COMPUTER SIMULATION OF PINEAPPLE GROWTH, DEVELOPMENT AND YIELD

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
MAY 1992

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This dissertation is dedicated to my parents, Huiqing and Yanglong Zhang, and my best and closest friend Xiaowen Zheng.

ACKNOWLEDGMENT

The central contribution of the CERES-Maize Model, which served as a framework for the construction of ALOHA-Pineapple, is acknowledged. The support of the Hawaii pineapple industry and the Governor's Agricultural Coordinating Committee is also gratefully acknowledged.

I would like to thank Dr. Duane Bartholomew for his advice, his guidance, encouragement, patience, love, and care during my five years as a graduate student. His teaching, guidance, encouragement, and patience built up my academic knowledge and living skills. His love and care built up my self-confidence. He is much more than an advisor in research. He is a great teacher, a counselor and a father. I also wish to thank his wife Mrs. Sally Bartholomew for her love, care, and help.

I am indebted to Dr. Wallace Sanford for his invaluable comments on the experimental design and data collection. I also appreciate Dr. James Silva's comments on the experimental design, Dr. H. Ikawa's assistance in installing the weather station, and John Lee's help in program debugging.

Special thanks are given to Calvin Oda for his assistance in providing and selecting the experimental plots and to Del Monte personnel at Kunia for their assistance in field maintenance.

I gratefully acknowledge the following individuals for their invaluable assistance in data collection: Jessica and Huifeng Chang, Dongmei Zhang, Lin Qiu,

Tingting Zhou, Lin Xie, Stella Chang, Jung-ying Lu, Corry Young, Xiangjia Min, Yinong Xing, Zhaoliang Lu, Stanley Oshita, Victoria Lasmarias, and Nick Hahn.

Special thanks are extended to Drs. R. Caldwell, E. Graser, K. Kobayashi, and G. Uehara for serving as members of my committee and for providing support, encouragement, and help throughout the course of my studies. I also wish to thank Dr. R. Green and Dr. S.A. El-Swaify for their spiritual and financial support, and thank the department secretaries Gayle, Susan, and Kathy for their assistance.

Finally, I thank my girlfriend Xiaowen Zheng for her love, encouragement, and support during a critical time in my studies.

ABSTRACT

Fruit yield and harvest date of pineapple [*Ananas comosus* (L.) Merr.] are difficult to predict. Site-specific studies improve the predictability at one location but usually cannot be generalized to other environments. This study examined the effects of plant population density (PPD) and planting date (PD) on pineapple growth and fruiting and the data were used to develop a pineapple growth simulation model. 'Smooth Cayenne' pineapple was planted at Kunia, Hawaii; the crop was drip-irrigated. PPDs ranged from 2.61 to 12.81 plants m^{-2} and PDs were June and August 15, and October 18, 1989. Flower development was forced with ethylene on September 18, 1990. Leaf emergence rate was constant until 200 days after planting (DAP) and then decreased 0.9 leaves 1000-°C-day^{-1} with each increase in PPD of one plant m^{-2}. Dry weight per plant decreased as PPD increased and as PD was delayed. Light interception reached 95% at a leaf area index of 4 to 5, which was attained at 350 DAP at 12.81 plants m^{-2} and later as PPD decreased. Dry matter partitioning (DMP) to leaves and stem during vegetative growth was not affected by PPD or PD. DMP to stem during fruiting decreased linearly and DMP to fruit increased curvilinearly as PPD increased and as PD was delayed. Fruit harvest date was delayed seven days for each PPD increase of 2.5 plants m^{-2} from 2.61 to 12.81 plants m^{-2}. Fruit yield was asymptotically related to PPD; the economic yield-PPD relationship was parabolic. There was no effect of PD on rate of leaf emergence or fruit development. A pineapple simulation model (ALOHA-Pineapple) was developed

using data from the experiment and the literature. ALOHA-Pineapple is process-oriented and incremented daily. It simulates the effects of PPD, PD, plant size at planting and forcing, and weather on crop growth and yield. When ALOHA-Pineapple was validated with data from eleven plantings in four locations in Hawaii, pineapple growth, fruit development and yield was simulated with reasonable accuracy although harvest date and yield were over- and under-predicted in some locations. ALOHA-Pineapple has potential to serve as a frame-work for pineapple research and as a decision aid for farmers.

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LIST OF SYMBOLS

1T	Fruits with a diameter greater than 9.5 cm but less than or equal to 10.8 cm.
2.5T	Fruits with a maximum diameter greater than 13.65 cm.
2T	Fruits with a diameter greater than 10.8 but less than or equal to 13.65 cm.
A	Green leaf area per plant.
A_0	Initial green leaf area per plant.
AdjR-SQ	Adjusted coefficient of determination.
AI	Agreement Index.
ANOVA	Analysis of variance.
ATGU	Air temperature growth-unit.
BL	Leaf basal tissue dry weight per plant.
BL_0	Initial leaf basal tissue dry weight per plant.
BLWPC	Leaf basal tissue weight partitioning coefficient.
BLWR	Leaf basal tissue weight ratio.
D	Fruit development rate (day^{-1}).
DAP	Days after planting.
DMP	Dry matter partitioning.
FLI	Fraction of light intercepted.
FLT	Fraction of light transmitted.
FOF	Fraction of the total fruits for that designated size.
FY_{tot}	Total fruit yield (Mg ha^{-1}).

FY_{zisc}	Yield (Mg ha^{-1}) of a specific size of fruits.
GDD	Growing degree-days.
GDH	Growing degree-hour.
LAR	Green leaf area ratio.
GLM	General linear model.
LWPC	Green leaf weight partitioning coefficient.
LWR	Green leaf weight ratio.
GROSUB	A subroutine for growth in ALOHA-Pineapple.
FWR_H	Fruit-plant weight ratio at harvest.
SWR_H	Stem-plant weight ratio at harvest.
I_a	Photosynthetic photon flux density above the canopy.
I_b	Photosynthetic photon flux density below the canopy.
K_a	The relative growth rate of green leaf area (cm^2 cm^{-2} d^{-1}).
K_b	Relative growth rate of leaf basal tissue (g g^{-1} d^{-1}).
K_l	Relative growth rate of green leaf tissue (g g^{-1} d^{-1}).
K_s	Relative growth rate of stem (g g^{-1} d^{-1}).
K_w	Relative growth rate of plant (g g^{-1} d^{-1}).
L	Green leaf dry weight per plant.
L_0	Initial green leaf dry weight per plant.
LACKFIT	Lack of fit.
LAI	Leaf area index, green leaf area index for pineapple.
LANR	Ratio of green leaf area to leaf number.

LAP	Leaf area partitioning coefficient.
LER	Leaf emergence rate in leaves day^{-1}.
LN	Leaf number.
Log_e	Natural logarithm.
MSEP	Mean squared error of prediction.
NAA	Naphthaleneacetic acid.
NAR	Net assimilation rate (g m^{-2} d^{-1}).
P/m^2, Pm^{-2}	Plants per meter square.
P1VOTH	Planting 1 vs other plantings.
P2V3	Planting 2 vs Planting 3.
PD	Planting date.
PHASEI	A subroutine for phase initiation in ALOHA-Pineapple.
PHENOL	A subroutine for phenological development in ALOHA-Pineapple.
PHL	Phyllochron.
PI	Planting 1 (planted on June 15, 1989).
PII	Planting 2 (planted on August 15, 1989).
PIII	Planting 3 (planted on October 18, 1989).
PPA	Plants per acre.
PPD	Plant population density.
PPFD	Photosynthetic photon flux density.
PPH	Plants per hectare.
R^2	Coefficient of determination.

R1	A growth stage of pineapple where leaf initiation ceases, leaf and root growth decline.
R2	A growth stage of pineapple where the first flower primordia to develop on the youngest flower completely encloses the petal primordia, indicating the end of flower initiation.
R3	A growth stage of Pineapple where leaf growth ceases, and flowering begins.
R4	A growth stage of pineapple where flowering ends, fruit growth (if any, sucker initiation).
R5	A growth stage of pineapple where fruitlet growth end.
R6	A growth stage of pineapple where fruit maturation occurs and sucker growth is initiated.
REG	Regression.
Root MSE	Root mean square error.
RGR	Relative growth rate ($g\ g^{-1}\ d^{-1}$).
RSREG	Response surface regression.
S	Stem dry weight.
S_0	Initial stem dry weight.
S1T	Fruits having a maximum diameter less than 9.5 cm.
SAS	Statistic Analysis System.
S_{dm}	Standard deviation of the mean of the differences.
SLAE	Specific green leaf area expansion.
SLAR	Specific green leaf area ratio.
SWPC	Stem weight partitioning coefficient.
SWR	Stem weight ratio.

T_m	Mean air temperature (°C).
V1	A growth stage used in ALOHA-Pineapple that defines the time of root initiation.
V2	A growth stage used in ALOHA-Pineapple defining the emergence of the first new leaf.
V3	A growth stage used in ALOHA-Pineapple defining dry matter partitioning, mostly to new growing leaves and roots with no net stem growth.
V4:	A growth stage used in ALOHA-Pineapple that defines the beginning of stem growth.
W	Total plant dry weight.
W_0	Initial total plant dry weight.
$\partial LN/\partial GDD$	Leaf emergence rate (leaves degree-day^{-1}).

PART I. GENERAL INTRODUCTION

CHAPTER 1

INTRODUCTION

Pineapple [*Ananas comosus* (L.) Merr.] is the only commercial food crop among the approximately 1400 known species in the family of Bromeliaceae. It is intensively and commercially cultivated over a wide range of latitudes from approximately 30° N to 34° S (Bartholomew and Kadzimin, 1977). The major production areas include Hawaii, the Philippines, Ivory Coast, Kenya, Costa Rica, Australia, Malaysia and Thailand. Pineapple is the second most important crop in Hawaii in dollar value and has contributed considerably to the state's economy.

1.1 PROBLEMS OF PINEAPPLE FARMERS AND LIMITATION OF TRADITIONAL EXPERIMENTS

A significant problem of pineapple farmers is the low predictability of fruit yield and harvest date. This makes it difficult to manage the crop and the use of resources. Fruit yield is the end product of complex processes of plant growth and development and harvest date is a timestep in these processes. Both yield and harvest date are influenced by a variety of variables including cultivar (or clone), soil, weather, pests and diseases, plant population density, fertilizer levels and other practices. The effects of many agronomic practices and environmental factors on pineapple growth, development and yield have been studied extensively (Bartholomew and Kadzimin, 1977; Py, et al., 1987). In spite of the effort, the prediction of

harvest date and yield of pineapple is still done by experienced field personnel using historical information or by simple heat unit models (Medcalf, 1949; Fleisch and Bartholomew, 1987). This might be due to the limitation of traditional experiments that can only statistically test the effect of a few factors and the effect of all variables on fruit yield and harvest date cannot be easily expressed by simple mathematical equations. With the development of high speed computers and high performance instruments, simulating the complexities of plant growth and development in response to a changing environment becomes possible. The improvement in predictability of yield and harvest dates hypothetically could be achieved using plant growth and development simulation models.

