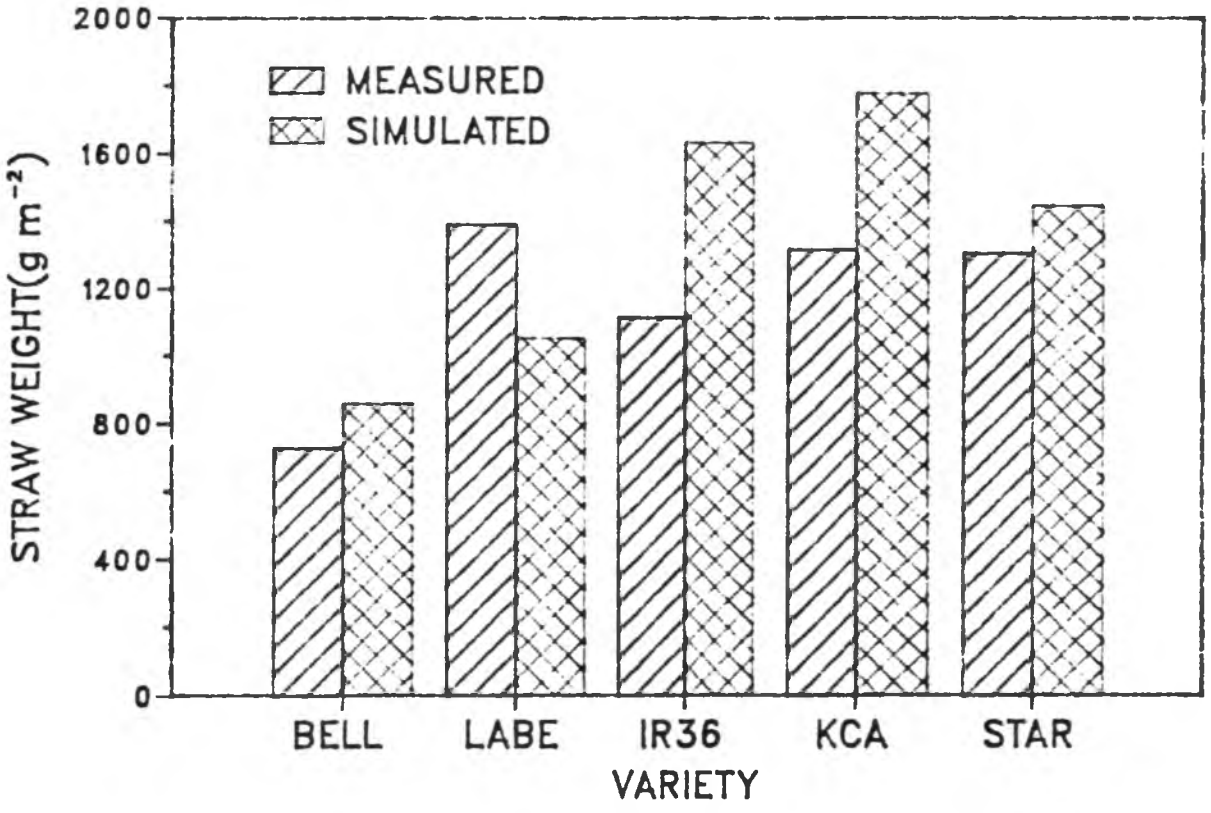

Figure 4.9 Comparison of measured and simulated straw weights for five rice varieties planted to lowland condition at Wailua, Kauai in 1986. BELL=Bellemont, LABE=Labelle, IR36=IR-36, KCA=K-C-A, STAR=Starbonnet.

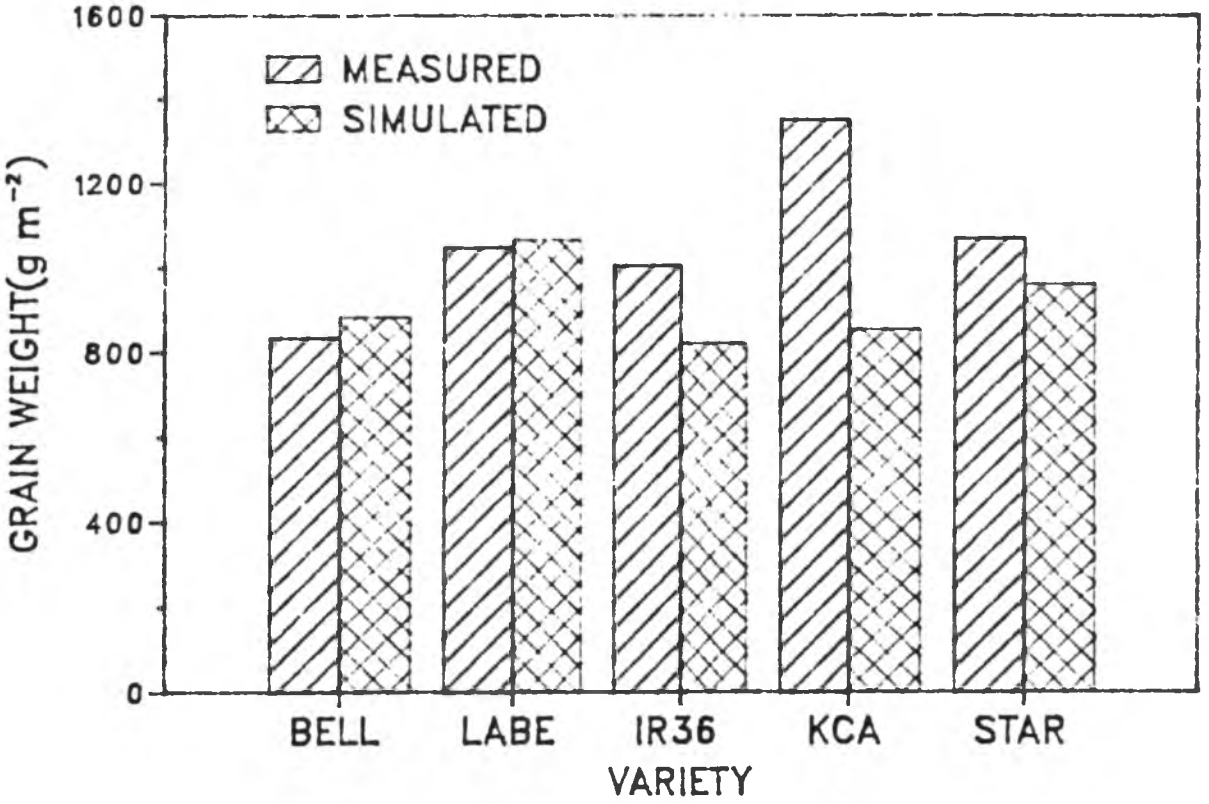

Figure 4.10 Comparison of measured and simulated grain yields for five rice varieties planted to lowland condition at Wailua, Kauai in 1986

Table 4.20

Predicted final harvest of five rice varieties grown in Wailua, Kauai

Variety	Grain Weight ($g\ m^{-2}$)		Straw Weight ($g\ m^{-2}$)		Total Above Ground Biomass ($g\ m^{-2}$)		Panicle Straw Ratio	
	85	86	85	86	85	86	85	86
Bellemont	803.0	884.0	537.4	858.3	1348.7	1751.1	1.7	1.2
Labelle	747.0	1066.0	681.9	1051.4	1687.3	2127.6	1.6	1.1
IR-36	846.0	821.0	977.2	1630.1	2046.8	2459.4	1.2	0.6
K-C-A	1024.0	855.0	1152.0	1775.4	2186.2	2639.2	1.0	0.5
Starbonnet	637.0	962.0	1103.2	1442.9	2203.8	2414.1	1.1	0.7

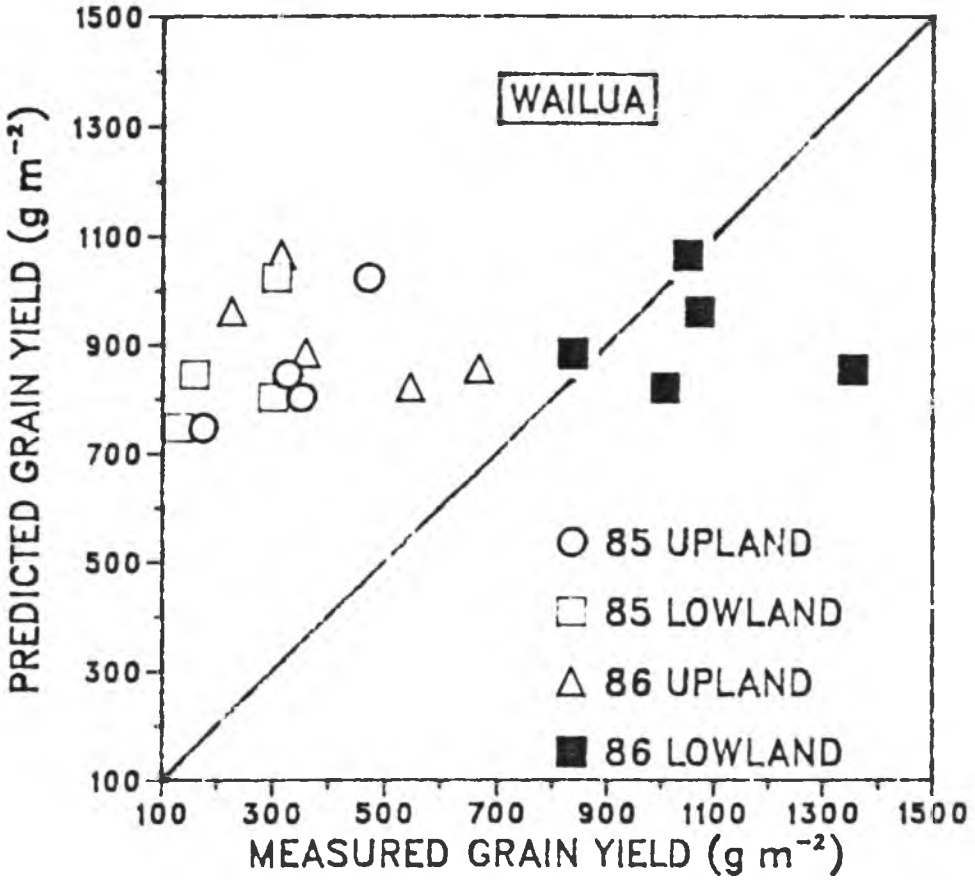

Figure 4.11 Comparison of measured and simulated grain yields at Wailua, Kauai

Comparison of measured and simulated 1000-grain weight was shown in Figure 4.12. The model overpredicted the 1000-grain weight for all varieties except K-C-A. In the model, the grain filling rate is identical for all varieties, and grain weight is a function of grain filling rate and degree thermal time (DTT) during the grain filling period. The grain filling period of K-C-A was shortest among the five varieties and resulted in the lowest predicted 1000-grain weight. It may be necessary to adjust grain filling rate for each variety and grain size.

In general the results tend to indicate that the growth component of IBSNAT/CERES Rice Model is able to simulate trends in the growth of the rice plant, particularly for short duration varieties such as the Bellemont and Labelle. However, further calibrations of biomass partitioning are needed in order to predict the growth components accurately throughtout the growing season. Future research should be directed towards establishing the need for a grain filling rate genetic coefficient.

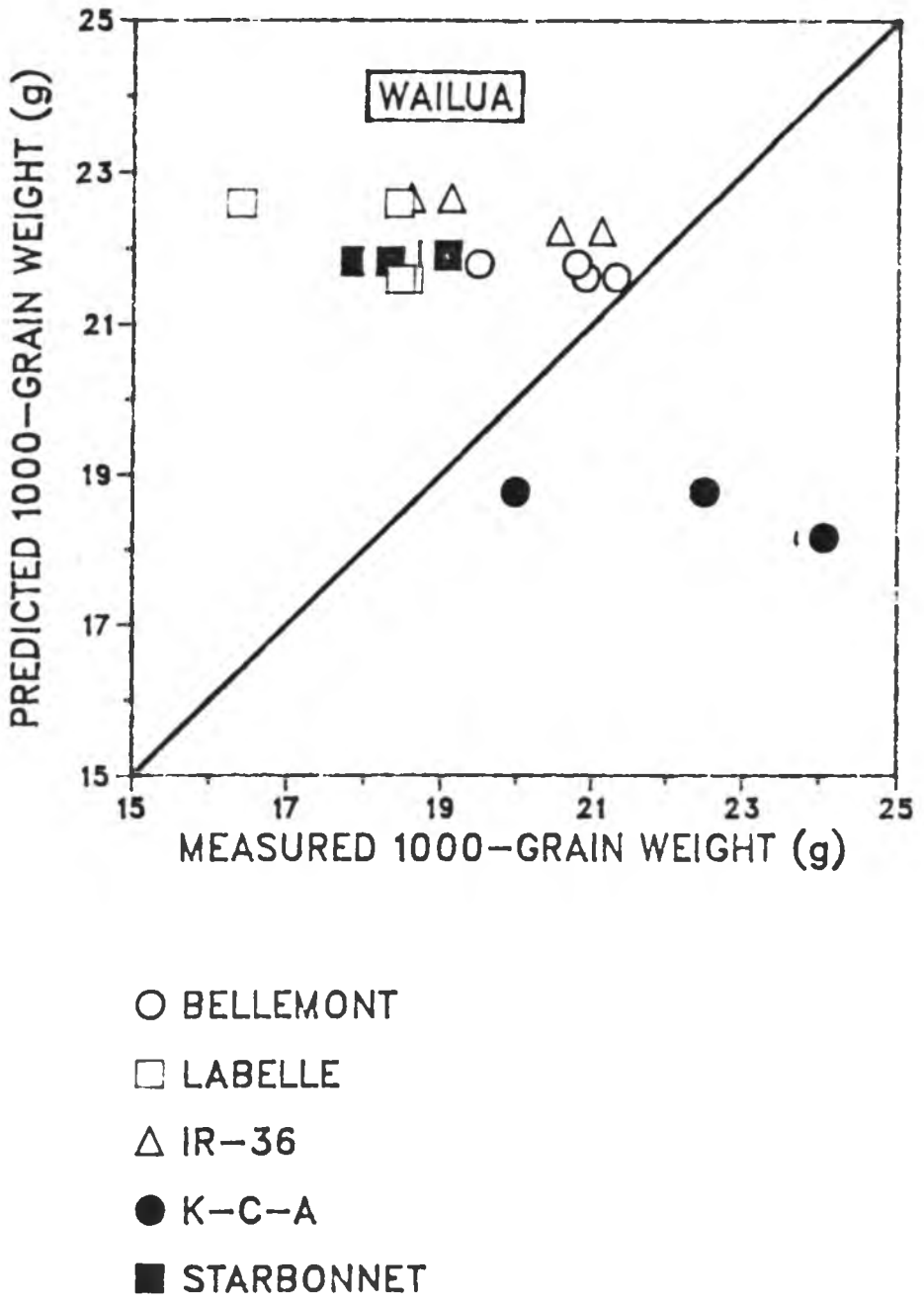

Figure 4.12 Comparison of measured and simulated 1000-grain weights for five rice varieties

4.3.4 Validation of IBSNAT/CERES Rice Model

The experiments conducted on Kuiaha, Haleakala, and Olinda sites, Island of Maui under isohyperthermic, isothermic, and isomesic soil temperature regime were used to validate the IBSNAT/CERES Rice Model. The rice varieties selected for model validation were K-C-A and IR-36. Data from these experiments were not used for calibration. Since it was not possible to calibrate the growth component of the model the validation is restricted to the phenological events. No attempt was made to subject the validation results to a statistical test. Only a visual comparison illustrated by scatter of points around the 1:1 line is presented. Singh (1985) has examined the subject of statistical validation.

The model simulated events for days to emergence for both varieties at three sites differed by no more than two days from the observed (Table 4.21). The model was able to simulate difference in emergence due to environmental difference among sites. The model predicted earlier panicle initiation by about six days at the two lower elevations (Kuiaha and Haleakala). For the highest elevation, the model predicted time was eleven days earlier than the oberved. Determination of panicle initiation requires destructive sampling of the plants and is likely to be observed after 50% initiation than before. However,

the model was able to simulate the delay in days to panicle initiation cause by increasing elevation and decreasing temperature. The observed difference in days to panicle initiation between the lowest and highest elevation was 26 days for IR-36 and 36 days for K-C-A. The simulated difference was 24 days difference for both varieties.

The model accurately predicted heading for both varieties at Kuiaha and Haleakala sites except for K-C-A at Kuiaha site (Table 4.21). Heading is a visible event which requires less rigorous plant examination. The fact that observed heading tends to occur earlier than the simulated time and more than make up for the lost time in panicle initiation suggest that field observations were more reliable for readily observed heading and less reliable for the difficult to measure panicle initiation. The model also predicted the days to maturity much earlier than the observed days. In fact, the observed days to maturity correspond not to maturity but to the time of harvest. Here again harvest generally occurs after a crop reaches maturity and therefore the simulated results may in fact correspond to the actual date of maturity. These results suggest the need to select easily measured or observed phenomena for use in model validation.

Table 4.21

Validation of simulated phenological events with the observed data at three sites

Variety	Emergence		Panicle Initiation		Heading		Physiological maturity	
	Days After Planting							
	O	S	O	S	O	S	O	S
				*				
			Kuiaha					
IR-36	6	6	82	76	111	114	161	147
K-C-A	7	6	69	70	101	108	145	138
					**			
			Haleakala					
IR-36	8	7	90	85	121	123	188	155
K-C-A	9	7	84	78	118	116	188	145
					***			
			Olinda					
IR-36	9	9	108	100	162	142	239	185
K-C-A	10	9	105	94	151	135	239	172

* Planting date : 4/17/86

** Planting date : 4/23/86

*** Planting date : 4/21/86

In general, the model simulated the phenological events satisfactorily except for the site at the highest elevation (Figure 4.13). Although the model simulated delay in events due to low temperature, the actual delay was exceeded the simulated delay. No reasonable explanation can be offered at this time to explain the discrepancies between observed and simulated results for cool environments.

From the results of these sites, it seems reasonable to conclude that the IBSNAT/CERES Rice Model is capable of simulating phenological development for rice on a wide range of agroenvironments with reasonable accuracy.

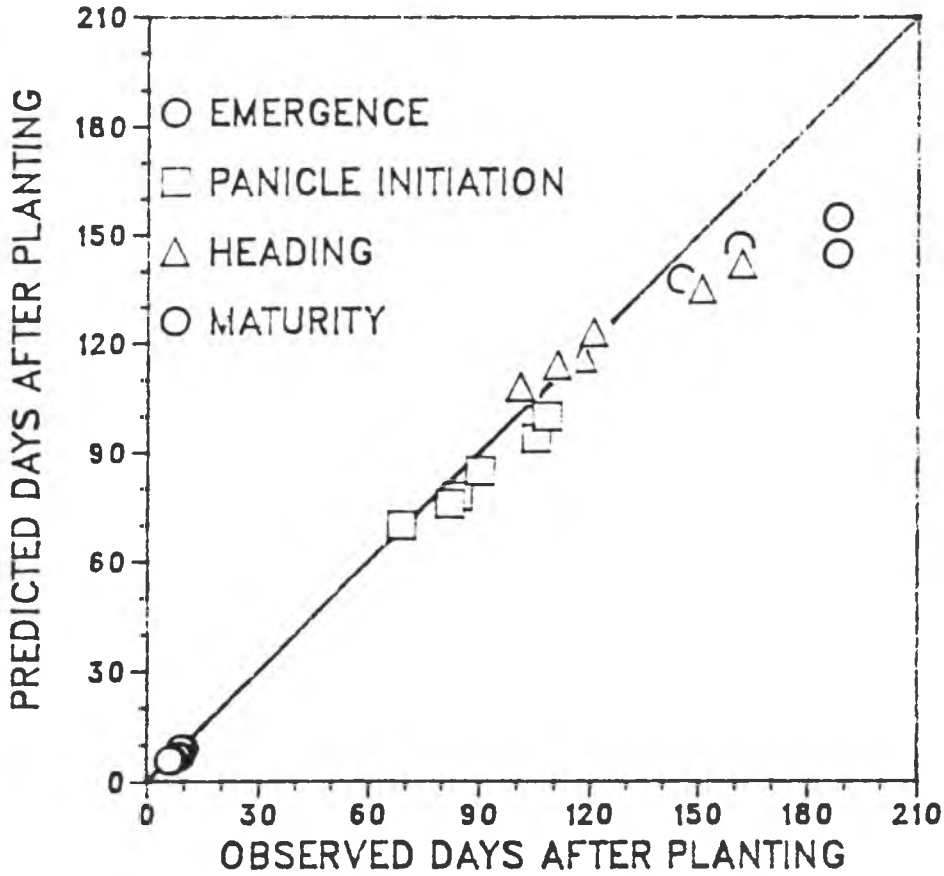

Figure 4.13 Comparison of observed and simulated days after planting for two rice varieties planting at three sites of Maui

4.3.5 Sensitivity Analysis

The sensitivity of IBSNAT/CERES Rice Model to weather variables was analyzed by changing an individual input variable and holding all others constant. The result of changing the values of temperature and solar radiation are given in Appendix C.

Increased solar radiation resulted in increased grain yield, straw yield, and total above ground biomass. However, the effects are more pronounced in the 1985 planting than in the 1986 planting for all varieties. The difference is due to the non-linear response to solar radiation. The solar radiation was lower in the 1985 planting, and the response to it was more marked than in the 1986 summer planting when solar radiation was higher. A reduction in solar radiation as expected resulted in the reduction of grain yield, straw yield, and total biomass. The changes in the solar radiation, however, did not alter the timing of the phenological events.

Air temperature changes resulted in phenological development and yield changes. Increasing the minimum and maximum air temperatures by 2 ^{o}C resulted in hastened phenological development and reduced total biomass in both 1985 and 1986 plantings. However, the 1985 grain yield increased with increasing temperature in most varieties except for Bellemont and K-C-A, and all varieties suffered

yield reductions in 1986 when temperature was increase. This decreased biomass and grain yield when temperature is decreased can be attributed to rapid completion of the life cycle without benefit of adequate solar radiation. Although such situations rarely occur in nature, the results show that the model is sensitive to environmental changes. On the other hand, decreasing both the minimum and maximum air temperature by 2 ^{o}C resulted in delaying the phenological development and increasing the total biomass. However, the grain yield was lower for the 1985 planting due to cold injury.

The sensitivity analysis of the IBSNAT/CERES Rice Model indicates the need of reliable weather variables for simulation. Thus, faulty weather data would result in faulty simulation. The necessity for well calibrated, standard weather station at all sites where modeling experiments are carried out is clearly illustrated by sensitivity analysis.

4.4 Conclusion

Planting date had a highly significant effect on grain yield. The yield of the 1986 planting is higher than the 1985 planting owing to higher temperature and solar radiation.

The IBSNAT/CERES Rice Model was calibrated with experimential data collected at Wailua, Kauai. The calibrated model is able to simulate phenological development over a wide range of agroenvironments. Model prediction for final total biomass was acceptable. However, the partitioning of biomass during the course of growth is still unsatisfactory so that modification of the growth subroutine is necessary. The model simulated the effect of seasonal variation with reasonable accuracy. During the winter planting (1985), lower temperature delayed the maturity date. Low temperature and solar radiation were the principal limiting factors for grain yield during the winter planting in Wailua, Kauai.

The IBSNAT/CERES Rice Model is sensitive to temperature fluctuations and is able to mimic the sensitivity of rice to temperature. This was illustrated by the difference in phenological development at three experimental sites on Maui. Sensitivity analysis also shows that changing both maximum and minimum temperature changes the phenological development of rice.

The IBSNAT/CERES Rice Model is also sensitive to solar radiation. Increased solar radiation results in higher yield. This was illustrated by the yield difference between the 1985 and 1986 experimental planting at Wailua, Kauai and by simulated sensitivity analysis.

CHAPTER V

SUMMARY

Experiments were conducted in the greenhouse and growth chambers to study the effects of temperature, variety and N fertilization on N uptake, development and growth of rice. Two N rates, 0 and 1.88 g N per pot, two rice varieties, K-C-A and Starbonnet, represinting two extreme maturity types, and three temperature regimes, high, intermediate, and low were used in the experiment.

Nitrogen fertilization had a direct influence on grain and straw yields by increasing tiller numbers and LAI during the early development stages. Plants supplied with a high N rate produced 71.5 g and 62.4 g grain per pot, 60.7 g and 99.7 g straw per pot for K-C-A and Starbonnet respectively. Plants grown under N stress produced 29.9 g and 16.7 g grain and 18.7 g and 29.0 g straw per pot for K-C-A and Starbonnet, respectively. Nitrogen stress did not delay the timing of phenological events of Starbonnet, but delayed panicle initiation by seven days in K-C-A .

Temperature affected the yield and nitrogen uptake during the grain filling stage of both varieties. Under high temperature, 35 ^{o}/30 ^{o}C (day/night), maturation was hastened and duration of grain filling was shortened

resulting in lower filled grain percentage, lower 1,000-grain weight and lower overall grain yield. The nitrogen concentration and N uptake were higher in the higher temperature regime than in the lower temperature regime ($25^{o}/20^{o}$ C). However, the persistence of green color and the low ratio of grain N to straw N indicate that nitrogen translocation from straw to grain was diminished at the higher temperature.