1.2 SIMULATION MODELS IN AGRICULTURE

A plant growth and development simulation model explicitly accounts for the effects of genetic characteristics, soil properties, management strategies and meteorological conditions on crop performance. It simulates the effects of changing variables over time. Dynamic plant growth simulation models have been developed in recent years for such crops as cotton (COTCROP) (Jones, et al. 1980), soybean (SOYGRO) (Wilkerson et al. 1983), beans (BEANGRO) (Hoogenboom, et al. 1991) and maize (CERES-maize) (Jones and Kiniry, 1986). These models, except for COTCROP, have been integrated into Decision Support System for AgroTechnology Transfer (DSSAT) by International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT, 1988 and 1989). Also, a comprehensive simulation model

(CROPSYS) for multiple cropping has been developed by Caldwell and Hansen (Caldwell, personal communication). The model simulates the performance of temporal and spatial combinations of crops in response to genotype, environment and management. Little work has been done to develop a pineapple model because of the high cost associated with the development of a comprehensive model and of lack of quantitative information on pineapple plant-environment relationships (Bartholomew, personal communication).

Fleisch (1988) developed regression models that predict pineapple vegetative growth, leaf area development, and development of the inflorescence after forcing. However, he did not integrate (or unify) the models into a comprehensive simulation model to predict plant growth and fruit yield, and his models did not account for genotype or management. The models were sufficiently empirical that further development, or calibration for other locations, was assumed to be extremely difficult.

A preliminary simulation model of pineapple growth was developed by revising some of the CERES-Maize subroutines using unpublished data from Hawaii and from the pineapple research literature. However, phenological development in the model did not account for plant population density effects on growth and yield because of a lack of quantitative information. Air temperature and photoperiod are the dominant factors affecting phenological development of maize (Jones and Kiniry, 1986). Pineapple leaf emergence rate and fruit development are assumed not to be sensitive to photoperiod but are influenced by air temperature and plant exposure to sunlight, which is influenced by plant population density.

1.3 IMPORTANCE AND NECESSITY OF DEVELOPING A FRAMEWORK

Rimmington and Charles-Edwards (1987) classified research activity in the agricultural sciences into three types: 1) the acquisition of knowledge, 2) the ordering of knowledge and the development of understanding based on that knowledge, and 3) the application of knowledge and/or understanding to the solution of practical problems. The priority assigned to the three types of activities is usually consistent with their numerical order.

Typically, breakthroughs in research come out of an accumulation of knowledge, which increases our understanding of processes. With regard to pineapple, little attention has been paid to the systematic acquisition of basic knowledge. Most research efforts have emphasized activities of the third type, in hopes of solving practical problems immediately. This inverted the priority of pineapple research activities because in the short run, these activities seem worthy in terms of return of profit. In the long run, they are of limited value because they are all problem oriented, and such research activities are not closely related and lack continuity. In other words, there is no theme in pineapple research so steady progress towards a comprehensive understanding of the crop is slow. Time and money might be wasted on some research activities, for example, repeated plant population density trials. There is, therefore, a need to integrate the pineapple research literature, establish a data bank, and develop a framework for pineapple within which is able to carry out development, testing, and validation with available experimental techniques and data. The framework should have system concepts so that its main components

are amenable either to direct measurement or to inference from plant growth data. The framework must be detailed enough to interface observations of growth at the whole-plant level with more detailed knowledge of the underlying plant growth processes. The advantages of developing a framework are:

(1) Establishing a theme in pineapple research.

(2) Guiding experimental data collection, for example, what data are necessary to collect in order not to conduct the experiment again.

The objectives of this study were to:

I. Quantify the responses of pineapple growth and development to plant population density and plant size within a population at forcing.

II. Develop a pineapple simulation model (CERES-PINEAPPLE), based on CERES-MAIZE model (Jones and Kiniry, 1986) subroutine structures and growth data for pineapple obtained from the literature and from recent field experiments.

PART II. EXPERIMENTAL BASE: RESPONSE OF PINEAPPLE TO PLANT POPULATION DENSITY AND PLANTING DATE

INTRODUCTION

Manipulation of plant population density is one of the most important agronomic practices available to pineapple growers. Early in this century, plant population densities used in Hawaii were about 30,000 to 34,600 plants per hectare (PPH) (12,000 to 14,000 plants per acre (PPA)). As late as the 1970s, plant populations were as low as 10,000 to 15,000 PPH (4,000 to 6,000 PPA) in India (Ghosh and Medhi, 1981). With improvements in agronomic practices, such as drip irrigation, plant population densities currently range from 54,000 to 81,500 PPH (22,000 to 33,000 PPA) depending on the soil type, aerial environment, and desired fruit size (W.G. Sanford, personal communication; D.P. Bartholomew, personal communication).

Several studies have been conducted to determine the optimal plant population density for specific areas where pineapple is grown. No work has been done to study quantitatively the effect of plant population density and plant size on morphogenesis, fruit development, and canopy light interception of pineapple. In order to develop a growth simulation model of pineapple, information is needed on the effects of plant population density and planting date on leaf emergence rate, dry matter partitioning, and fruit development.

Therefore, the objectives of the study were to:

1) Quantify the relationships between leaf emergence rate and air temperature and plant population density.

2) Examine the vegetative growth responses of pineapple to plant population density and planting date.

3) Examine the effects of plant population density and planting date on canopy development and light interception, and quantify the relationship between canopy light interception and leaf area index.

4) Examine the effects of plant population density and planting date on reproductive development and fruit yield, and quantify the relationship between fruit development and plant population density and plant size within population.

CHAPTER 2

LEAF EMERGENCE AND ITS RELATION TO PLANT POPULATION DENSITY AND AIR TEMPERATURE

2.1 INTRODUCTION

Leaf initiation and expansion are the major morphogenetic processes of crops. Pineapple mass is mostly leaves (up to 90 percent of total plant weight (Py, et al., 1987)). Growth depends on leaf development. Predicting plant growth requires an understanding of the effects of environment and management on leaf emergence. In some dynamic crop growth models, simulating the number of new leaves emerged is a key step in predicting vegetative growth.

Air temperature and daylength are the two primary environmental factors affecting leaf emergence rate of cereal crops (Cao and Moss, 1989a, 1989b; Baker et al., 1980). In the CERES-Maize model, air temperature and photoperiod were considered in simulating leaf emergence (Jones and Kiniry, 1986). Shiroma (1972) reported that leaf emergence rate of 'Smooth Cayenne' pineapple was a function of air temperature in Okinawa, Japan. However, plots of leaf emergence vs. temperature (unpublished data collected from Maui and Oahu, Hawaii), indicated that factors other than temperature could affect leaf emergence rate of pineapple. Plant exposure to sunlight, plant temperature, daylength, and soil temperature also might be important. Those factors, except for soil temperature and daylength, are difficult to measure. Plant population density directly affects plant and soil exposure to sunlight, and at

some age, likely affects soil and plant temperature as well. This study was conducted primarily to quantify the effect of plant population density on leaf emergence rate of field-grown pineapple. The effect of air temperature as it varied over season on leaf emergence rate was also evaluated.

2.2 LITERATURE REVIEW

Leaf emergence rates of crops are determined by genotype, environment and management. For a given cultivar and a set management practices, the leaf emergence rate is mainly influenced by environment.

A number of experiments have been conducted to determine the factors that influence leaf emergence of cereal crops. Gallagher (1979) reported that wheat leaf appearance rate slowed during mid-winter and increased during spring. Both wheat and barley leaf number increased linearly with thermal time (Gallagher, 1979). The reciprocal of the slope, called the phyllochron (degree-days required for the emergence of one leaf), was constant for both crops. The CERES-maize model uses a constant phyllochron to predict leaf emergence (Jones and Kiniry, 1986).

However, others have shown that the leaf emergence rate (leaves degree-day^{-1}) of cereal crops also varied with genotype (Bauer et al., 1984, Delecolle et al., 1984; Baker et al., 1986) and sowing date (Kirby et al., 1982; Baker et al., 1980). The effect of sowing date on leaf emergence was due to a change in daylength (Baker et al. 1980; Kirby et al., 1982; Delecolle et al., 1984; Kirby and Perry, 1987). Cao and Moss (1989a) confirmed the effect of daylength on leaf emergence rate of wheat

and barley under controlled environments. They found that leaf emergence rate increased curvilinearly with increasing daylength. Cao and Moss (1989b) also found that the phyllochron of wheat and barley was not constant in controlled environments, but increased exponentially as temperature increased. Furthermore, the relationship between temperature and leaf emergence rate (leaves day^{-1}) was quadratic. The relationship between leaf emergence rate (leaves day^{-1}) in maize (*Zea mays* L.) and temperature in a controlled environment was best described by a cubic equation (Tollenaar et al., 1979) or a fourth-degree polynomial equation (Warrington and Kanemasu, 1983). This indicates that the thermal efficiency varies in different temperature regimes.

Hay and Wilson (1982) found that leaf emergence of winter wheat was better correlated with soil temperature than with air temperature. Bauer et al. (1984) reported that soil water content and fertilizer N had no effect on main-stem leaf emergence in spring wheat. On the contrary, Baker et al. (1986) found that drought reduced the phyllochron (or increased leaf emergence rate). This was thought to be the results of the drought-stressed plants accumulating thermal units faster because they were warmer than the well-watered plants.

Few data were reported on the effect of environment on pineapple leaf emergence. Shiroma (1972) found that for 'Smooth Cayenne' pineapple, leaves per month increased exponentially as average monthly air temperature increased. Friend and Lydon (1979) reported that the total number of leaves and primordia of Smooth Cayenne pineapple at 692 days after planting increased with increasing daylength in

controlled environments. The result, however, appears to be confounded because they also reported that plants in an 8-h daylength started flowering 600 days after planting while plants under 16-h remained vegetative. Thus, at 692 days after planting, plants in 16 hr days initiated leaves three months longer than those in 8 hr days. Whether the leaf emergence rate (leaves day^{-1}) under different daylengths differed was not determined.

The factors influencing leaf emergence of pineapple might differ from those influencing cereal crops. Pineapples are propagated vegetatively, and they do not go through a true juvenile stage. Plant temperature might be the primary factor influencing leaf emergence of pineapple.

2.3 MATERIALS AND METHODS

2.3.1 General Experimental Description

The experiment was located at an elevation of about 216 meters above sea level in a Del Monte Company field at Kunia, Oahu, Hawaii. Pineapple (*Ananas comosus* (L.) Merr.) crowns were planted on June 15 (PI), August 15 (PII) and October 18 (PIII), 1989. All plants in the three plantings were forced to flower on September 18, 1990 by applying ethylene to the plants. Because of management and field-area constraints, planting date was not randomized or replicated. At each planting date (PD), plant population densities (PPD) of 2.61, 5.22, 7.83, 10.06, and 12.81 plants m^{-2} were established. Plant population density treatments were replicated three times and the treatments were arranged in a randomized complete block design

(Fig 2.1). Treatment plot size within each replicate was varied to assure that each plot contained a minimum of 325 plants/plot in at least three beds. In three-bed plots, data were collected only from the center bed.