Field experiments conducted at Wailua, Kauai with five rice varieties, Bellemont, IR-36, K-C-A, Labelle, and Starbonnet, were used to calibrate the phasic and growth subroutines of the IBSNAT/CERES Rice Model. Appropriate coefficients in the model were adjusted until reasonable agreement between observed and simulated results were obtained. Adjustments were made for (1) rice genetics coefficients, (2) the critical temperatures for the heading and grain filling stages, (3) the grain filling rate, and (4) panicle growth rate.

The calibrated IBSNAT/CERES Rice Model was then validated by using data collected from Kuiaha, Haleakala, and Olinda rice experiments conducted on Maui Island. The model was able to perform well for phenological development on a wide range of agroenvironments. The sites ranged from 283 to 1150 meters above sea level, the temperature regimes included ishyperthermic, isothermic and isomesic, and the

soils included Ultisols and Inceptisols. The model simulated seasonal variation and altitudinal difference accurately.

The calibrated model adequately predicted final total biomass, ~~however~~, biomass partitioning needs additional calibration.

Sensitivity analysis shows that the IBSNAT/CERES Rice Model responds to fluctuations in temperature and solar radiation.

Appendix A

Soil Profile Properties of Experimental Sites

Table A.1

Soil profile properties of Wailua site

Soil name: Hanalei Soil no.: S70Ha-2-1-(1-4)

Classification: Tropic Fluvaquents,very-fine,oxidic,nonacid isohyperthermic

	Water content				Bulk	Organic	NH_4	NO_3	pH
Depth	LL	DUL	SAT	SW	density	carbon			
		$cm^3\ cm^{-3}$			$g\ cm^{-3}$		$mg\ kg^{-1}$		
-cm-	-----		-----		-	---%---			-
0-10	0.27	0.32	0.34	0.32	1.51	6.64	2.1	7.5	4.6
10-30	0.31	0.42	0.50	0.42	0.98	5.20	3.8	5.7	4.7
30-50	0.33	0.70	0.70	0.70	0.70	9.43	3.9	1.8	3.7
50-70	0.33	0.70	0.70	0.70	0.33	22.00	3.9	1.0	2.7
70-90	0.33	0.70	0.70	0.70	0.33	22.00	3.9	1.0	2.7

LL : lower limit of plant-extabctable soil water

DUL: drained upper limit soil water content

SAT: saturated water content

SW : soil water content

Table A.2

Soil profile properties of Kuiaha site

Soil name: Haiku Soil no.: S84HA4-3

Classification: Humoxic Tropohumults, clayey, ferritic, isohyperthermic

	Water content				Bulk	Organic	NH_4	NO_3	pH
Depth	LL	DUL	SAT	SW	density	carbon			
		$cm^3\ cm^{-3}$			$g\ cm^{-3}$				
-cm-	-----		-----		-	---% ---	-mg kg^{-1} -		
0-10	0.44	0.57	0.60	0.44	1.47	2.92	0.1	15.9	5.1
10-30	0.40	0.54	0.74	0.40	1.38	2.92	0.8	5.7	4.9
30-50	0.40	0.54	0.72	0.40	1.39	2.14	0.9	1.8	4.8
50-70	0.25	0.43	0.79	0.25	1.15	2.26	0.9	1.0	4.8

Table A.3

Soil profile properties of Haleakala site

Soil name: Makawao Soil no.: S83HA4-12

Classification: Humoxic Tropohumults, clayey, oxidic, isothermic

	Water content				Bulk	Organic	NH_4	NO_3	pH
Depth	LL	DUL	SAT	SW	density	carbon			
		$cm^3\ cm^{-3}$			$g\ cm^{-3}$				
-cm-	-----cm cm -----				-gcm -	---%---	-mg kg^{-1} -		
0-10	0.26	0.44	0.71	0.26	1.37	3.58	6.4	60.8	4.7
10-30	0.26	0.43	0.70	0.26	1.41	2.22	6.4	50.7	4.8
30-50	0.26	0.43	0.69	0.26	1.40	2.22	5.9	41.8	4.5
50-70	0.38	0.47	0.72	0.38	1.72	1.36	5.9	33.0	4.7

Table A.4

Soil profile properties of Olinda site

Soil name: Olinda Soil no.: S83HA4-11

Classification: Entic Dystrandepts, medial over loamy-skeletal, isometic

	Water content				Bulk	Organic	NH_4	NO_3	pH
Depth	LL	DUL	SAT	SW	density	carbon			
		$cm^3\ cm^{-3}$			$g\ cm^{-3}$		$mg\ kg^{-1}$		
-cm-	-----		-----		-	---%---			-
0-10	0.23	0.51	0.79	0.23	0.91	7.54	4.6	0.5	5.5
10-30	0.01	0.37	0.63	0.01	1.28	4.56	3.8	0.7	5.3
30-50	0.02	0.37	0.60	0.02	1.04	2.71	3.9	0.8	5.5
50-70	0.13	0.42	0.57	0.13	1.13	7.15	3.9	0.0	5.5

APPENDIX B

Phenological and Growth subroutines

of IBSNAT/CERES Rice Model

```
0010 C     ********* PROGRAM INITIALIZATION ************
0020 C
0030       SUBROUTINE PROGRI(APTNUP,CRAIN,CUMDTT,
0040      +   CUMPH,DTT,GNP,GRAINN,GPP,
0050      +   GRN,GRNWT,ISTAGE,ICSDUR,INSOIL,ITRANS,
0060      +   IOUTNU,JDATEX,LAI,LFWT,
0070      +   NFAC,NHDUP,PA,PAN,PLA,PDL,PDLWT,
0080      +   PERPAWT,PLANTS,PLTWT,PPAWT,
0090      +   PRECIP,RANC,RNFAC,ROOTN,RTWT,SEEDRV,
0100      +   STMWT,STOVN,STOVWT,SUMDTT,
0120      +   TANC,TBASE,TILNO,TMNC,TMFAC,TNUP,
0130      +   TRWU,XSTAGE,WTLF)
0140       REAL INSOIL,LAI,LFWT,NDEF1,NDEF2,NFAC
0150       COMMON/PROGR1/ NDEF1,NDEF2
0160       COMMON/PROGR2/ SWDF1,SWDF2,SWDF3
0170       COMMON/WRIT4/ IOUTGR,IOUTWA,JHEAD,KHEAD
0180       DIMENSION RNFAC(10),TMFAC(8)
0190       DO 20 L=1,10
0200         RNFAC(L)=1.0
0210    20 CONTINUE
0220       IOUTGR=0
0230       IOUTWA=0
0240       IOUTNU=0
0250       ITRANS=0
0260       JHEAD=0
0270       KHEAD=0
0280       PLTWT=0.0044
0290       STMWT=0.
0300       PPAWT=0.
0310       PDLWT=0.
0320       TILNO=0.
0330       PLA=0.
0340       LAI=0.
0350       PA=0.
0360       PERPAWT=0.
0370       GRNWT=0.
0380       PDL=0.
0390       LFWT=0.0035
0400       RTWT=0.0009
0410       STOVWT=0.0035
0420       WTLF=0.4
0430       CUMPH=0.8
```

```
0440        SEEDRV=0.024*PLANTS
0450        PAN=0.00115
0460        GRN=0.000063
0470        GPP=0.
0480        ISTAGE=7
0490        TBASE=8.
0500        JDATEX=367
0510        CUMDTT=0.
0520        SUMDTT=0.
0530        OUTDTT=0.
0540        DTT=0.
0550        GRAINN=1.0
0560        APTNUP=0.0
0570        TMNC=0.0045
0580        XPLANT=PLANTS
0590        XSTAGE=0.1
0600        DO 30 I=1,8
0610          TMFAC(I)=0.931+0.114*I-0.0703*I**2+0.0053*I**3
0620     30 CONTINUE
0630        SWDF1=1.0
0640        SWDF2=1.0
0650        SWDF3=1.0
0660        INSOIL=1.1
0670        TRWU=0.0
0680        NFAC=1.0
0690        ICSDUR=0
0700        NDEF1=1.0
0710        NDEF2=1.0
0720        TANC=0.0
0730        RANC=0.0
0740        STOVN=0.0
0750        ROOTN=0.0
0760        GNP=1.0
0770        TNUP=0.0
0780 C      NHDMN=0
0790        NHDUP=0
0800        CRAIN=0.
0810        PRECIP=0.
0820        RETURN
0830        END
0840 C      ***** SUBROUTINE TO CALCULATE PHENOLOGICAL STAGE
0850 C
0860        SUBROUTINE PHENOL (ISWNIT,ISWSWB,IQUIT,
0870       +   JTRANSP,NCYCLE,PLANTS,
0880       +   SDEPTH,YIELD,SOLRAD,TMFAC,TEMPM,IVARTY,
0890       +   VARTY,CUMDTT,SUMDTT,
0900       +   DTT,ISTAGE,TBASE,CUMPH,SWSD,PLTWT,
0910       +   PPAWT,PERPAWT,PDLWT,WTLF,
0920       +   GRNWT,PLA,LAI,PDL,SEEDRV,GRN,PA,PAN,
0930       +   TILNO,GPP,GRORT,LFWT,
```

```
0940       +    RTWT,STMWT,CUMDEP,ESW,ICSDUR,RLV,
0950       +    CRAIN,RTDEP,TANC,TCNP,RCNP,
0960       +    RANC,TMNC,VANC,VMNC,XSTAGE,GNP,
0970       +    NFAC,DSTOVN,ROOTN,STOVN,PDWI,
0980       +    STOVWT,PGRORT,NDEM,PANN,RNFAC,
0990       +    RNLOSS,TNUP,KOUTGR,FAC,PNUP,
1010       +    DLAYR,LL,SW,NLAYR,RWU,IHVON,BIOMAS)
1020 C
1030        REAL LAI,LFWT,LL,NDEM,NH4,NO3,NDEF1,NDEF2,NFAC
1040        CHARACTER *16 VARTY
1050        DIMENSION TMFAC(8),RNO3U(10),RNH4U(10),
1060       +   ESW(10),RLV(10),RNFAC(10),
1070       +  RNLOSS(10),SNH4(10),SNO3(10),NH4(10),
1080       +   NO3(10),FAC(10),PNUP(10),
1090       +  DLAYR(10),LL(10),SW(10),RWU(10)
1100 C
1110        COMMON/IPTRT2/ P1,P2R,P5,P2O
1120        COMMON/IPTRT3/ G1,TR
1130        COMMON/IPWTH1/ S1,C1
1140        COMMON/PROGR1/ NDEF1,NDEF2
1150        COMMON/PROGR2/ SWDF1,SWDF2,SWDF3
1160        COMMON/SOILR1/ CEP,CES,CET
1170        COMMON/SOILR2/ NH4,NO3
1180        COMMON/SOILN4/ SNH4,SNO3
1190        COMMON/SOILN5/ TEMPMN,TEMPMX
1200        COMMON/CALDA1/ MO,ND,IYR,JDATE,JDATEX
1210        COMMON/PHENO2/ CSD1,CSD2
1220        COMMON/PHENO3/ RNO3U,RNH4U
1230        COMMON/PHENO4/ CNSD1,CNSD2
1240 C
1240 C       SAVE STRFACS,FERTILE,L0,OUTDTT,SIND,P3,P9,
1250        +    NDAS,TSTRESS,BIOMAS,
1260 C      +    PFR,PFL,PFC,PFP,PAWT,JPHEAD,JPMAT,HLAI
1270 C
1280        TEMPM=(TEMPMX+TEMPMN)/2.
1290        DTT=TEMPM-TBASE
1300        IF (TEMPMN.LE.TBASE .OR. TEMPMX .GE. 33) THEN
1310           DTT=0.
1320           DO 10 I=1,8
1330              TTMP=TEMPMN+TMFAC(I)*(TEMPMX-TEMPMN)
1340              IF(TTMP.GE.TBASE.AND.TTMP.LE.33)
1350                DTT=DTT+(TTMP-TBASE)/8.
1360              IF(TTMP.GT.33.AND.TTMP.LT.42)
1370               DTT=DTT+(33.-TBASE)*(1.-(TTMP-33.)/9.)/8.
1380     10     CONTINUE
1380          END IF
1400          SUMDTT=SUMDTT+DTT
1410          CUMDTT=CUMDTT+DTT
1420          GO TO (1,2,3,4,5,6,7,8,9), ISTAGE
```

```
1430 C      ****************DETERMINE SOWING DATE*********
1440       7 CALL CALDAT (IYR,JDATE,JDATEX,MO,ND)
1450         CALL OUTGR (BIOMAS,CUMDTT,CUMPH,GRAIN,GRNWT,
1460        +  IHVON,ISTAGE,IYR,JDATE,JTRANSP,LAI,LFWT,
1470        +  MO,ND,PDLWT,PNO,PPAWT,
1480        +  PSRATIO,PSTRAW,RTWT,STMWT,TILNO,YIELD)
1490         CALL PHASEI (CEP,CES,CET,CNSD1,CNSD2,
1500        +   CRAIN,CSD1,CSD2,CUMDTT,CUMDEP,DLAYR,DTT,
1510        +   ICSDUR,ISTAGE,ISWNIT,ISWSWB,NDAS,
1520        +   NDEF1,NDEF2,NLAYR,OUTDTT,P3,P9,PFR,PFL,
1530        +   PFC,PFP,PA,PAN,PANN,PLANTS,RANC,RLV,RTDEP,
1540        +   RWU,SDEPTH,SIND,SUMDTT,SWSD,TANC,TMNC,
1550        +   TSTRESS,VANC,VMNC)
1560         IF (ISWSWB.EQ.0) RETURN
1570         CUMDEP=0.
1580         DO 30 L=1,NLAYR
1590            CUMDEP=CUMDEP+DLAYR(L)
1600            IF (SDEPTH.LT.CUMDEP) GO TO 40
1610       30 CONTINUE
1620       40 L0=L
1620          RETURN
1640 C       ************DETERMINE GERMINATION DATE********
1650       8 IF (ISWSWB.NE.0.OR.SW(L0).LE.LL(L0)) THEN
1660            SWSD=(SW(L0)-LL(L0))*0.65
1670        +         +(SW(L0+1)-LL(L0+1))*0.35
1680         END IF
1690         NDAS=NDAS+1
1700         IF(NDAS.LT.40) THEN
1710            IF (SWSD.LT.0.02) RETURN
1720            IF (TEMPM.LT.16 .OR. TEMPM .GT. 42) RETURN
1730            IF (SUMDTT .LT. 45) RETURN
1740            CALL CALDAT (IYR,JDATE,JDATEX,MO,ND)
1740            CALL OUTGR (BIOMAS,CUMDTT,CUMPH,GRAIN,GRNWT,
1760        +  IHVON,ISTAGE,IYR,JDATE,JTRANSP,LAI,LFWT,MO,
1770        +  ND,PDLWT,PNO,PPAWT,PSRATIO,PSTRAW,RTWT,
1780        +  STMWT,TILNO,YIELD)
1790         CALL PHASEI (CEP,CES,CET,CNSD1,CNSD2,CRAIN,
1800        +   CSD1,CSD2,CUMDTT,CUMDEP,DLAYR,DTT,ICSDUR,
1810        +   ISTAGE,ISWNIT,ISWSWB,NDAS,
1820        +   NDEF1,NDEF2,NLAYR,OUTDTT,P3,P9,PFR,PFL,PFC,
1830        +   PFP,PA,PAN,PANN,PLANTS,RANC,RLV,RTDEP,RWU,
1840        +   SDEPTH,SIND,SUMDTT,SWSD,TANC,TMNC,
1850        +   TSTRESS,VANC,VMNC)
1860         ELSE
1870 C           WRITE (41,105)
1880 C   105     FORMAT (1X,'CROP FAILURE BECAUSE OF LACK OF
1890 C      +    GERMINATION', ' WITHIN 40 DAYS OF SOWING')
1900            STOP
1910         END IF
1920         RETURN
```

```
1930 C     ***********DETERMINE SEEDLING EMERGENCE DATE***
1940      9 RTDEP=RTDEP+0.15*DTT
1950        CALL GROWTH (BIOMAS,CNSD1,CNSD2,CUMDTT,CUMPH,
1960       +   DLAYR,DSTOVN,DTT,ESW,FAC,G1,GNP,GPP,GRN,
1970       +   GRNWT,GRORT,ICSDUR,IDAY,
1980       +   ISTAGE,ISWNIT,KOUTGR,LAI,LFWT,LL,NDEM,
1990       +   NDEF1,NDEF2,NFAC,NLAYR,
2000       +   NH4,NO3,PA,PANN,PAWT,PDL,PDLWT,PDWI,PFR,
2010       +   PFL,PFC,PFP,PGRORT,PLANTS,PLA,PLTWT,PERPAWT,
2020       +   PNUP,PPAWT,RANC,RCNP,RLV,RNFAC,
2030       +   RNLOSS,RNH4U,RNO3U,ROOTN,RTWT,RWU,SEEDRV,
2040       +   SNH4,SNO3,STMWT,STOVN,STOVWT,SW,SWDF1,SWDF2,
2050       +   SOLRAD,TANC,TCNP,TEMPM,TEMPMN,TEMPMX,TILNO,
2060       +   TMNC,TNUP,TR,TSTRESS,VANC,VMNC,XSTAGE)
2070        IF (SUMDTT .LT. P9) RETURN
2080        CALL CALDAT (IYR,JDATE,JDATEX,MO,ND)
2090        CALL OUTGR (BIOMAS,CUMDTT,CUMPH,GRAIN,GRNWT,
2100       +  IHVON,ISTAGE,IYR,JDATE,JTRANSP,LAI,LFWT,
2110       +  MO,ND,PDLWT,PNO,PPAWT,
2120       +  PSRATIO,PSTRAW,RTWT,STMWT,TILNO,YIELD)
2130        CALL PHASEI (CEP,CES,CET,CNSD1,CNSD2,CRAIN,
2140       +   CSD1,CSD2,CUMDTT,CUMDEP,DLAYR,DTT,ICSDUR,
2150       +   ISTAGE,ISWNIT,ISWSWB,NDAS,NDEF1,NDEF2,
2160       +   NLAYR,OUTDTT,P3,P9,PFR,PFL,PFC,PFP,PA,
2170       +   PAN,PANN,PLANTS,RANC,RLV,RTDEP,RWU,SDEPTH,
2180       + SIND,SUMDTT,SWSD,TANC,TMNC,TSTRESS,VANC,VMNC)
2190        RETURN
2200 C     ***********DETERMINE END OF JUVENILE STAGE*****
2210      1 XSTAGE=SUMDTT/P1
2220        OUTDTT=OUTDTT+DTT
2230        IF (JDATE.EQ.JTRANSP) THEN
2240           RTWT=RTWT*0.50
2250           CALL CALDAT (IYR,JDATE,JDATEX,MO,ND)
2260           CALL OUTGR (BIOMAS,CUMDTT,CUMPH,GRAIN,GRNWT,
2270       +      IHVON,ISTAGE,IYR,JDATE,JTRANSP,LAI,LFWT,
2280       +      MO,ND,PDLWT,PNO,PPAWT,PSRATIO,PSTRAW,
2290       +      RTWT,STMWT,TILNO,YIELD)
2300           IF (OUTDTT.GT.420) THEN
2310              P1=P1+P1*0.8*(OUTDTT-420)/420
2320              TSTRESS=0.5*(OUTDTT-420)/420
2330           END IF
2340        END IF
2350        CALL GROWTH (BIOMAS,CNSD1,CNSD2,CUMDTT,CUMPH,
2360       +   DLAYR,DSTOVN,DTT,ESW,FAC,G1,GNP,GPP,GRN,
2370       +   GRNWT,GRORT,ICSDUR,IDAY,ISTAGE,ISWNIT,
2380       +   KOUTGR,LAI,LFWT,LL,NDEM,NDEF1,NDEF2,NFAC,
2390       +   NLAYR,NH4,NO3,PA,PANN,PAWT,PDL,PDLWT,PDWI,
2400       +   PFR,PFL,PFC,PFP,PGRORT,PLANTS,PLA,PLTWT,
2410       +   PERPAWT,PNUP,PPAWT,RANC,RCNP,RLV,RNFAC,
2420       +   RNLOSS,RNH4U,RNO3U,ROOTN,RTWT,RWU,SEEDRV,
```

```
     +    SNH4,SNO3,STMWT,STOVN,STOVWT,SW,SWDF1,
     +    SWDF2,SOLRAD,TANC,TCNP,TEMPM,TEMPMN,TEMPMX,
     +    TILNO,TMNC,TNUP,TR,TSTRESS,VANC,VMNC,XSTAGE)