Prior to planting, the field area was subsoiled, disk harrowed, the soil was fumigated with 1,3-dichloropropene for initial control of nematodes according to company practices, and plastic mulch was laid to retard fumigant loss. At each planting date, fresh tops from fruit (crown) of the Smooth Cayenne pineapple clone Champaka 153 from a plantation field were selected to achieve relative uniformity of crown size within a planting date. Average data on the crowns used in each planting are shown in Table 2.1.

Table 2.1 Average crown fresh and dry weights at planting for June (PI), August (PII), and October (PIII) plantings (n=50).

Planting	Fresh Weight (g)	Standard deviation	Dry weight (g)	Standard deviation
PI	142.5	21.0	22.9	3.6
PII	130.7	17.0	20.0	3.2
PIII	307.2	61.0	35.6	7.6

The crowns were planted in two-row beds spaced 112 cm apart on centers with rows spaced 51 cm apart on the beds. Each plot was 9.75 m long. Plant spacings of 69, 38, 23, 18, and 14 cm were used to achieve the desired plant population densities. To accommodate at least 325 plants in each plot, including borders, the number of beds per plot was varied; there were 12, 6, 3, 3, and 3 beds per plot with the highest number of beds at the lowest plant population density.

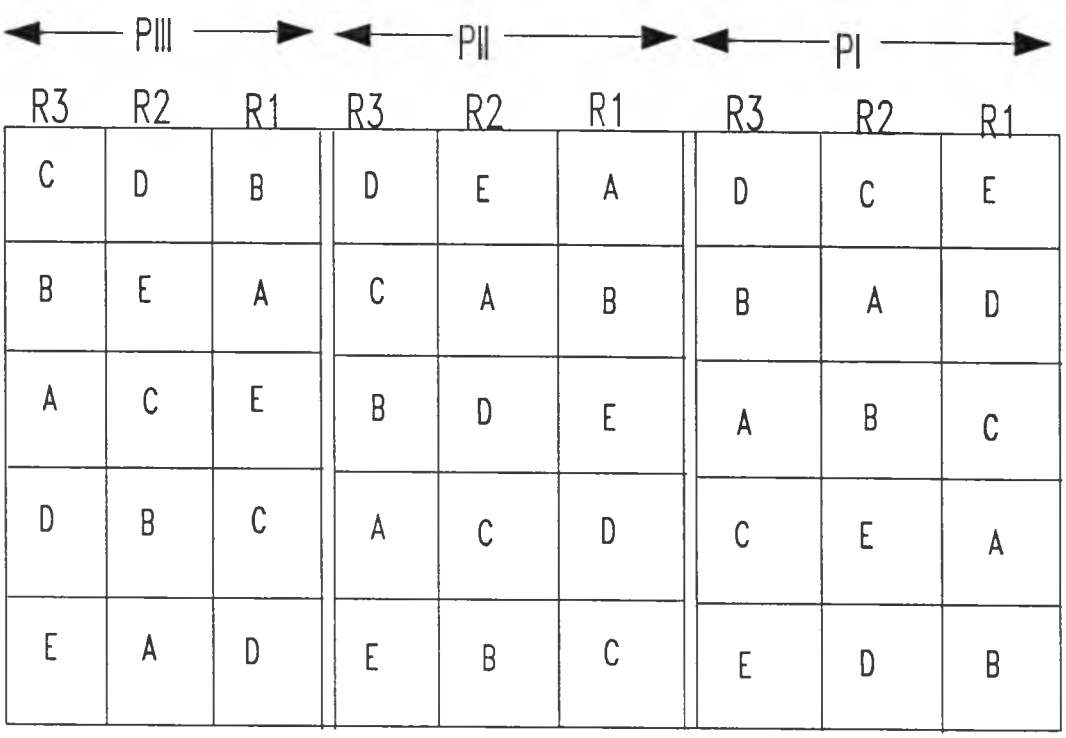


Fig. 2.1 Experimental layout of Kunia plant population density trials. A to E are plant population density 2.61, 5.22, 7.83, 10.06, and 12.81 plants m^{-2}, respectively. PI, PII and PIII are planting date June 15, August 15, and October 18, 1989, respectively. R1, R2 and R3 are replications.

Plants were maintained by Del Monte Plantation field personnel according to their field practices. Plants were drip irrigated, usually weekly, during periods when rainfall was low. Near-optimum levels of nutrients were maintained by injecting fertilizer through the drip irrigation system and by foliar spray.

A weather station (Campbell Scientific CR-21 weather data logger) was installed in the field adjacent to the experiment. Air temperature at a height of 2.0 m above bare soil was measured with a YSI 401 thermister temperature probe mounted under a radiation shield. A LI-COR LI 200S pyranometer was used to measure solar radiation. Sensors were sampled once each minute by the data logger and recorded values were a 30 minute total for solar radiation and a 30 minute average for air temperature. Daily values for maximum, minimum and average air and daily maximum, minimum and total solar radiation were also recorded and stored on a cassette tape. The tape was changed monthly. The data were transferred to a personal computer for analysis.

Missing values were estimated using data collected from a weather station at the Hawaiian Sugar Planters Association Kunia Substation located approximately 2.0 km to the east of the experiment. Fig. 2.2 shows the correlation between the two stations for total solar radiation, and maximum and minimum air temperature.

2.3.2 Data Collection and Analysis

New leaf emergence was recorded in the five plant population densities for PI and PII by counting leaves emerged over a specific time period, usually one month. The youngest visible leaf was marked on ten pre-designated plants from each plot

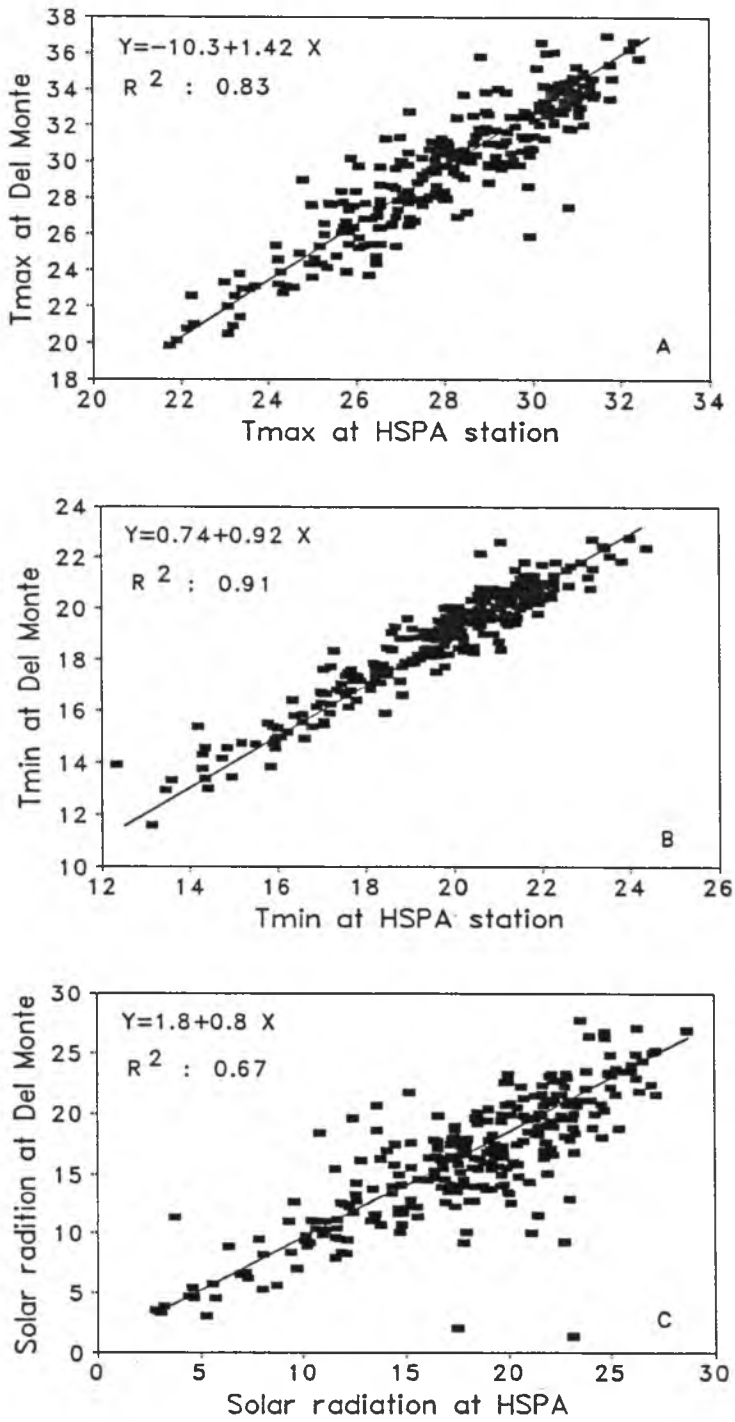


Fig. 2.2 Maximum air temperature (Tmax, °C, A), minimum air temperature (Tmin, °C, B), and daily total solar radiation (MJ m^{-2}, C) and their respective correlations between Del Monte research plots and the Hawaiian Sugar Planter's Association (HSPA) research station at Kunia, Hawaii.

every month using India ink. Plants in PI were first marked on August 4, 1989 (50 days after planting) and those in PII were first marked on October 19, 1989 (65 days after planting). Recording of leaf emergence data ended at the time inflorescence development was forced.

Thermal time (growing degree-days, GDD) during the period of measurements was calculated from: $\sum \{[(Tmax-Tmin)/2] - T_b\}$, where Tmax and Tmin are daily maximum and minimum air temperature, respectively, and T_b is the base temperature at which leaf growth ceases.

The following models were used to fit the field data:

$$Y=\beta_0 + \beta_1 X1_i + \beta_2 X2_i + \beta_3 X1_i X2_i + \epsilon_i \qquad (2.1)$$

$$Y=\beta_0 + \beta_1 X1_i + \beta_2 X2_i + \beta_3 X1_i^2 + \beta_4 X2_i^2 + \beta_5 X1_i X2_i + \epsilon_i \qquad (2.2)$$

where Y is the predicted value, $\beta 0$ to βn are model parameters, i=1 to n are observations, ϵ is the error.

Best-fit regression models were calculated using SAS REG and RSREG procedures (SAS Institute, 1985). The regression equations were generated and they were used to generate response surfaces for the number of emerged leaves and leaf emergence rate.

2.4 RESULTS AND DISCUSSION

2.4.1 Leaf Number

The daily maximum, minimum, and average air temperature and daily total solar radiation collected during the period of study are shown in Fig. 2.3 A, B, and C. Leaf emergence rate for the two plantings, as indicated from the slopes of leaf accumulation over time, varied with time after planting and plant population density (Fig. 2.4 A and B). The variation with time is likely attributable to the variation in air temperature during development, and plant ontogeny. The divergence in leaves per plant among different plant population densities for PI and PII is likely due to mutual shading effects on the regions of the plant where leaf growth occurs.

2.4.2 Response to Air Temperature and Plant Population

Shiroma (1972) reported that leaf emergence of pineapple could be predicted from air temperature. In this study, the data (Fig. 2.4) showed that leaf emergence was influenced by both air temperature and plant population density. In order to incorporate both the effects of temperature and the changing effects of plant population density over time into an equation suitable for the prediction of leaf number, it was necessary to analyze leaf emergence in terms of cumulative leaf number as function of cumulative thermal time and plant population density.