      IF (SUMDTT .LT. P1) RETURN
      CALL CALDAT (IYR,JDATE,JDATEX,MO,ND)
      XANC=(STOVN+PANN)/(STOVWT+PPAWT)*100.
      CALL OUTGR (BIOMAS,CUMDTT,CUMPH,GRAIN,GRNWT,
     +  IHVON,ISTAGE,IYR,JDATE,JTRANSP,LAI,LFWT,MO,
     +  ND,PDLWT,PNO,PPAWT,
     +  PSRATIO,PSTRAW,RTWT,STMWT,TILNO,YIELD)
      CALL PHASEI (CEP,CES,CET,CNSD1,CNSD2,CRAIN,
     +    CSD1,CSD2,CUMDTT,CUMDEP,DLAYR,DTT,ICSDUR,
     +    ISTAGE,ISWNIT,ISWSWB,NDAS,NDEF1,NDEF2,NLAYR,
     +    OUTDTT,P3,P9,PFR,PFL,PFC,PFP,PA,PAN,PANN,
     +    PLANTS,RANC,RLV,RTDEP,RWU,SDEPTH,SIND,
     +    SUMDTT,SWSD,TANC,TMNC,TSTRESS,VANC,VMNC)
      RETURN
C     **********DETERMINE DATE OF FLORAL INITIATION**
    2 XSTAGE=1.0+0.5*SIND
      DEC=0.4093*SIN(0.0172*(JDATE-82.2))
      DLV=(-S1*SIN(DEC)-0.1047)/(C1*COS(DEC))
      IF(DLV.LT.-.87) DLV=-.87
      HRLT=7.639*ACOS(DLV)
      RATEIN=1./136.
      IF(HRLT.GT.P20) RATEIN=1./(136.+P2R*(HRLT-P20))
      SIND=SIND+RATEIN*DTT
      CALL GROWTH (BIOMAS,CNSD1,CNSD2,CUMDTT,CUMPH,
     +    DLAYR,DSTOVN,DTT,ESW,FAC,G1,GNP,GPP,GRN,
     +    GRNWT,GRORT,ICSDUR,IDAY,ISTAGE,ISWNIT,
     +    KOUTGR,LAI,LFWT,LL,NDEM,NDEF1,NDEF2,NFAC,
     +    NLAYR,NH4,NO3,PA,PANN,PAWT,PDL,PDLWT,PDWI,
     +    PFR,PFL,PFC,PFP,PGRORT,
     +    PLANTS,PLA,PLTWT,PERPAWT,PNUP,PPAWT,RANC,
     +    RCNP,RLV,RNFAC,RNLOSS,RNH4U,RNO3U,ROOTN,
     +    RTWT,RWU,SEEDRV,SNH4,SNO3,STMWT,
     +    STOVN,STOVWT,SW,SWDF1,SWDF2,SOLRAD,TANC,
     +    TCNP,TEMPM,TEMPMN,TEMPMX,TILNO,TMNC,TNUP,TR,
     +    TSTRESS,VANC,VMNC,XSTAGE)
      IF (SIND.LT.1.0) RETURN
      CALL CALDAT (IYR,JDATE,JDATEX,MO,ND)
      CALL OUTGR (BIOMAS,CUMDTT,CUMPH,GRAIN,GRNWT,
     +  IHVON,ISTAGE,IYR,JDATE,JTRANSP,LAI,LFWT,MO,
     +  ND,PDLWT,PNO,PPAWT,PSRATIO,
     +  PSTRAW,RTWT,STMWT,TILNO,YIELD)
      CALL PHASEI (CEP,CES,CET,CNSD1,CNSD2,CRAIN,
     +    CSD1,CSD2,CUMDTT,CUMDEP,DLAYR,DTT,ICSDUR,
     +    ISTAGE,ISWNIT,ISWSWB,NDAS,NDEF1,NDEF2,NLAYR,
     +    OUTDTT,P3,P9,PFR,PFL,PFC,PFP,PA,PAN,PANN,
     +    PLANTS,RANC,RLV,RTDEP,RWU,SDEPTH,SIND,
     +    SUMDTT,SWSD,TANC,TMNC,TSTRESS,VANC,VMNC)
```

```
      RETURN
C     ***DETERMINE HEADING AND END OF LEAF GROWTH ***
    3 XSTAGE=1.5+3.0*SUMDTT/P3
      CALL GROWTH (BIOMAS,CNSD1,CNSD2,CUMDTT,CUMPH,
     +   DLAYR,DSTOVN,DTT,ESW,FAC,G1,GNP,GPP,GRN,
     +   GRNWT,GRORT,ICSDUR,IDAY,ISTAGE,ISWNIT,
     + KOUTGR,LAI,LFWT,LL,NDEM,NDEF1,NDEF2,NFAC,NLAYR,
     +   NH4,NO3,PA,PANN,PAWT,PDL,PDLWT,PDWI,PFR,PFL,
     +   PFC,PFP,PGRORT,PLANTS,PLA,PLTWT,PERPAWT,
     +   PNUP,PPAWT,RANC,RCNP,RLV,RNFAC,
     +   RNLOSS,RNH4U,RNO3U,ROOTN,RTWT,RWU,SEEDRV,
     +   SNH4,SNO3,STMWT,STOVN,STOVWT,SW,SWDF1,
     +   SWDF2,SOLRAD,TANC,TCNP,TEMPM,TEMPMN,
     +   TEMPMX,TILNO,TMNC,TNUP,TR,TSTRESS,VANC,
     +   VMNC,XSTAGE)
      IF (SUMDTT .LT. P3) RETURN
      IF (TEMPM .GT. 22 .AND.TEMPM.LT. 35) STRFACS=1.
      IF (TEMPM .GE. 35) STRFACS=0.75-0.1*(TEMPM-35)
      IF (TEMPM .LE. 22) STRFACS=0.75-0.1*(22-TEMPM)
      CALL CALDAT (IYR,JDATE,JDATEX,MO,ND)
      JPHEAD=JDATE
      HLAI=LAI
      CALL OUTGR (BIOMAS,CUMDTT,CUMPH,GRAIN,GRNWT,
     +  IHVON,ISTAGE,IYR,JDATE,JTRANSP,LAI,LFWT,MO,
     +  ND,PDLWT,PNO,PPAWT,
     +  PSRATIO,PSTRAW,RTWT,STMWT,TILNO,YIELD)
      CALL PHASEI (CEP,CES,CET,CNSD1,CNSD2,CRAIN,
     +   CSD1,CSD2,CUMDTT,CUMDEP,DLAYR,DTT,ICSDUR,
     +   ISTAGE,ISWNIT,ISWSWB,NDAS,NDEF1,NDEF2,
     +   NLAYR,OUTDTT,P3,P9,PFR,PFL,PFC,PFP,PA,PAN,
     +   PANN,PLANTS,RANC,RLV,RTDEP,RWU,SDEPTH,SIND,
     +   SUMDTT,SWSD,TANC,TMNC,TSTRESS,VANC,VMNC)
      RETURN
C DETERMINE BEGINNING OF EFFECTIVE GRAIN FILLING PERIOD
    4 XSTAGE=4.5+1.5*SUMDTT/(P5*0.95)
      CALL GROWTH (BIOMAS,CNSD1,CNSD2,CUMDTT,CUMPH,
     +   DLAYR,DSTOVN,DTT,ESW,FAC,G1,GNP,GPP,GRN,
     +   GRNWT,GRORT,ICSDUR,IDAY,ISTAGE,ISWNIT,
     +   KOUTGR,LAI,LFWT,LL,NDEM,NDEF1,NDEF2,
     +   NFAC,NLAYR,NH4,NO3,PA,PANN,PAWT,PDL,PDLWT,
     +   PDWI,PFR,PFL,PFC,PFP,PGRORT,PLANTS,PLA,
     +   PLTWT,PERPAWT,PNUP,PPAWT,RANC,RCNP,RLV,
     +   RNFAC,RNLOSS,RNH4U,RNO3U,ROOTN,RTWT,RWU,
     +   SEEDRV,SNH4,SNO3,STMWT,STOVN,STOVWT,SW,
     +   SWDF1,SWDF2,SOLRAD,TANC,TCNP,TEMPM,TEMPMN,
     +   TEMPMX,TILNO,TMNC,TNUP,TR,TSTRESS,VANC,VMNC,
     +   XSTAGE)
      IF (SUMDTT .LT. 170.) RETURN
      IF (TEMPM .GT. 22 .AND. TEMPM.LT.33)
           FERTILE=0.853-0.00028*PLANTS
```

```
      IF (TEMPM .GE. 33) FERTILE=0.75-0.1*(TEMPM-33)
      IF (TEMPM .LE. 22) FERTILE=0.75-0.1*(22-TEMPM)
      CALL CALDAT (IYR,JDATE,JDATEX,MO,ND)
      CALL OUTGR (BIOMAS,CUMDTT,CUMPH,GRAIN,GRNWT,
     +  IHVON,ISTAGE,IYR,JDATE,JTRANSP,LAI,LFWT,MO,
     +  ND,PDLWT,PNO,PPAWT,
     +  PSRATIO,PSTRAW,RTWT,STMWT,TILNO,YIELD)
      CALL PHASEI (CEP,CES,CET,CNSD1,CNSD2,CRAIN,
     +   CSD1,CSD2,CUMDTT,CUMDEP,DLAYR,DTT,ICSDUR,
     +   ISTAGE,ISWNIT,ISWSWB,NDAS,NDEF1,NDEF2,NLAYR,
     +   OUTDTT,P3,P9,PFR,PFL,PFC,PFP,PA,PAN,PANN,
     +   PLANTS,RANC,RLV,RTDEP,RWU,SDEPTH,SIND,
     +   SUMDTT,SWSD,TANC,TMNC,TSTRESS,VANC,VMNC)
      RETURN
C     **********DETERMINE END OF GRAIN FILLING*******
    5 XSTAGE=6.0+4.0*SUMDTT/P5
      CALL GROWTH (BIOMAS,CNSD1,CNSD2,CUMDTT,CUMPH,
     +   DLAYR,DSTOVN,DTT,ESW,FAC,G1,GNP,GPP,GRN,
     +   GRNWT,GRORT,ICSDUR,IDAY,ISTAGE,ISWNIT,KOUTGR,
     +   LAI,LFWT,LL,NDEM,NDEF1,NDEF2,NFAC,NLAYR,
     +   NH4,NO3,PA,PANN,PAWT,PDL,PDLWT,PDWI,PFR,PFL,
     +   PFC,PFP,PGRORT,PLANTS,PLA,PLTWT,PERPAWT,
     +   PNUP,PPAWT,RANC,RCNP,RLV,RNFAC,RNLOSS,RNH4U,
     +   RNO3U,ROOTN,RTWT,RWU,SEEDRV,SNH4,SNO3,STMWT,
     +   STOVN,STOVWT,SW,SWDF1,SWDF2,SOLRAD,TANC,
     +   TCNP,TEMPM,TEMPMN,TEMPMX,TILNO,TMNC,TNUP,
     +   TR,TSTRESS,VANC,VMNC,XSTAGE)
      IF (SUMDTT .LT. 0.95*P5) RETURN
      CALL CALDAT (IYR,JDATE,JDATEX,MO,ND)
      CALL OUTGR (BIOMAS,CUMDTT,CUMPH,GRAIN,GRNWT,
     +  IHVON,ISTAGE,IYR,JDATE,JTRANSP,LAI,LFWT,MO,
     +  ND,PDLWT,PNO,PPAWT,
     +  PSRATIO,PSTRAW,RTWT,STMWT,TILNO,YIELD)
      CALL PHASEI (CEP,CES,CET,CNSD1,CNSD2,CRAIN,
     +   CSD1,CSD2,CUMDTT,CUMDEP,DLAYR,DTT,ICSDUR,
     +   ISTAGE,ISWNIT,ISWSWB,NDAS,NDEF1,NDEF2,NLAYR,
     +   OUTDTT,P3,P9,PFR,PFL,PFC,PFP,PA,PAN,PANN,
     +   PLANTS,RANC,RLV,RTDEP,RWU,SDEPTH,SIND,
     +   SUMDTT,SWSD,TANC,TMNC,TSTRESS,VANC,VMNC)
      RETURN
C      *******DETERMINE PHYSIOLOGICAL MATURITY*******
    6 IF (DTT .EQ. 0.0) SUMDTT=P5
      CALL GROWTH (BIOMAS,CNSD1,CNSD2,CUMDTT,CUMPH,
     +   DLAYR,DSTOVN,DTT,ESW,FAC,G1,GNP,GPP,GRN,
     +   GRNWT,GRORT,ICSDUR,IDAY,ISTAGE,ISWNIT,KOUTGR,
     +   LAI,LFWT,LL,NDEM,NDEF1,NDEF2,NFAC,NLAYR,
     +   NH4,NO3,PA,PANN,PAWT,PDL,PDLWT,PDWI,PFR,PFL,
     +   PFC,PFP,PGRORT,PLANTS,PLA,PLTWT,PERPAWT,
     +   PNUP,PPAWT,RANC,RCNP,RLV,RNFAC,RNLOSS,RNH4U,
     +   RNO3U,ROOTN,RTWT,RWU,SEEDRV,SNH4,SNO3,STMWT,
```

```
3930      +    STOVN,STOVWT,SW,SWDF1,SWDF2,SOLRAD,TANC,
3940      +    TCNP,TEMPM,TEMPMN,TEMPMX,TILNO,TMNC,TNUP,
3950      +    TR,TSTRESS,VANC,VMNC,XSTAGE)
3960       IF (SUMDTT .LT. P5) RETURN
3970       CALL CALDAT (IYR,JDATE,JDATEX,MO,ND)
3980       JPMAT=JDATE
3990       PNO=PPAWT/PERPAWT
4000       GRAIN=(PPAWT*0.9/GRNWT)/PNO*STRFACS*FERTILE
4010       PSTRAW=STOVWT+(PPAWT*0.1)
4020       PSRATIO=PPAWT/PSTRAW
4030       DYIELD=(PNO*GRAIN*GRNWT)/100
4040       YIELD=DYIELD/0.86
4050       GRNWT=GRNWT*1000
4060       DLN=(PDLWT/WTLF)/PLANTS
4070       CALL OUTGR (BIOMAS,CUMDTT,CUMPH,GRAIN,GRNWT,
4080      +  IHVON,ISTAGE,IYR,JDATE,JTRANSP,LAI,LFWT,
4090      +  MO,ND,PDLWT,PNO,PPAWT,
4100      +  PSRATIO,PSTRAW,RTWT,STMWT,TILNO,YIELD)
4110       CALL PHASEI (CEP,CES,CET,CNSD1,CNSD2,CRAIN,
4120      +   CSD1,CSD2,CUMDTT,CUMDEP,DLAYR,DTT,ICSDUR,
4130      +   ISTAGE,ISWNIT,ISWSWB,NDAS,NDEF1,NDEF2,NLAYR,
4140      +   OUTDTT,P3,P9,PFR,PFL,PFC,PFP,PA,PAN,PANN,
4150      +   PLANTS,RANC,RLV,RTDEP,RWU,SDEPTH,SIND,
4160      +   SUMDTT,SWSD,TANC,TMNC,TSTRESS,VANC,VMNC)
4170       TILNO=0.
4180       IQUIT=1
4190       CALL OPHARV (IHVON,JPHEAD,JPMAT,YIELD,GRNWT,
4200      +   PNO,GPP,HLAI,BIOMAS,PSTRAW,GRAINN,APTNUP,
4210      +   ATANC,AGRN,PSRATIO)
4220       RETURN
4230       END
4240 C     ****** PHASE INITIALIZATION SUBROUTINE *******
4250 C
4260       SUBROUTINE PHASEI (CEP,CES,CET,CNSD1,CNSD2,
4270      +   CRAIN,CSD1,CSD2,CUMDTT,CUMDEP,DLAYR,DTT,
4280      +   ICSDUR,ISTAGE,ISWNIT,ISWSWB,NDAS,NDEF1,NDEF2,
4290      +   NLAYR,OUTDTT,P3,P9,PFR,PFL,PFC,PFP,PA,PAN,
4300      +   PANN,PLANTS,RANC,RLV,RTDEP,RWU,SDEPTH,SIND,
4310      +   SUMDTT,SWSD,TANC,TMNC,TSTRESS,VANC,VMNC)
4320       DIMENSION DLAYR(10),RLV(10),RWU(10)
4330       REAL NDEF1,NDEF2,NDEF3
4340 C      SAVE NITSW
4350 C
4360       CNSD1=0.0
4370       CNSD2=0.0
4380       CSD1=0.
4390       CSD2=0.
4400       ICSDUR=0
4410       GO TO (1,2,3,4,5,6,7,8,9), ISTAGE
4420     1 ISTAGE=2
```

```
4430          SIND=0.
4440          RETURN
4450        2 ISTAGE=3
4460          P3=450.+0.15*SUMDTT
4470          SUMDTT=0.
4480          PA=PAN
4490          RETURN
4500        3 ISTAGE=4
4510          SUMDTT=SUMDTT-P3
4520          RETURN
4530        4 ISTAGE=5
4540          PFR=0.
4550          PFL=-0.1
4560          PFC=0.
4570          PFP=1.1
4580          VANC=TANC
4590          VMNC=TMNC
4600          RETURN
4610        5 ISTAGE=6
4620          NITSW=ISWNIT
4630          ISWNIT=0
4640          RETURN
4650        6 ISTAGE=7
4660          ISWNIT=NITSW
4670          CUMDTT=0.
4680          DTT=0.
4690          CRAIN=0.
4700          CES=0.
4710          CEP=0.
4720          CET=0.
4730          RETURN
4740        7 ISTAGE=8
4750          CUMDTT=0.
4760          SUMDTT=0.
4770          SWSD=1.0
4780          RTDEP=SDEPTH
4790          NDAS=0
4800          RETURN
4810        8 ISTAGE=9
4820          P9=7.*SDEPTH
4830          SUMDTT=SUMDTT-45
4840          PFL=0.
4850          PFC=0.
4860          PFP=0.
4870          CET=0.
4880          CES=0.
4890          CEP=0.
4900          CUMDTT=0.
4910          NDEF1=1.0
4920          NDEF2=1.0
```

```
      NDEF3=1.0
      CRAIN=0.
      RANC=0.022
      TANC=0.044
      RETURN
    9 ISTAGE=1
      SUMDTT=SUMDTT-P9
      OUTDTT=0.
      TSTRESS=0.
      CUMDEP=0.
      IF (ISWSWB.EQ.0) RETURN
      DO 30 L=1,NLAYR
        CUMDEP=CUMDEP+DLAYR(L)
        RLV(L)=0.20*PLANTS/DLAYR(L)
        IF (CUMDEP.GT.RTDEP) GO TO 40
   30 CONTINUE
   40 RLV(L)=RLV(L)*(1.-(CUMDEP-RTDEP)/DLAYR(L))
      L1=L+1
      DO 60 L=L1,10
        RLV(L)=0.
   60 CONTINUE
      DO 70 L=1,10
        RWU(L)=0.
   70 CONTINUE
      PANN=0.0
   80 RETURN
      END
C
C     ********** GROWTH SUBROUTINE ****************
C
      SUBROUTINE GROWTH (BIOMAS,CNSD1,CNSD2,CUMDTT,
     +   CUMPH,DLAYR,DSTOVN,DTT,ESW,FAC,G1,GNP,GPP,
     +   GRN,GRNWT,GRORT,ICSDUR,IDAY,ISTAGE,ISWNIT,
     +   KOUTGR,LAI,LFWT,LL,NDEM,NDEF1,NDEF2,NFAC,
     +   NLAYR,NH4,NO3,PA,PANN,PAWT,PDL,PDLWT,PDWI,
     +   PFR,PFL,PFC,PFP,PGRORT,PLANTS,PLA,PLTWT,
     +   PERPAWT,PNUP,PPAWT,RANC,RCNP,RLV,RNFAC,
     +   RNLOSS,RNH4U,RNO3U,ROOTN,RTWT,RWU,SEEDRV,
     +   SNH4,SNO3,STMWT,STOVN,STOVWT,SW,SWDF1,SWDF2,
     +   SOLRAD,TANC,TCNP,TEMPM,TEMPMN,TEMPMX,TILNO,
     +   TMNC,TNUP,TR,TSTRESS,VANC,VMNC,XSTAGE)
      DIMENSION DLAYR(10),ESW(10),FAC(10),LL(10),
     +   NH4(10),NO3(10),PNUP(10),RLV(10),RNFAC(10),
     +   RNLOSS(10),RNH4U(10),RNO3U(10),
     +   RWU(10),SNH4(10),SNO3(10),SW(10)
      REAL LAI,LFWT,LL,NDEM,NDEF1,NDEF2,NFAC,NH4,NO3,
     +   NPOOL,NPOOL1,NPOOL2,NSINK,NSDR
C
C     SAVE PLF,RRATIO
      IF (PLANTS .EQ. 0.) RETURN
```

```
5430        RRATIO=0.2*EXP(-PLTWT/PLANTS)
5440        PRFT=1.-0.0025*((0.25*TEMPMN+0.75*TEMPMX)-26.)
5450       +     **2
5460        IF (PRFT.LT.0.) PRFT=0.
5470        IF (PRFT.GT.1.) PRFT=1.
5480        POPFAC=0.94+0.0006*PLANTS
5490        IF (POPFAC .GT. 1.) THEN
5500           IF (POPFAC .LT. 2.) THEN
5510              POPFAC=2.-POPFAC
5520           ELSE
5530              POPFAC=0.5
5540           END IF
5550        END IF
5560        PHINT=DTT/83.
5570        TI=PHINT
5580        TNO=TILNO
5590        TLPOPF=TR*PFL*100/PLANTS
5600        TILNO=TILNO+TI*TLPOPF*G1*7
5610        IF (TEMPM.GT.6.0) THEN
5620           SLFT=1.
5630           IF (TEMPMN.LE.0.0) SLFT=0.0
5640        ELSE
5650           SLFT=1.-(6.0-TEMPM)/6.0
5660           IF (SLFT.LT.0.) SLFT=0.
5670        END IF
5680 C      ******GROWTH FROM GERMINATION TO EMERGENCE*****
5690        IF (ISTAGE .EQ. 9) THEN
5700           PCARB=0.00008265*PLANTS*DTT
5710           CARBO=PCARB*AMIN1(PRFT,SWDF1)
5720           PFR=RRATIO
5730           PFL=1-PFR
5740           ROOTN=RANC*RTWT
5750           STOVN=STOVWT*TANC
5760           SENESR=0.
5770           SENESL=0.
5780           SENESC=0.
5790           GO TO 888
5800        END IF
5810        IF (PLTWT.GT.SEEDRV.AND.ISWNIT.NE.0) CALL
5820       +   NFACTO (CNSD1,CNSD2,NDEF1,NDEF2,NFAC,RCNP,
5830       +   TANC,TCNP,TMNC,XSTAGE)
5840        GO TO (1,2,3,4,5,6),ISTAGE
5850 C      GROWTH FROM EMERGENCE TO END OF JUVENILE STAGE
5860      1 IF (PLTWT .LE. SEEDRV) THEN
5870           PCARB=0.001*PLANTS*LOG(DTT)
5880           CARBO=PCARB*AMIN1(PRFT,SWDF1)
5890           PFR=RRATIO
5900           PFL=1-PFR
5910           ROOTN=RANC*RTWT
5920           STOVN=STOVWT*TANC
```

```
5930        ELSE
5940           PFR=0.15+TSTRESS
5950           PFC=0.01
5960           PFL=1-PFR-PFC
5970           CALL CARB (CARBO,G1,LAI,NDEF1,PCARB,
5980       +   POPFAC,PRFT,SOLRAD,SWDF1)
5990        END IF
6000        PLF=PFL
6010        SENESR=0.
6020        SENESL=0.
6030        SENESC=0.
6040        GO TO 999
6050 C      **** GROWTH FROM BEGINNING OF INDUCTION TO
6060 C                   FLORAL INITIATION ****
6070      2 PFR=0.15
6080        PF=0.001*DTT
6090        PFC=PFC+PF
6100        PFL=1-PFR-PFC
6110        PLF=PFL
6120        SENESR=0.0005
6130        SENESL=0.0003
6140        SENESC=0.
6150        CALL CARB (CARBO,G1,LAI,NDEF1,PCARB,POPFAC,
6160       +   PRFT,SOLRAD,SWDF1)
6170        GO TO 999
6180 C      *** GROWTH FROM FLORAL INITIATION TO HEADING **
6190      3 PFR=0.10
6200        PFL=PLF
6210        PF=-0.0014*DTT
6220        PFL=PFL+PF
6230        IF (PFL .LE. 0.) PFL=0.
6240        PLF=PFL
6250        PF=0.00072*DTT
6260        PFC=PFC+PF
6270        PFP=1-PFR-PFL-PFC
6280        SENESR=0.001
6290        SENESL=0.0006
6300        SENESC=0.0005
6310        CALL CARB (CARBO,G1,LAI,NDEF1,PCARB,POPFAC,
6320       +   PRFT,SOLRAD,SWDF1)
6330        GO TO 999
6340 C     GROWTH FROM HEADING TO JUST BEFORE GRAIN FILLING
6350      4 PFR=0.1
6360        PFL=PLF
6370        PF=-0.0006*DTT
6380        PFL=PFL+PF
6390        PLF=PFL
6400        PF=-0.00215*DTT
6410        PFC=PFC+PF
6420        IF (PFC .LE. 0.) PFC=0.
```

```
      PFP=1-PFR-PFL-PFC
      SENESR=0.003
      SENESL=0.0006
      SENESC=0.0008
      PHINT=0.
      CALL CARB (CARBO,G1,LAI,NDEF1,PCARB,POPFAC,
     +   PRFT,SOLRAD,SWDF1)
      GO TO 999
C     ******* GROWTH DURING GRAIN FILLING **********
    5 PF=-0.0009*DTT
      PFL=PFL+(PF*.7)
      PFC=PFC+(PF*.3)
      PFP=PFP-PF
      SENESR=0.005
      SENESL=0.001
      SENESC=0.0015
      PHINT=0.
      CALL CARB (CARBO,G1,LAI,NDEF1,PCARB,POPFAC,
     +   PRFT,SOLRAD,SWDF1)
      GROGRN=GRN*DTT
      GRNWT=GRNWT+GROGRN
      IF (ISWNIT.NE.0) THEN
C****** GRAIN N ALLOWED TO VARY BETWEEN .01 AND .018.
C****** HIGH TEMP., LOW SOIL WATER, AND HIGH N
        INCREASE GRAIN N ***************************
         TFAC=0.69+.0125*TEMPM
         SFAC=1.125-.125*SWDF2
         GNP=(.007 +.010*NDEF2)*AMAX1(TFAC,SFAC)
         NSINK=PAWT*GNP
         IF (NSINK.NE.0.0) THEN
            RMNC=0.75*RCNP
            VANC=STOVN/STOVWT
            NPOOL1=STOVWT*(VANC-VMNC)
            NPOOL2=RTWT*(RANC-RMNC)
            NPOOL=NPOOL1+NPOOL2
C           IF (ICSDUR .EQ. 1)
             GPP=AMIN1(GPP,(NPOOL/(.2*.0095)))
            NSDR=NPOOL/NSINK
            IF (NSDR.LT.1.0) PAWT=PAWT*NSDR
            NSINK=PAWT*GNP
            IF (NSINK.LE.NPOOL1) THEN
               NPOOL1=NPOOL1-NSINK
               STOVN=NPOOL1+VMNC*STOVWT
               VANC=STOVN/STOVWT
            ELSE
               VANC=VMNC
               STOVN=STOVWT*VANC
               NPOOL2=NPOOL2-(NSINK-NPOOL1)
               NPOOL1=0.0
               ROOTN=RTWT*RMNC+NPOOL2
```

```
6930                  RANC=ROOTN/RTWT
6940               END IF
6950            END IF
6960            PANN=PANN+NSINK
6970          END IF
6980 C        ******* CALCULATES LEAF AREA *********
6990 999      IF (ISTAGE .LE. 3) THEN
7000             PLAG=0.008*CARBO*PFL*TR*G1
7010         +   *AMIN1(SWDF2,NDEF2,SLFT)
7020          ELSE
7030             PLAG=0.004*CARBO*PFL*TR*G1
7040         +        *(2-AMIN1(SWDF2,NDEF2,SLFT))
7050          END IF
7060          PLA=PLA+PLAG
7070          LAI=PLA
7080          IF (ISTAGE.NE.5) THEN
7090             PFL=PFL*AMIN1(SWDF2,NDEF1)
7100             PFR=1-PFL-PFC-PFP
7110          END IF
7120 C        ****** CALCULATES AREA AND WEIGHT OF DEAD LEAVES
7130          IF (PLAG.LE.0.) PDL=-PLAG
7140          DLWT=PDL*POPFAC*90.
7150          PDLWT=PDLWT+DLWT
7160 C        ****** CALCULATES WEIGHT OF PLANT PARTS
7170 888      GRORT=CARBO*PFR
7180          GROLF=CARBO*PFL
7190          GROSTM=CARBO*PFC
7200          PAWT=CARBO*PFP
7210          PNWT=PA*DTT
7220          TOPWT=GROLF+GROSTM+PAWT
7230          RTWT=RTWT+GRORT-(RTWT*SENESR)
7240          LFWT=LFWT+GROLF-(LFWT*SENESL)
7250          STMWT=STMWT+GROSTM-(STMWT*SENESC)
7260          PPAWT=PPAWT+PAWT
7270          PERPAWT=PERPAWT+PNWT
7280          STOVWT=LFWT+STMWT
7290          BIOMAS=LFWT+STMWT+PPAWT
7300          PLTWT=BIOMAS+RTWT
7310          CUMPH=CUMPH+PHINT
7320 C        ****** POTENTIAL GROWTH FOR N DEMAND  ******
7330          IF (ISWNIT.NE.0.AND.PLTWT.GT.SEEDRV) THEN
7340             PDWI=PCARB*(1.0-GRORT/(CARBO+1.E-10))
7350             PGRORT=PCARB*GRORT/CARBO
7360             CALL NUPTAK (DLAYR,DSTOVN,ESW,FAC,GRORT,LL,
7370         +   NDEM,NH4,NLAYR,NO3,PDWI,PGRORT,PNUP,RANC,
7380         +   RCNP,RLV,RNFAC,RNLOSS,RNH4U,RNO3U,ROOTN,
7390         +   RTWT,RWU,SNH4,SNO3,STOVN,
7400         +   STOVWT,SW,TANC,TCNP,TNUP,XSTAGE)
7410          END IF
7420          IF (ISTAGE.EQ.4.OR.ISTAGE.EQ.5) THEN
```

```
7430            TLNO=PPAWT/PERPAWT+1.E-10
7440            IF (TLNO.GT.TILNO) TILNO=TLNO
7450            IF (TILNO.GT.TNO) TILNO=TNO
7460          END IF
7470          RETURN
7480        6 TILNO=PPAWT/PERPAWT
7490          RETURN
7500          END
7510 C
7520 C     * SUBROUTINE THAT CALCULATES PCARB AND CARBO *
7530 C
7540          SUBROUTINE CARB (CARBO,G1,LAI,NDEF1,PCARB,
7550         +   POPFAC,PRFT,SOLRAD,SWDF1)
7560 C
7570          REAL LAI,K,NDEF1
7580          PAR=0.02092*SOLRAD
7590          IF (LAI .LE. 0.6) K=EXP(-LAI)
7600          IF (LAI .GT. 0.6 .AND. LAI .LE. 5)
7610                K=0.58-0.04*LAI
7620          IF (LAI .GT. 5) K=0.36
7630          SHINE=-K*LAI
7640          PCARB=G1*PAR*(1-EXP(SHINE))
7650          CARBO=PCARB*POPFAC*PRFT*AMIN1(SWDF1,NDEF1)
7660          RETURN
7670          END
```