Response of leaf emergence to air temperature and plant population density was investigated by regressing number of leaves on cumulative growing degree days (thermal time) and plant population density. Using cumulative growing degree days and cumulative leaves per plant removed month to month variation in leaf emergence

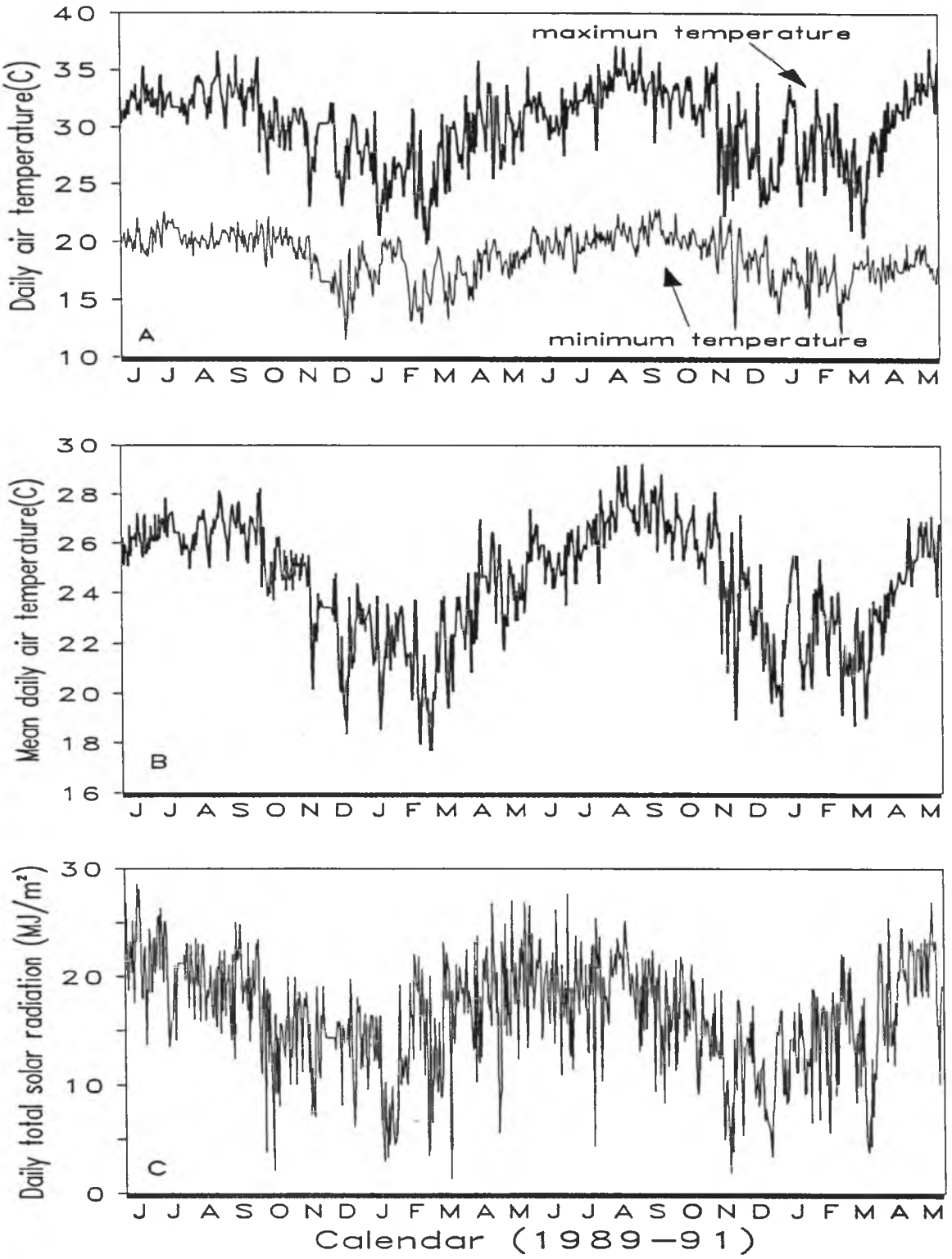


Fig. 2.3 Daily maximum, minimum (A) and mean (B) air temperatures (°C), and daily total solar radiation (C) from June, 1989 to May, 1991 at Kunia, Hawaii.

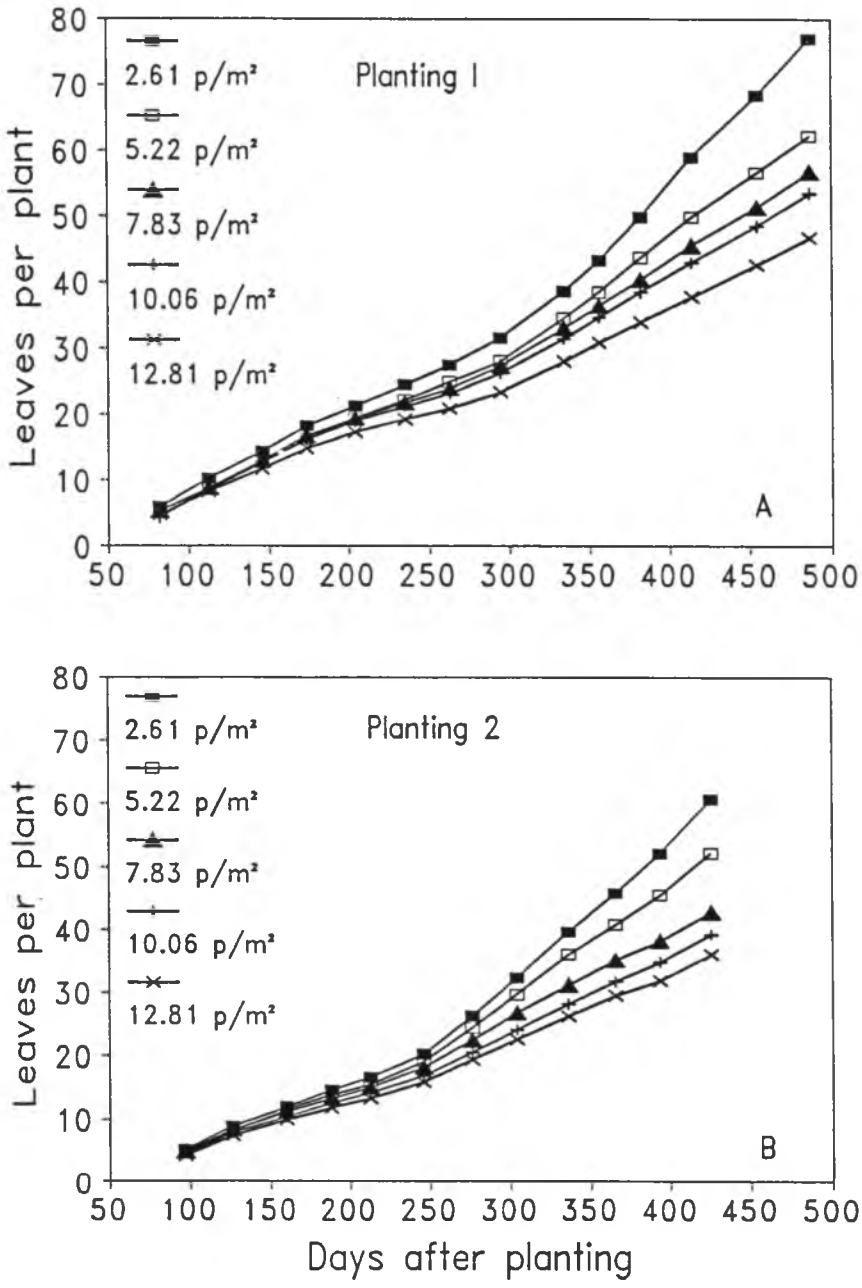


Fig. 2.4 Leaf number accumulation of pineapple after planting for plants planted at plant population densities 2.61, 5.22, 7.83, 10.06, and 12.81 plants m^{-2} (p/m^2) in June (A) and in August (B), 1989.

due to air temperature fluctuations during the period, ontogenetic effects, and sampling errors. It also made it possible to evaluate the effects of plant population density over time on cumulative leaf number.

To evaluate the effects of thermal time on leaf number, a suitable base temperature had to be selected for the calculation of growing degree days. Leaf growth was reported to cease at 7 °C (Sanford, 1962) but Shiroma (1972) used a base temperature of 12 °C to fit leaf emergence data collected in growth chamber and field studies. A range of base temperatures from 12 to 20 °C, in 2 °C intervals, was used in this study to estimate thermal time. Model 2.1 and 2.2 were fitted to the data.

The base temperatures were determined by maximizing the variation in cumulative leaf number accounted for by the regressions. The amount of variation accounted for was affected by planting dates and types of regression (Table 2.2). The best fit for regression Model 2.2 was obtained at a T_b of 14 °C for PI and at 18 °C for PII. For regression Model 2.1, a best fit was obtained at a T_b of 16 °C for both plantings. The R^2 values obtained by fitting the data with regression Model 2.1 and 2.2 for were greater than 0.991. In Model 2.2 regressions, the variation accounted for by linear regression was at least 95 percent (Table 2.3).

Which model better describes leaf emergence of plants mathematically and physiologically? Physiologically, the base temperature is the temperature at which leaf emergence ceases. Unless leaf emergence is also influenced by photoperiod, the base temperature should be the same regardless of planting date. Since there was no evidence of any photoperiod effect, the linear with cross product models with a base

temperature of 16 °C were chosen to describe the response of leaf emergence to thermal time and PPD. This contrasts with a T_b for pineapple leaf emergence of 12 °C in Okinawa (Shiroma, 1972) and 7 °C reported by Sanford (1962).

Table 2.2 Coefficients of determination (R^2) and associated root mean square errors (Root MSE) for the regression of pineapple leaves per plant on thermal time and plant population density over a range of base temperatures (T_b) (n=14 and 12).

Planting Date	Regression		T_b (°C)				
			12	14	16	18	20
June 15	Model 2.1†	R^2	0.990	0.990	*0.991*	0.990	0.980
		Root MSE	1.750	1.650	*1.575*	1.660	2.280
	Model 2.2‡	R^2	0.993	*0.993*	0.993	0.992	0.990
		Root MSE	1.451	*1.445*	1.470	1.613	1.780
August 15	Model 2.1	R^2	0.991	0.993	*0.994*	0.992	0.992
		Root MSE	1.290	1.180	*1.104*	1.220	1.220
	Model 2.2	R^2	0.994	0.994	0.995	*0.996*	0.996
		Root MSE	1.129	1.087	1.021	*0.920*	0.920

† $Y=\beta_0 + \beta_1 X1_i + \beta_2 X2_i + \beta_3 X1_i X2_i + \epsilon_i$ (2.1)

‡ $Y=\beta_0 + \beta_1 X1_i + \beta_2 X2_i + \beta_3 X1_i^2 + \beta_4 X2_i^2 + \beta_5 X1_i X2_i + \epsilon_i$ (2.2)

Table 2.3 Partitioning of coefficients of determination (R^2) for Model 2.2 regression of pineapple leaves per plant on thermal time and plant population density (n=14 for planting 1 and n=12 for planting 2).

Regression	Coefficients of Determination (R^2)	
	Planting 1	Planting 2
Linear	0.9615 ***	0.9480 ***
Quadratic	0.0024 ***	0.0069 ***
Crossproduct	0.0293 ***	0.0413 ***

*** indicates significance at 0.0001 of probability.

The discrepancy between the base temperature derived from field data for Hawaii and that for Okinawa could be due to the higher temperature and narrower temperature range prevailing in Hawaii.

Plots of number of leaves against thermal time with a T_b of 16 °C for each PPD (Fig. 2.5A and B) were essentially linear. Response surfaces showing leaves per plant against thermal time and PDD descended from higher thermal time and lower PPD to lower thermal time and higher PPD (Fig. 2.6A and B).

The quantitative relationship between leaves per plant (LN), thermal time and PPD for PI and PII, respectively, were described by the equations:

$$\mathbf{LN=-6.93+0.61PPD+0.022475GDD-0.00081PPD*GDD} \quad \mathbf{(2.3)}$$
$$\mathbf{(\pm 0.116)\ (\pm 0.00045)\ (\pm 0.000053)}$$

and

$$\mathbf{LN=-2.57+0.435PPD+0.022272GDD-0.0009PPD*GDD} \quad \mathbf{(2.4)}$$
$$\mathbf{(\pm 0.079)\ (\pm 0.0004)\ (\pm 000047)}$$

where PDD is plant population density, and GDD is the cumulative growing degree-days. The values in parenthesis are the standard errors for the coefficients of regression.

In most crop growth simulation models, simulation is done on a daily time-step. Instantaneous leaf emergence rate is more useful than cumulative number of leaves, because it permits the calculation of the daily fraction of leaf emerged. LN was a function of two independent variables, so leaf emergence rate was obtained by fixing PPD and taking the partial derivative of LN with respect to GDD. The leaf emergence rate $\partial LN/\partial GDD$ (leaves °C-day^{-1}) for a given plant population density for PI and PII is described by the equations:

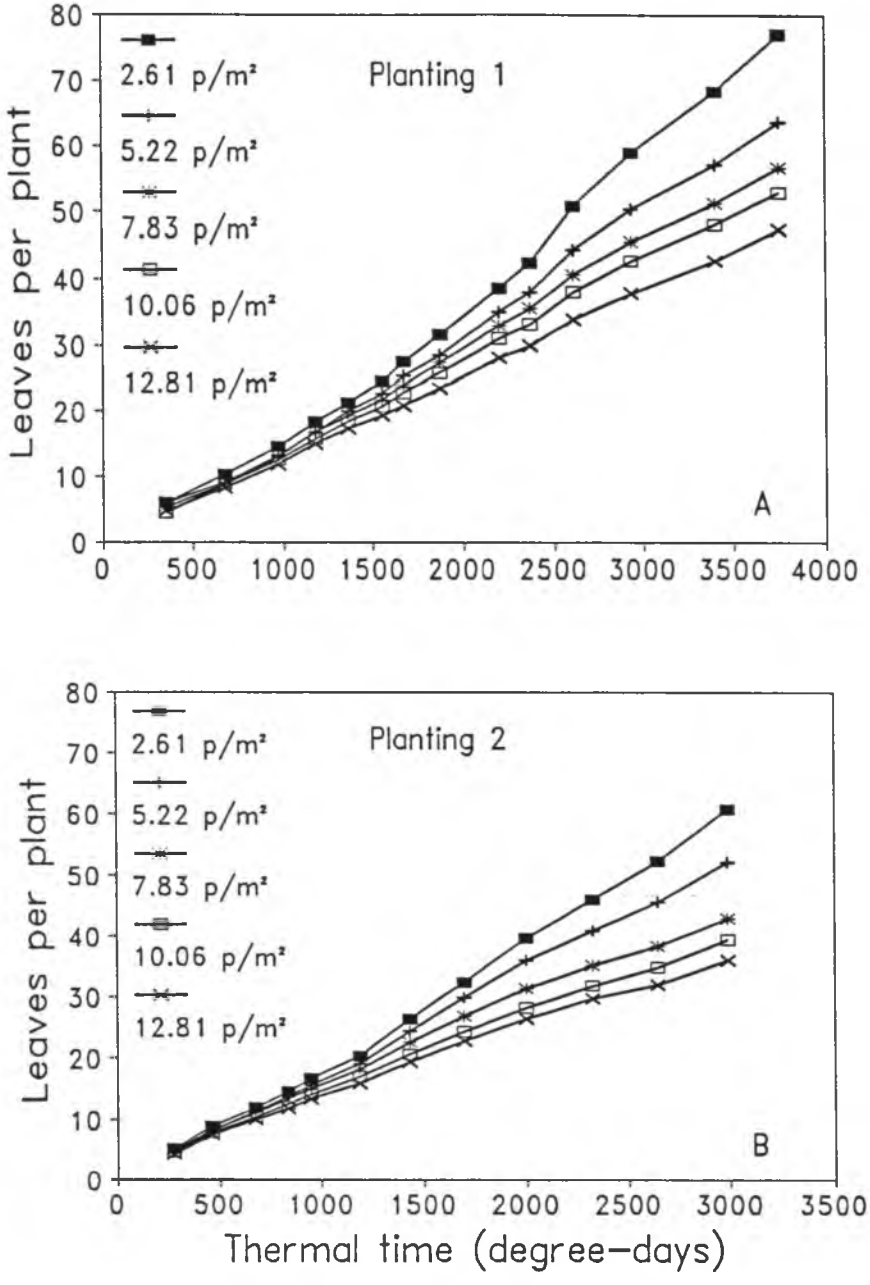
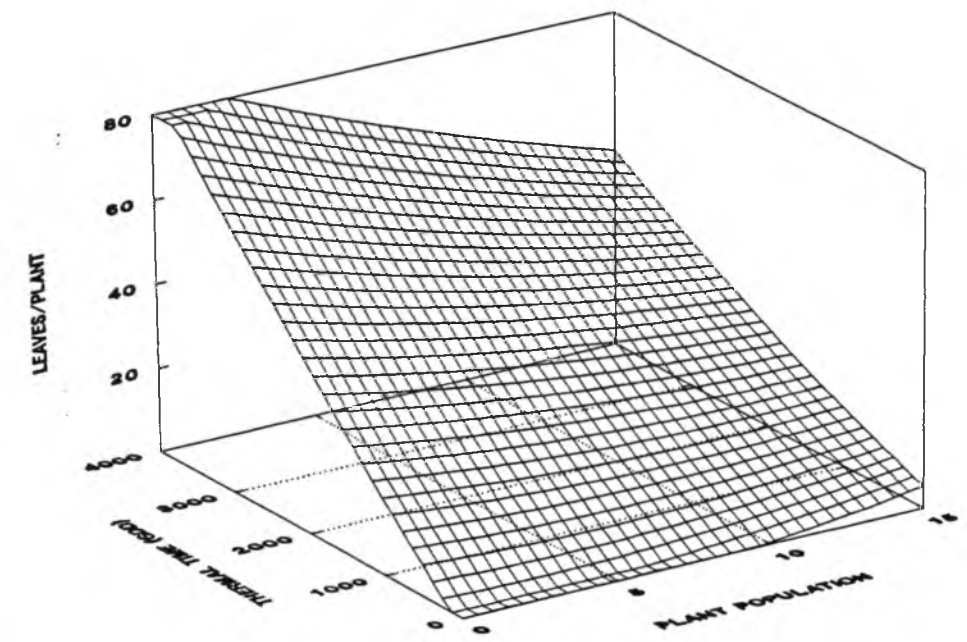
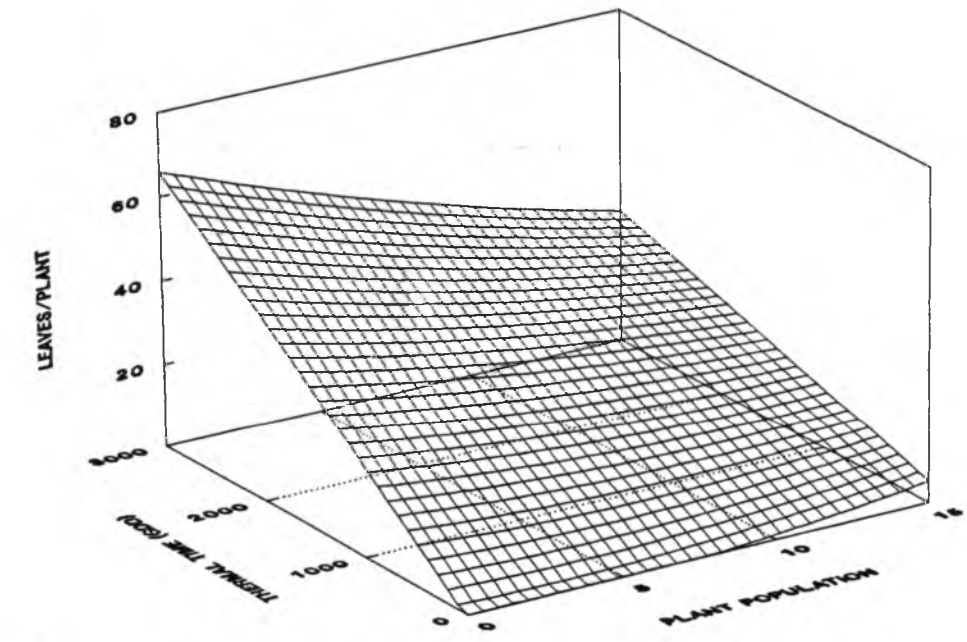


Fig. 2.5 Relationship between leaves per plant of pineapple and the thermal time (°C-day) for pineapple plants planted in June (A) and in August (B), 1989.



A



B

Fig. 2.6 Response-surfaces of pineapple leaves per plant, plant population density (plants m^{-2}) and thermal time (degree-day) for pineapple plants planted in June, 1989 (A) and August, 1989 (B).

$$\partial LN/\partial GDD = 0.022475 - 0.00081PPD \quad (2.5)$$

and

$$\partial LN/\partial GDD = 0.022272 - 0.0009PPD \quad (2.6)$$

The leaf emergence rate (leaves °C-day^{-1}) of field-grown pineapple was a linear function of plant population density (Eqn. 2.5 and 2.6). Leaf emergence rate declined 8.1×10^{-4} to 9.0×10^{-4} leaves °C-day^{-1} with each increase of one plant m^{-2} in PPD.

From Equation 2.5 and 2.6, for field-grown pineapple at a given plant population density, the leaf emergence rate (leaves °C-day^{-1}) was a constant. The results agreed with the response of leaf emergence to GDD in cereal crops (Gallagher, 1979; Baker et al., 1980; Klepper et al., 1982; Kirby et al., 1982; and Kirby and Perry, 1987).

The phyllochron (PHL), the reciprocal of the leaf emergence rate, has an inverse linear relationship with plant population density. PHL is described for PI and PII, respectively, by the equations:

$$PHL = 1/(0.022475 - 0.00081PPD) \quad (2.7)$$

$$PHL = 1/(0.022272 - 0.0009PPD) \quad (2.8).$$

For a given PPD, phyllochron was constant.