APPENDIX C

Table C.1

Comparison of observed and simulated phenological events of five rice varieties planted in two seasons

Variety	Emergence		Panicle Initiation		Heading		Physiological maturity	
	Days After Planting							
	a O	b S	O	S	O	S	O	S
				Wailua (1985 Winter)*				
Bellemont	5	4	43	43	79	78	118	117
IR-36	5	4	52	51	89	89	129	129
K-C-A	5	4	48	48	85	85	122	120
Labelle	5	4	42	42	78	77	117	116
Starbonnet	5	4	61	62	103	104	142	143
				Wailua (1986 Summer)**				
Bellemont	4	4	45	45	76	76	105	106
IR-36	5	4	59	58	91	91	121	121
K-C-A	5	4	53	53	85	85	113	112
Labelle	4	4	43	44	75	75	104	105
Starbonnet	4	4	61	61	94	94	123	125

[a] Observed value

[b] Simulated value

* Planting date:09/05/85

** Planting date:06/10/86

Table C.2

Sensitivity of IBSNAT/CERES Rice Model to solar radiation and temperature for Starbonnet rice yield

	Yield ($g\ m^{-2}$)		Percentage changes	
	1985	1986	1985	1986
		Grain		
Standard simulation	637	962	-	-
Radiation				
+ 4.19 MJ m/2	833	1211	+31	+26
- 4.19 MJ m/2	491	698	-23	-27
Max. and Min. temperature				
+ 2 °C	884	802	+39	-17
- 2 °C	489	1291	-23	+34
		Straw		
Standard simulation	1103	1443	-	-
Radiation				
+ 4.19 MJ m/2	1501	1779	+36	+23
- 4.19 MJ m/2	678	1005	-38	-30
Max. and Min. temperature				
+ 2 °C	923	1191	-16	-17
- 2 °C	1313	1476	+19	+ 2
		Total biomass		
Standard simulation	2204	2414	-	-
Radiation				
+ 4.19 MJ m/2	2939	3002	+33	+24
- 4.19 MJ m/2	1383	1710	-37	-29
Max. and Min. temperature				
+ 2 °C	1816	2001	-18	-17
- 2 °C	2731	2780	+24	+15

Table C.3

Sensitivity of IBSNAT/CERES Rice Model to solar radiation and temperature for Bellemont rice yield

	Yield ($g\ m^{-2}$)		Percentage changes	
	1985	1986	1985	1986
		Grain		
Standard simulation	803	884	-	-
Radiation				
+ 4.19 MJ m/2	1140	1157	+30	+31
- 4.19 MJ m/2	466	593	-42	-33
Max. and Min. temperature				
+ 2 °C	652	788	-19	-11
- 2 °C	328	874	-60	- 1
		Straw		
Standard simulation	537	858	-	-
Radiation				
+ 4.19 MJ m/2	785	1140	+46	+33
- 4.19 MJ m/2	316	533	-41	-38
Max. and Min. temperature				
+ 2 °C	450	605	-16	-29
- 2 °C	696	948	+30	+11
		Total biomass		
Standard simulation	1349	1751	-	-
Radiation				
+ 4.19 MJ m/2	1937	2308	+44	+32
- 4.19 MJ m/2	787	1131	-42	-35
Max. and Min. temperature				
+ 2 °C	1108	1401	-18	-20
- 2 °C	1718	1831	+29	+ 5

Table C.4

Sensitivity of IBSNAT/CERES Rice Model to solar radiation and temperature for Labelle rice yield

	Yield ($g\ m^{-2}$)		Percentage changes	
	1985	1986	1985	1986
		Grain		
Standard simulation	747	1066	-	-
Radiation				
+ 4.19 MJ m/2	1029	1348	+38	+27
- 4.19 MJ m/2	616	741	-18	-31
Max. and Min. temperature				
+ 2 °C	815	943	+ 9	-12
- 2 °C	399	1056	-47	+11
		Straw		
Standard simulation	682	1051	-	-
Radiation				
+ 4.19 MJ m/2	946	1341	+39	+28
- 4.19 MJ m/2	434	686	-36	-31
Max. and Min. temperature				
+ 2 °C	586	767	-14	-27
- 2 °C	902	1166	+32	+11
		Total biomass		
Standard simulation	1687	2128	-	-
Radiation				
+ 4.19 MJ m/2	2332	2702	+38	+27
- 4.19 MJ m/2	1057	1434	-37	-33
Max. and Min. temperature				
+ 2 °C	1409	1721	-16	-19
- 2 °C	2143	2233	+27	+ 5

Table C.5

Sensitivity of IBSNAT/CERES Rice Model to solar radiation and temperature for IR-36 rice yield

	Yield ($g\ m^{-2}$)		Percentage changes	
	1985	1986	1985	1986
		Grain		
Standard simulation	846	821	-	-
Radiation				
+ 4.19 MJ m/2	1130	1053	+34	+28
- 4.19 MJ m/2	664	572	-21	-30
Max. and Min. temperature				
+ 2 °C	877	728	+ 4	-11
- 2 °C	389	1210	-54	+47
		Straw		
Standard simulation	977	1630	-	-
Radiation				
+ 4.19 MJ m/2	1311	1992	+34	+22
- 4.19 MJ m/2	614	1149	-37	-30
Max. and Min. temperature				
+ 2 °C	826	1372	-16	-16
- 2 °C	1172	1600	+20	-02
		Total biomass		
Standard simulation	2047	2459	-	-
Radiation				
+ 4.19 MJ m/2	2740	3056	+34	+24
- 4.19 MJ m/2	1286	1727	-37	-30
Max. and Min. temperature				
+ 2 °C	1711	2108	-16	-14
- 2 °C	2513	2823	+23	+15

Table C.6

Sensitivity of IBSNAT/CERES Rice Model to solar radiation and temperature for K-C-A rice yield

	Yield ($g\ m^{-2}$)		Percentage changes	
	1985	1986	1985	1986
		Grain		
Standard simulation	1024	855	-	-
Radiation				
+ 4.19 MJ m/2	1355	1083	+32	+27
- 4.19 MJ m/2	711	615	-31	-28
Max. and Min. temperature				
+ 2 °C	922	903	-10	+ 6
- 2 °C	705	1080	-31	+26
		Straw		
Standard simulation	1152	1775	-	-
Radiation				
+ 4.19 MJ m/2	1495	2099	+30	+18
- 4.19 MJ m/2	772	1312	-36	-26
Max. and Min. temperature				
+ 2 °C	971	1429	-16	-20
- 2 °C	1318	1785	+14	+01
		Total biomass		
Standard simulation	2186	2639	-	-
Radiation				
+ 4.19 MJ m/2	2864	3193	+31	+21
- 4.19 MJ m/2	1490	1933	-32	-27
Max. and Min. temperature				
+ 2 °C	1902	2342	-13	-11
- 2 °C	2568	2875	+17	+ 9

Table C.7

Sensitivity of IBSNAT/CERES Rice Model to solar radiation and temperature for Starbonnet rice phenological events

	Day after planting(DAP)		DAP changes	
	1985	1986	1985	1986
		Panicle initiation		
Standard simulation	62	61	-	-
Radiation				
+ 4.19 MJ m/2	62	61	0	0
- 4.19 MJ m/2	62	61	0	0
Max. and Min. temperature				
+ 2 °C	56	55	- 6	- 6
- 2 °C	70	69	+ 8	+ 8
		Heading		
Standard simulation	104	94	-	-
Radiation				
+ 4.19 MJ m/2	104	94	0	0
- 4.19 MJ m/2	104	94	0	0
Max. and Min. temperature				
+ 2 °C	91	85	-13	-11
- 2 °C	119	107	+15	+13
		Physiological maturity		
Standard simulation	143	125	-	-
Radiation				
+ 4.19 MJ m/2	143	125	0	0
- 4.19 MJ m/2	143	125	0	0
Max. and Min. temperature				
+ 2 °C	125	112	-18	-13
- 2 °C	167	142	+24	+17

Table C.8
Sensitivity of IBSNAT/CERES Rice Model to solar radiation and temperature for Bellemont rice phenological events

	Day after planting(DAP)		DAP changes	
	1985	1986	1985	1986
		Panicle initiation		
Standard simulation	43	45	-	-
Radiation				
+ 4.19 MJ m/2	43	45	0	0
- 4.19 MJ m/2	43	45	0	0
Max. and Min. temperature				
+ 2 °C	38	41	- 5	- 4
- 2 °C	48	51	+ 5	+ 6
		Heading		
Standard simulation	78	76	-	-
Radiation				
+ 4.19 MJ m/2	78	76	0	0
- 4.19 MJ m/2	78	76	0	0
Max. and Min. temperature				
+ 2 °C	71	69	- 7	- 7
- 2 °C	89	86	+11	+10
		Physiological maturity		
Standard simulation	117	106	-	-
Radiation				
+ 4.19 MJ m/2	117	106	0	0
- 4.19 MJ m/2	117	106	0	0
Max. and Min. temperature				
+ 2 °C	103	96	-14	-10
- 2 °C	136	120	+19	+14

Table C.9

Sensitivity of IBSNAT/CERES Rice Model to solar radiation and temperature for Labelle rice phenological events

	Day after planting(DAP)		DAP changes from standard	
	1985	1986	1985	1986
		Panicle initiation		
Standard simulation	42	44	-	-
Radiation				
+ 4.19 MJ m/2	42	44	0	0
- 4.19 MJ m/2	42	44	0	0
Max. and Min. temperature				
+ 2 °C	37	40	- 5	- 4
- 2 °C	48	50	+ 6	+ 6
		Heading		
Standard simulation	77	75	-	-
Radiation				
+ 4.19 MJ m/2	77	75	0	0
- 4.19 MJ m/2	77	75	0	0
Max. and Min. temperature				
+ 2 °C	69	68	- 8	- 7
- 2 °C	89	85	+12	+10
		Physiological maturity		
Standard simulation	116	105	-	-
Radiation				
+ 4.19 MJ m/2	116	105	0	0
- 4.19 MJ m/2	116	105	0	0
Max. and Min. temperature				
+ 2 °C	102	94	-14	-11
- 2 °C	136	119	+20	+14

Table C.10

Sensitivity of IBSNAT/CERES Rice Model to solar radiation and temperature for IR-36 rice phenological events

	Day after planting(DAP)		DAP changes	
	1985	1986	1985	1986
		Panicle initiation		
Standard simulation	51	58	-	-
Radiation				
+ 4.19 MJ m/2	51	58	0	0
- 4.19 MJ m/2	51	58	0	0
Max. and Min. temperature				
+ 2 °C	46	53	- 5	- 5
- 2 °C	57	65	+ 6	+ 7
		Heading		
Standard simulation	89	91	-	-
Radiation				
+ 4.19 MJ m/2	89	91	0	0
- 4.19 MJ m/2	89	91	0	0
Max. and Min. temperature				
+ 2 °C	80	83	- 9	- 8
- 2 °C	102	103	+13	+12
		Physiological maturity		
Standard simulation	129	121	-	-
Radiation				
+ 4.19 MJ m/2	129	121	0	0
- 4.19 MJ m/2	129	121	0	0
Max. and Min. temperature				
+ 2 °C	113	110	-16	-11
- 2 °C	149	137	+20	+16

Table C.11

Sensitivity of IBSNAT/CERES Rice Model to solar radiation and temperature for K-C-A rice phenological events

	Day after planting(DAP)		DAP changes	
	1985	1986	1985	1986
		Panicle initiation		
Standard simulation	48	53	-	-
Radiation				
+ 4.19 MJ m/2	48	53	0	0
- 4.19 MJ m/2	48	53	0	0
Max. and Min. temperature				
+ 2 °C	43	48	- 5	- 5
- 2 °C	52	60	+ 4	+ 7
		Heading		
Standard simulation	85	85	-	-
Radiation				
+ 4.19 MJ m/2	85	85	0	0
- 4.19 MJ m/2	85	85	0	0
Max. and Min. temperature				
+ 2 °C	76	77	- 9	- 8
- 2 °C	96	97	+11	+12
		Physiological maturity		
Standard simulation	120	112	-	-
Radiation				
+ 4.19 MJ m/2	120	112	0	0
- 4.19 MJ m/2	120	112	0	0
Max. and Min. temperature				
+ 2 °C	105	101	-15	-11
- 2 °C	137	127	+17	+15

BIBLIOGRAPHY

Agrawal, R., R.C. Jain, M.P. Jha, and D. Singh. 1980. Forecasting of rice (Oryza sativa) yield using climatic variables. Indian J. Agric. Sci. 50(9):680-684.

Alva, A.K., and S.W. Bille. 1981. Diagnostic techniques for cereals based on plant analysis I. Stage of plant development. Commun. in Soil Sci. Plant Anal. 12(12): 1207-1225.

Angus, J.F. and H.G. Zandstra. 1980. Climatic factors and the modeling of rice growth and yield. p189-199. In Agrometeorology of the Rice Crop. IRRI/WMD.

Baier, W. 1977. Crop weather models and their use in yield assessments. Tech. Note 151. World Meteorological Organization, Geneva, Switzerland.

Barber, S.A. and J.H. Cushman. 1981. Nitrogen uptake model for agronomic crops. p382-409. In I.K. Iskandar (ed.) Modeling Waste Water Renovation Land Treatment. J. Wiley and Sons Inc., New York.

Beek, J. and M.J. Frissel. 1973. Simulation of Nitrogen Behavior in Soil. Pudoc. Wageningen.

Bolton, F.R. and H.G. Zandstra. 1981. A soil moisture-based yield model of wet land rainfed rice. IRRI Res. Pap. Ser.62. 10p.

Byrnes, B.H., N.K. Savant, and E.T. Craswell. 1983. Effect of a Urease inhibitor phenyl phosporodiamidate on the efficiency of Urea applied to rice. Soil Sci. Soc. Am. J. 47:270-274.

Chang, J.H. 1985. A climatological analysis of yield difference between the first and second rice crop in Taiwan. Agricultural and Forest Meteorology 36: 113-120.

Chaudhry, M.S. and E.O. McLean. 1963. Comparative effects of flooded and unflooded soil conditions and nitrogen application on growth and nutrient uptake by rice plant. Agronomy J. 55:565-567.

Chowdhury, S.I. and I.F. Wardlaw. 1978. The effect of temperature on kernel development in cereals. Aust. J. Agric. Res. 29:205-223.

da Mota, F.S. 1980. Meteorological aspect of rice production in Central and South America--current and future. p9-17. In Agrometeorology of the Rice Crop. World Meteorological Organization and International Rice Research Institute. Los Banos, Philippines.

da Mota, F.S. and J.B. da Silva. 1980. A weather technology model for rice in Southern Brazil. p235-238. In Agrometeorology of the Rice Crop. World Meteorological Organization and International Rice Research Institute. Los Banos, Philippines.

De Datta, S.K. 1981. Principles and Practices of Rice Production. John Wiley & Sons. New York.

Dijkshoorn, W. and M. Ismunadji. 1972. Nitrogen nutrition of rice plants measured by growth and nutrient content in pot experiments. 3. Changes during growth. Neth. J. Agric. Sci. 20:133-144.

Fernandes, M.S. 1984. N-carriers, light and temperature influences on uptake and assimilation of nitrogen by rice seedlings. Turrialba 34(1):9-18.

Fujita, K., V.P. Coronel, and S. Yoshida. 1984. Grain filling characteristics of rice varieties (Oryza sativa L.) differing in grain size under controlled environmental conditions. Soil Sci. Plant Nutr. 30(3):445-454.

Godwin, D.C., C.A. Johes, J.T. Ritchie, P.L.G. Vlek, and L.J. Youngdahl. 1984. The water and nitrogen components of CERES models. p101-106. In Minimun Data Sets for Agrotechnology Transfer. Proceeding of the International Symposium at ICRISAT center. Patancheru, India.

IBSNAT Project. 1986. Technical Report 5, Decision Support System for Agrotechnology Transfer (DSSAT), Documentation for IBSNAT Crop Model Input and Output Files, Version 1.0.

Ishizuka, Y. 1965. Nutrient uptake at different stage of growth. p198-218. In The Mineral Nutrition of Rice Plant. Symposium Proceedings. International Rice Research Institute.

Iwaki, H. 1977. Computer simulation of growth process of paddy rice. JARQ 11(1):6-11.

Jones, C.A. and J.R. Kiniry (eds.) 1986. CERES-Maize: A Simulation Model of Maize Growth and Development. Texas A & M University Press. College Station, Texas, USA.

Jones, D.B., M.L. Peterson, and S. Geng. 1979. Association between grain filling rate and duration and yield components in rice. Crop Sci. 19:641-644.

Lin, H.C. and T.S. Chang. 1976. The influences of temperature and light-climate on the growth and nutrition of rice plant I. The influence on the vegetative growth of rice plant. J. of Chinese Agricultural Chemical Society 14(3-4):208-221.

Matsushima S. 1965. Nitrogen requirements at different stages of growth. p219-242. In the Mineral Nutrition of Rice Plant. Proceedings of a Symposium at the International Rice Research Institute.

McMennamy, J.A. and J.C. O'Toole. 1983. RICEMOD: A physiologically based rice growth and yield model. IRPS No.87.

Moore, P.A., J.T. Gilmour, and B.R. Wells. 1981. Seasonal patterns of growth and soil nitrogen uptake by rice. Soil Sc. Soc. Am. J. 45:875-879.

Murata, Y. 1975. Estimation and simulation of rice yield from climatic factors. Agricultural Meteorology 15: 117-131.

Murayama, N. 1968. Nitrogen nutrition of rice plant. JARQ 2:1-5.

Nishiyama, I. 1976. Effects of temperature on the vegetative growth of rice plants. p159-185. In International Rice Research Institute Climate and Rice.

Nowick, E.M. and H.Hoffpauir. 1984. Varietal differences in nitrogen uptake at two N levels and three growth stages. p51-55. In 76th Annual Progress Report, Rice Research Station. Crowley, Louisiana.

Okajima, H. 1976. Environental factors and nutrient uptake. p63-73. In the Mineral Nutrition of the Rice Plant. Proceedings of a Symposium at the International Rice Research Institute.

Olsen, R.A. and L.T. kurtz. 1982. Crop nitrogen requirements, utilization, and fertilization. p567-604. In F.J. Stevenson (ed) Nitrogen in Agricultural Soils. Agronomy Monograph No.22. ASA Inc. Madison, Wisconsin.

Owen, P.C. 1971. The effects of temperature on the growth and development of rice. Field Crop Abstracts 24:1-8.

Owen, P.C. 1972. Effects of night temperature on growth and development of IR8 Rice. Exper. Agric. 8:213-218.

Patnaik, S. and M.V. Rao. 1979. Sources of nitrogen for rice production. p25-44. In Nitrogen and Rice. International Rice Research Institute. Los Banos, Philippines.

Rao, M.V., B.B. Reddy, B.B. Ghosh and M.M. Panda. 1985. Nitrogen management in direct sown intermediate deep water rice (15-50cm) I. Effect of form, method, and time of urea N application on growth, yield, and N uptake. Plant and Soil 83(2):243-253.

Ritchies, J.T. and S. Otter. 1985. Description and performance of CERES-Wheat: A user-oriented wheat model. In W.O. Willis (ed.), ARS Wheat Yield Project, and Agric. Res. U.S. Dep. Agric. Res. Serv. 38: 159-175.

Ritchie, J.T., E.C. Alocilja, U. Singh and G. Uehara. 1986. IBSNAT/CERES Rice Model. Agrotechnology Transfer No.3:1-5.

Robertson, G.W. 1975. Rice and weather. Tech. Note 144. World Meteorol. Org. Geneva, Switzerland.

Russell, D.A., D.M. Henshaw, C.E. Shauble, and R.B. Diamond. 1970. High-yielding cereals and fertilizer demand. Natl. Fert. Dev. Cent., Tenn. Val. Auth. Muscle Shoals, Ala. Bull. Y-4.

Sarkar, R.P. 1980. Acquisition and analysis of rice and weather data. p101-114. In Agrometeorology of Rice Crop. World Meteorological Organization and International Rice Research Institute. Los Banos, Philippines.

Sato, K. 1971. The development of rice grains under controlled environment II. The effect of temperature combined with air-humidity and light intensity during ripening on grain development. Tohoku Journal of Agricultural Research 22(2):69-79.

Sato, K. 1979. High temperature damage to ripening in rice plant. JARQ 13(2):90-95.

Sato, K. and M. Takahashi. 1971. The development of rice grains under controlled environment I. The effects of temperature, its daily range and photoperiod during ripening on grain development. Tohoku Journal of Agricultural Research 22(2):57-67.

Sato, K., K. Inaba, K. Honjo, and S. Haruyama. 1974. The development of rice grains under controlled environment IV. Properties of temperatures combined with different light intensity and air-humidity. Tohoku Journal of Agricultural Research 25(3):97-103.

Seligman, N.G. and H. van Keulen. 1981. PAPRAN: A simulation model of annual pasture production limited by rainfall and nitrogen. In M.J. Fissel and J.A. van Veen (eds.) Simulation of Nitrogen Behavior of Soil Plant Systems. Pudoc, Wageningen, Neth..

Seshu, D.V. and F.B. Cady. 1984. Response of rice to solar radiation and temperature estimated from international yield trials. Crop Sci. 24(4):649-654.

Singh, U. 1985. A crop growth model for predicting cron (Zea Mays L.) performance in the tropic. Ph. D. Dissertation submitted to graduate division of the University of Hawaii.

Stangel, P.J. 1979. Nitrogen requirement and adequacy of supply for rice production. p45-69. In Nitrogen and Rice. International Rice Research Institute. Los Banos, Philippines.

Ta, T.C. and K. Ohira. 1981. Effects of various environmental and medium conditions on the response of Indica and Japonica rice plants to ammonium and nitrate nitrogen. Soil Sci. Plant Nutr. 27:347-355.

TA, T.C. and K. Ohira. 1982. Effects of temperature and light intensity on the uptake and assimilation of ^{15}N-labelled ammonium and nitrate in Indica and Japonica rice plants. Soil Sci. Plant Nutr. 28(1)91-98.

Thornley, J.H.M. 1976. Mathematical Models in Plant Physiology. Academic Press, London.

van Keulen, H. 1978. Simulation of influence of climatic factors on rice production. p345-358. In Climatic Change and Food Production: proceedings of an international symposium. University of Tokyo Press, Tokyo.

Vergara, B.S. and T.T. Chang. 1976. The Flowering Response of the Rice Plant to Photoperiod. Int. Rice Res. Inst. Tech. Bull. 8. 75p. Los Banos, Philippines.

Wada, G. 1969. The effects of nitrogenous nutrition on the yield-determining process of rice plant. Bull. Natl. Inst. Agric. Sci. 16:127-167.

Yoshida, S. 1973. Effects of temperature on growth of the rice plant (Oryza sativa L.) in a controlled environment. Soil Sci. Plant Nutri. 19(4):299-310.

Yoshida, S. 1981. Fundamentals of Rice Crop Science. The International Rice Research Institute. Los Banos, Philippines.

Yoshida, S. and F.T. Parao. 1976. Climatic influence on yield and yield components of lowland rice in the tropics. p471-494. In Climate and Rice. International Rice Research Institute. Los Banos, Philippines.

Yoshida, S. and T. Hara. 1977. Effects of air temperature and light on grain filling of an Indica and Japonica Rice (Oryza sativa L.) Under controlled environmental conditions. Soil Sci. Plant Nutr. 23(1):93-107.