Because the experiment was conducted in the field, all equations have the defined boundaries of PPD $\geq$ 2.61 plants m^{-2} and $\leq$ 12.81 plants m^{-2} and average air temperature $>$ 16 °C and $<$ 30 °C.

In summary, air temperature and plant population density significantly affect the leaf emergence of 'Smooth Cayenne' pineapple. The multiple linear regression

model of number of leaves emerged versus cumulative growing degree-days and PPD best described leaf emergence. For a given plant population density, the leaf emergence rate (leaves degree-day^{-1}) and the phyllochron were constant. Both are linearly related to plant population density. It is clear that the plant population density effect must be taken into account when modeling pineapple leaf growth and development. At present, the regression equations are only suitable for use under Hawaii conditions. More experiments under more variable environments are needed in order to predict leaf emergence of pineapple in other environments.

CHAPTER 3

RESPONSE OF CANOPY DEVELOPMENT AND LIGHT INTERCEPTION

3.1 INTRODUCTION

Dry matter production by crops (or plant communities) depends on canopy photosynthesis. Canopy photosynthesis rate is related to the amount of light intercepted by the crop canopy and light interception varies with canopy development. Canopy development is the result of leaf emergence and expansion. In Chapter 2, leaf emergence rate was shown to be a function of plant population density and thermal time. Understanding how plant population density influences canopy development and light interception will provide basic information that can be used to help optimize plant population density for maximum yield. This information is also necessary for modeling crop growth, for predicting the probability of soil erosion, and for intercropping. The objectives of this study were to:

1. Examine the effect of plant population density and planting date on canopy development and light interception.
2. Quantify the relationship between plant population density and canopy development.
3. Quantify the relationship between green leaf area index and light interception.

3.2 LITERATURE REVIEW

Dry matter production of crop plants is directly proportional to their interception of radiant energy (Duncan et al. 1973; Loomis and Gerakis 1975; Monteith 1977). This is because dry matter accumulation is related to canopy photosynthetic rate and canopy photosynthesis rate is linearly related to the quantity of photosynthetically active radiation (PAR) intercepted by that canopy (Wells, 1991). PAR intercepted by a soybean canopy increased curvilinearly as leaf area index (LAI) increased until canopy closure (Wells, 1991). The maximum crop growth rate (CGR, g m^{-2} d^{-1}) is attained at full canopy closure when 95 percent of incident light is intercepted (Brougham, 1956). LAI at that stage of canopy development was defined as the critical LAI. The LAI at canopy closure was considered to be one determinant of maximum seed yield of soybean (Shibles and Weber, 1966).

The important question is what plant size or stage of plant development and plant density provide the critical LAI required to maximize potential yield (Duncan,1986). Egli (1988) discovered that a determinate cultivar of soybean produced maximum yield at the plant density that resulted in 95% light interception at growth stage R5. However, he also found that the yield of an indeterminate cultivar increased as plant density increased above the density required for 95% light interception at growth stage R5. Early reproductive growth was the period of ultimate importance for soybean seed yield determination (Ashley and Boerma, 1989; Wells et al., 1982).

Data on the critical LAI for pineapple are not available. Py (1959) gives data

showing that pineapple attained a LAI of 9.3 with a plant population density of 38,461 plants ha^{-1} (about 15,600 plants $acre^{-1}$) 14 months after planting. Although no published data on the relationship between canopy development and light interception were found, Fleisch (1988) reported that 95 percent of light was intercepted by pineapple at a PPD of 7.0 plants m^{-2} when the LAI was greater than or equal to 4.2.

Efficient interception of the radiant energy incident on a crop surface requires adequate leaf area that is uniformly distributed to completely shade the ground. This is achievable by manipulating planting density and its distribution over the land surface. The potential yield of crops can generally be maximized by utilizing the plant population density that produces enough leaf area to provide maximum insolation interception during reproductive growth. Equidistant planting minimizes interplant competition (Egli, 1988). Corn grown in an equidistant plant-spacing pattern yields more grain per unit area of land than that grown in conventional plant-spacing patterns (Bullock et al., 1988). Similarly, peanut grown in equidistant spacing produced higher pod and kernel yields than conventional rows (Jaaffar and Gardner, 1988). Equidistant spacing in pineapple is not practical because two-row beds provide the space needed by harvesters to walk through the field. In addition, the use of plastic mulch, drip irrigation, and soil fumigation make a two row per bed system more practical in Hawaii and in the other countries where such practices are used. Sanford (personal communication) pointed out that for a given planting density, the differences in total yields or average fruit weights are relatively minor among different planting systems.

3.3 MATERIALS AND METHODS

3.3.1 General Experimental Description

The experimental design and management was described in Chapter 2.

3.3.2 Data Collection and Analysis

Beginning about three months after planting until fruit harvesting, plant biomass and leaf area per plant was measured on plant samples collected approximately once every three months (Table 3.1).

Table 3.1 Dates of plant biomass sampling for pineapple planted on June 15 (PI), August 15 (PII), and October 18 (PIII), 1989.

Sampling number	PI	PII	PIII
1	09-18-89	11-15-89	01-22-90
2	10-30-89	12-29-89	05-30-90
3	12-14-89	02-15-90	08-06-90
4	03-15-90	05-15-90	09-19-90
5	05-22-90	08-06-90	12-17-90
6	08-01-90	09-19-90	04-15-91
7	09-14-90	12-17-90	
8	12-13-90	04-15-91	
9	04-15-91		

Because the number of plants available for sampling was limited, plants were harvested systematically from one end of the beds. At each sampling date, one border plant was discarded in each row from which plants were sampled. For most harvests, four plants were harvested on each sampling date. Two plants were sampled from the two rows in the center bed of three bed plots. In 6 and 12 bed plots, one plant was sampled from each of four rows at each sampling date. Fifteen plants were harvested from each plot at the time of forcing and ten plants at the time of fruit harvesting to reduce sampling error.

The fresh weight of all plants was measured and recorded in the field. Two mid-sized plants from the plot were taken to the laboratory for detailed analysis. The plants were dissected and measurements were made of green leaf area (LA), total leaf fresh and dry weight, weight and area of the youngest fully expanded leaf (the D-leaf (Py et al., 1987)) and stem fresh and dry weight. Green leaf area was defined as the area of the dark green and presumably photosynthetically active part of a leaf. The green leaf tissue was separated from the basal pale green and white tissue. Leaf area was measured with a LI-COR LI 3100 area meter. Dry weights were obtained by drying to a constant weight at 70 °C in a forced-draft oven. Because of limited time, only one plant was taken for detailed analysis beginning in March, 1990.

Plant dry matter contents for each plant in the subsample were calculated from tissue fresh and dry weights. The data on dry matter content and leaf area for the two plants was averaged and the results were used to estimate leaf areas and dry tissue mass for the whole-plot sample. Where detailed measurements were taken on only one plant, the data for that plant were used to estimate leaf area and tissue mass for the whole-plot sample. Leaf area index was calculated as:

$$LAI = \frac{LA \times PPD}{10000} \qquad (3.1)$$

Light Interception by the leaf canopy was measured approximately monthly (Table 3.2) in areas of the plots reserved for estimation of fruit yield in Replication 3 for PI, and Replication 1 for PII and III.

Table 3.2 Dates of canopy light measurements for pineapple planted on June 15 (PI), August 15 (PII), and October 18 (PIII), 1989.

Sampling number	PI	PII	PIII
1	11-21-89	02-15-90	02-20-90
2	12-19-89	04-05-90	05-19-90
3	02-19-90	05-15-90	08-06-90
4	03-15-90	08-03-90	09-13-90
5	05-18-90	09-12-90	10-16-90
6	08-01-90	10-15-90	12-02-90
7	09-11-90	11-30-90	
8	10-13-90		
9	11-29-90		

Measurements were begun about three months after planting and were continued until light was completely intercepted by the canopy. Instantaneous measurements of photosynthetic photon flux density (PPFD) were measured below the canopy with a one-meter line quantum sensor (LI-COR LI-191SB) and above the canopy with a quantum sensor (LI-COR LI-190sb). The measurements were made on a sunny day and as near solar noon as possible. The two PPFD measurements were saved to a LI-COR LI-1000 datalogger that automatically calculated the fractions of light transmitted and intercepted by the equations

$$FLT = \frac{I_a}{I_b} \tag{3.2}$$

$$FLI = 1 - FLT \tag{3.3}$$

where FLT is the fraction of light transmitted; I_a is the PPFD above the canopy, I_b is the average PPFD at ground level, and FLI is the fraction of light intercepted. The sensors were cross-calibrated in an open area before measurement.

I_b was obtained by taking nine measurements at approximately equidistant spacing with the line quantum sensor (Fig. 3.1). Measurements were made below the plants and parallel to the rows from the center of one bed to the center of next one. Each result was the mean of the nine measurements.

Treatment effects were evaluated by analysis of variance using the SAS ANOVA procedure (SAS Institute, 1985). Leaf area per plant and LAI at the time of forcing were regressed against plant population density using the SAS GLM procedure (SAS Institute, 1985). The relationship between light interception and LAI calculated from plot mean LA of the closest sampling to light measurements was fitted using the SAS REG procedure (SAS Institute, 1985).

3.4 RESULTS AND DISCUSSION

3.4.1 Leaf Area Per Plant

Leaf area per plant increased over time and treatment effects were evident by the fourth sampling period for PI and PII, and by the third sampling for PIII (Fig. 3.2A, B, and C). From 300 days after planting, leaf area per plant decreased as plant population density increased. Relative leaf growth rate as indicated by the slopes of the lines declined as plant population density increased up to the time of forcing when new leaf production ceased (Fig. 3.2A, B, and C). Because nutrient and water supply were assumed to be non-limiting, differences in relative leaf growth rate resulted from different degrees of inter-plant competition for sunlight. Accumulated leaf area

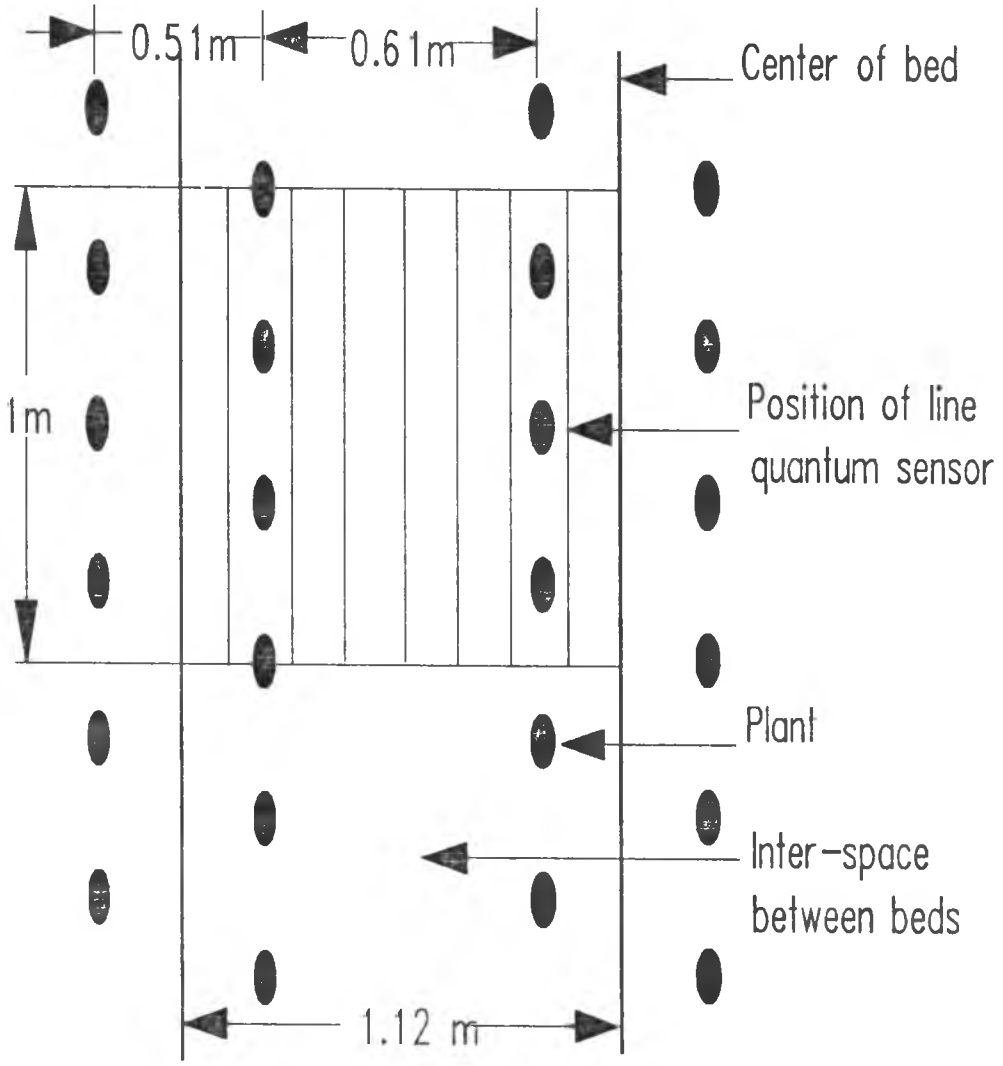


Fig. 3.1 Layout of plant arrangement and placement of line quantum sensor below pineapple canopy.

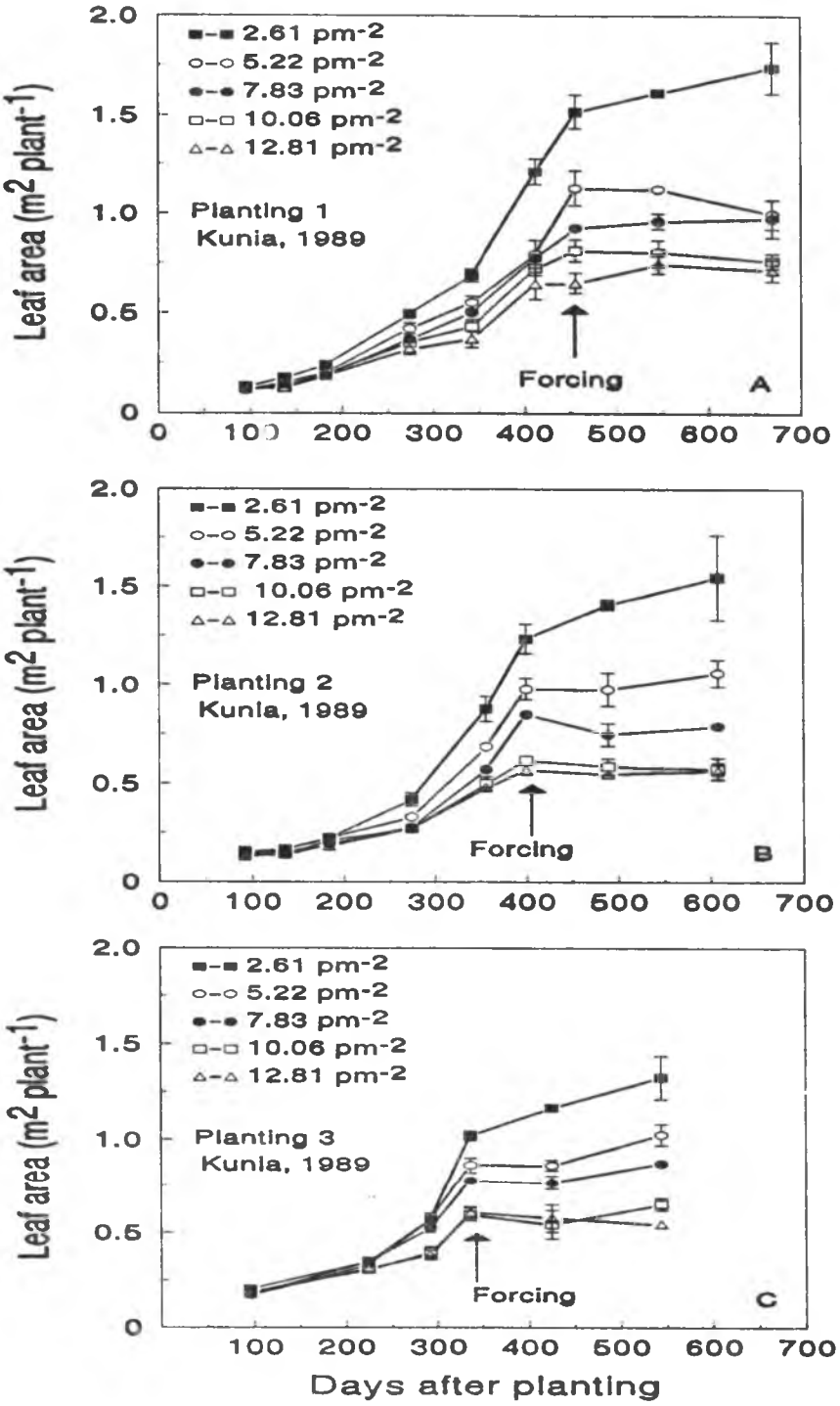


Fig. 3.2 Leaf area expansion of pineapple planted at five plant population densities on June 15 (A), August 15 (B), and October 18 (C), 1989. All plants were forced on September 18, 1990.

per plant is the result of leaf emergence and leaf expansion. The decline in rate of leaf expansion at the higher plant population densities was due at least in part to a suppressed leaf emergence rate (leaves °C-day^{-1}) (Chapter 2).

After forcing, leaf area per plant continued to increase in the lowest PPD, but increased only slightly or not at all in the other PPDs. Any increase in leaf area after forcing was due to the emergence and expansion of leaves initiated prior to forcing. The lack of any large increase in LA at the higher PPDs may be due to the mutual shading of leaves. The results for the three plantings were similar (Fig.3.2 B and C), but the divergence in leaf area among PPDs was greater in PI than in PII and PIII, and greater in PII than in PIII.

The effects of plant population density and planting date on leaf area per plant at forcing were tested using analysis of variance. The largest source of variation was the main effect of PPD, followed by the main effect of planting date (Appendix A.1). The interaction between planting date and plant population density was also significant, indicating that the response of leaf area per plant to PPD over planting date was different. Plant population density is a quantitative variable while planting date was treated as a qualitative environmental variable for purposes of this analysis. Therefore, the effect of PPD was analyzed using regression while the effect of planting date was analyzed by breaking it into single degree of freedom components. Each component of both PPD and planting date was incorporated into a general linear model and the model was fitted to the data. Error terms for testing for significance were calculated by hand. A polynomial term was gradually added into the model

until the effect due to lack of fit by regression was not significant. A planting date component was eliminated when it is not significant. This analysis combined experimental design and treatment design analysis. The final model represents the effects of PPD and planting date on green leaf area per plant. The equation fitted to the data is:

$$\mathbf{LA=15482+1340*P1VOTH-1289*P2V3-1237*PPD+39*PPD^2}$$
$$\mathbf{-90*P1VOTH*PPD+118*P2V3*PPD} \qquad \mathbf{(3.4)}$$

where P1VOTH is the effect of planting 1 vs. other plantings and P2V3 is the effect of planting 2 vs. planting 3.

The orthogonal values used for P1VOTH and P2V3 were:

planting	P1VOTH	P2V3
1	+2	0
2	-1	-1
3	-1	+1

Substituting the values of P1VOTH and P2V3 into Eqn. 3.4, it became:

for PI $\mathbf{LA=18162-1417*PPD+39*PPD^2}$ **(3.5)**

for PII $\mathbf{LA=15431-1265*PPD+39*PPD^2}$ **(3.6)**

for PIII $\mathbf{LA=12853-1021*PPD+39*PPD^2}$ **(3.7)**

The mean leaf area per plant at forcing across PPDs for PI was significantly greater ($P=0.001$) than those in PII and PIII. The mean leaf area per plant across PPDs at forcing for PII was significantly greater ($P=0.05$) than that in PIII. Leaf

area per plant at forcing decreased curvilinearly as plant population increased (Fig. 3.3). This indirectly confirmed that the decline in leaf area per plant resulted from increasing inter-plant competition as PPD increases. Since the amount of light intercepted by an individual plant during the early stage of the reproductive period is an important determinant of fruit weight (Sanford, 1962), the decrease in leaf area per plant as PPD increased would be expected to decrease fruit weight. This topic will be discussed in Chapter 5.

3.4.2 Leaf Area Index

The leaf area index accumulated over time for PI (Fig. 3.4 A) reached a maximum at the time of forcing and then remained about constant. The exceptionally low value at forcing for the highest PPD in this planting (Fig. 3.4A) likely was due to field variability and sampling error. Leaf area index continued to increase after forcing at the lowest PPD. For PII, LAI reached a maximum at the time of forcing at the three higher PPDs and continued to increase at the two lower ones (Fig. 3.4 B). The LAI also reached a maximum in PIII at the time of forcing at the highest PPD, but continued to increase at the other PPDs (Fig. 3.4 C). The increase in LAI after the time of forcing at the lower PPDs is due to the continued increase in leaf area per plant (previous section) at the lower PPDs. This also suggests that at higher PPDs, intense mutual shading may cause senescence and loss of leaves. Maximum LAIs (Table 3.3) ranged from 3.45 to 9.1 over the range of PPDs for the three plantings. The highest LAIs were well above those reported for field crops but not unusually high for pineapple (Py, 1959).

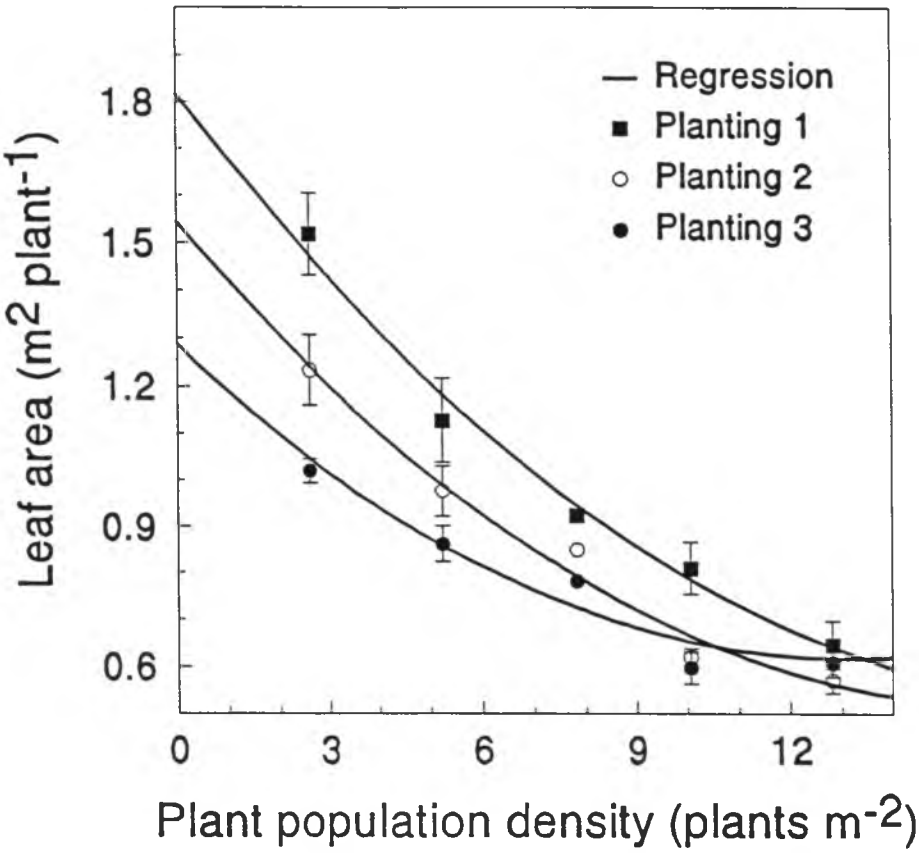


Fig. 3.3 Effect of plant population density on leaf area per plant at forcing for pineapple planted on June 15, August 15, and October 18, 1989. All plants were forced on September 18, 1990.

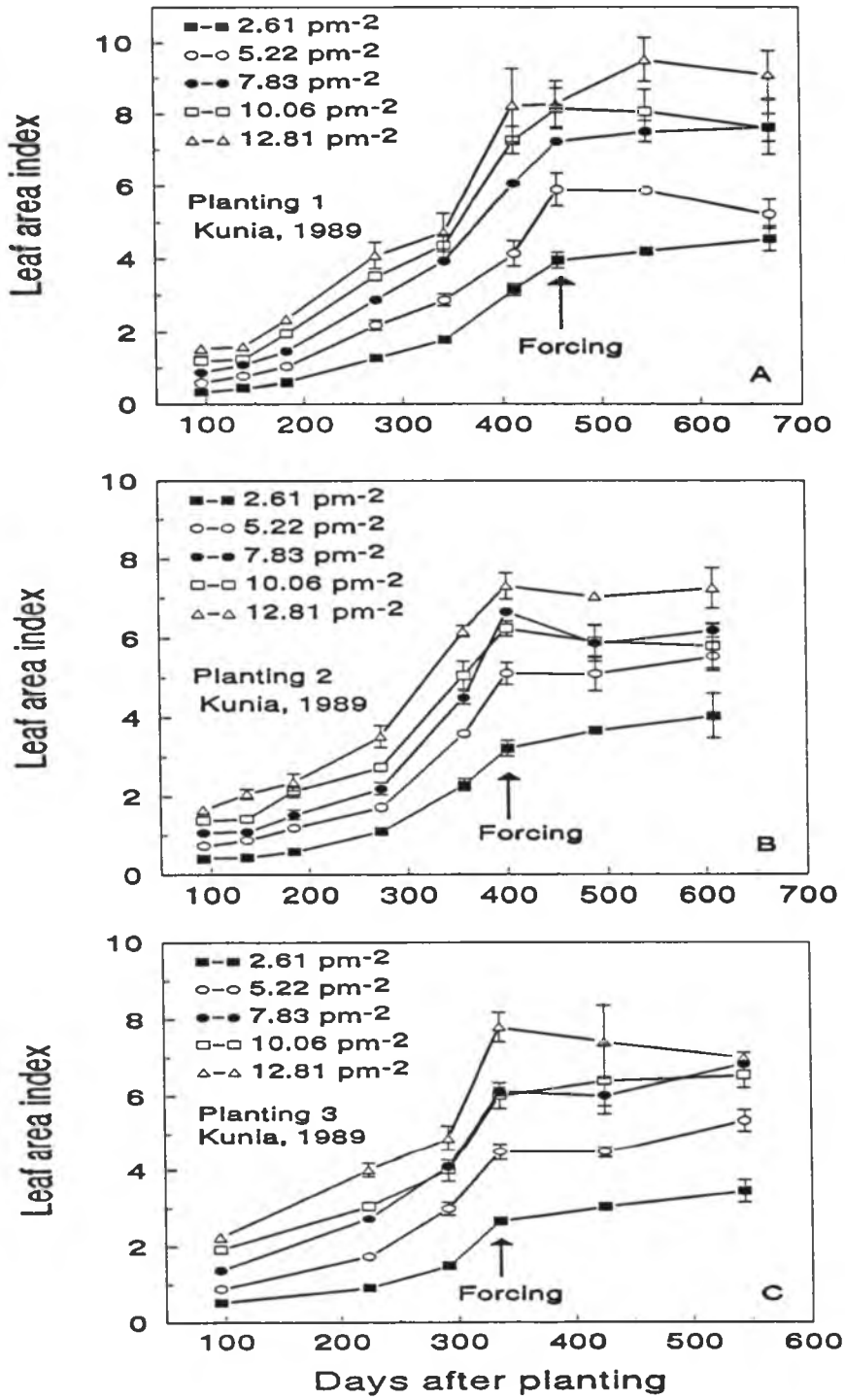


Fig. 3.4 Leaf area index of pineapple planted at five plant population densities on June 15 (A), August 15 (B), and October 18 (C), 1989. All plants were forced on September 18, 1990.

Table 3.3 Maximum leaf area indices (m^2 m^{-2}) of pineapple planted at five population densities (PPD) in June (PI), August (PII) and October (PIII), 1989.

PPD (plants m^{-2})	PI	PII	PIII
2.61	4.54	4.03	3.45
5.22	5.89	5.53	5.35
7.83	7.24	6.65	6.83
10.06	8.18	6.23	6.54
12.81	9.1	7.3	7.4

Up to about 200 days after planting, at a given time, LAI increased linearly as PPD increased. Thereafter, LAI increased curvilinearly (Fig. 3.5 A, B and C). This suggests that no plant competition was present during early growth but became more and more intense as the crop developed. As would be expected, this result is in agreement with the results for leaf area per plant.

3.4.3 Leaf Canopy Light Interception

Light interception measurements were begun in each planting about 150 days after planting (Table 3.2). By that time, leaf growth and expansion was sufficient to extend the plants' leaf canopy slightly beyond that of the crown at planting. Initial differences in light interception among PPDs was due primarily to differences in PPD. The fraction of light intercepted (FLI) by the leaf canopy increased with time and plant population density (Fig. 3.6 A, B, and C). For PI, FLI reached 0.95 at the three higher PPDs by or one month before forcing. For the two lower PPDs, it reached 0.95 at about one month after forcing. The results were similar for PII and PIII , except that interception of 95% of the incident light did not occur in most treatments until at or after forcing. For the lowest population in PIII, full canopy

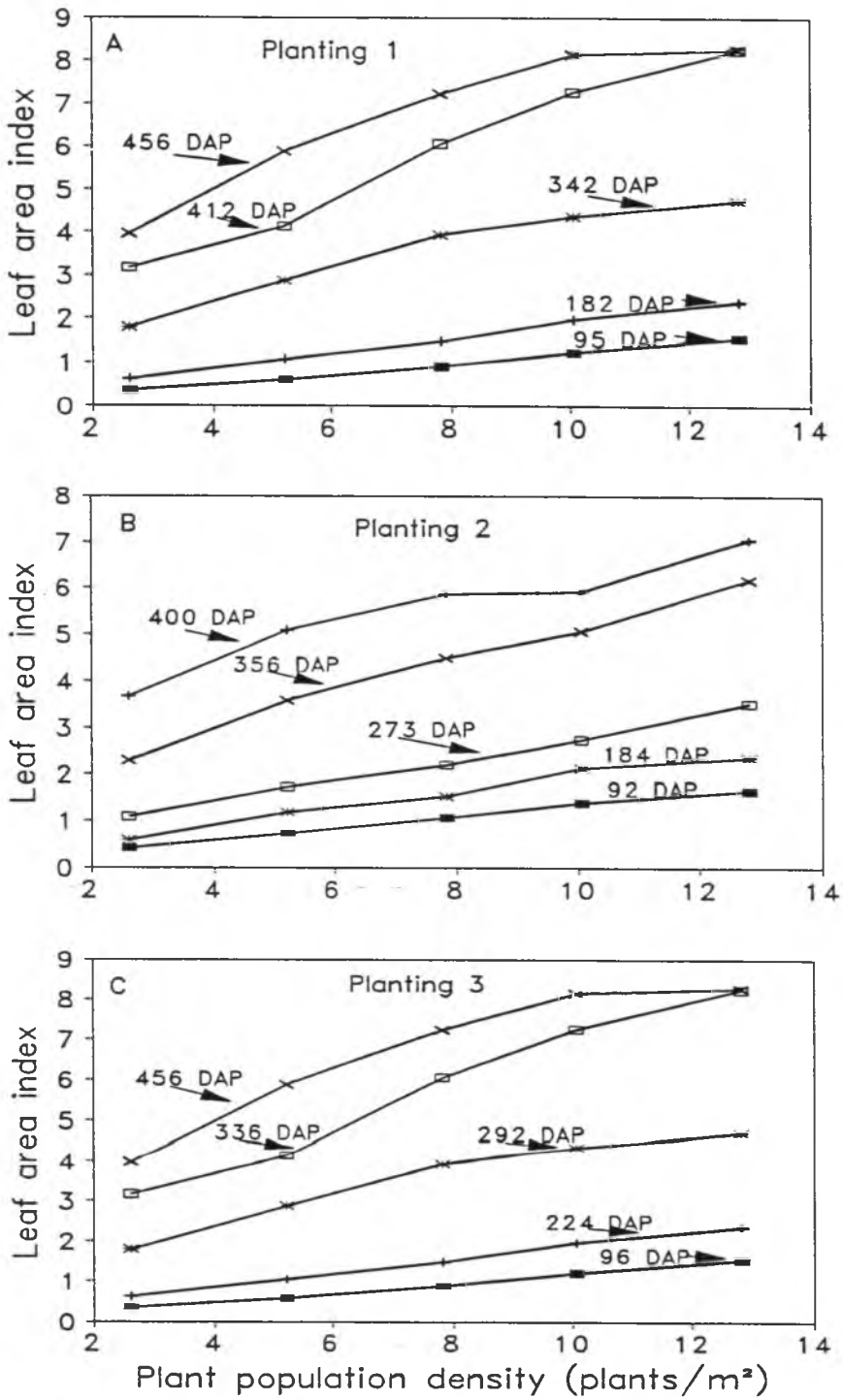


Fig. 3.5 Effect of plant population density and days after planting (DAP) on leaf area index of pineapple planted June 15 (A), August 15 (B), and October 18 (C), 1989. All plants were forced on September 18, 1990.

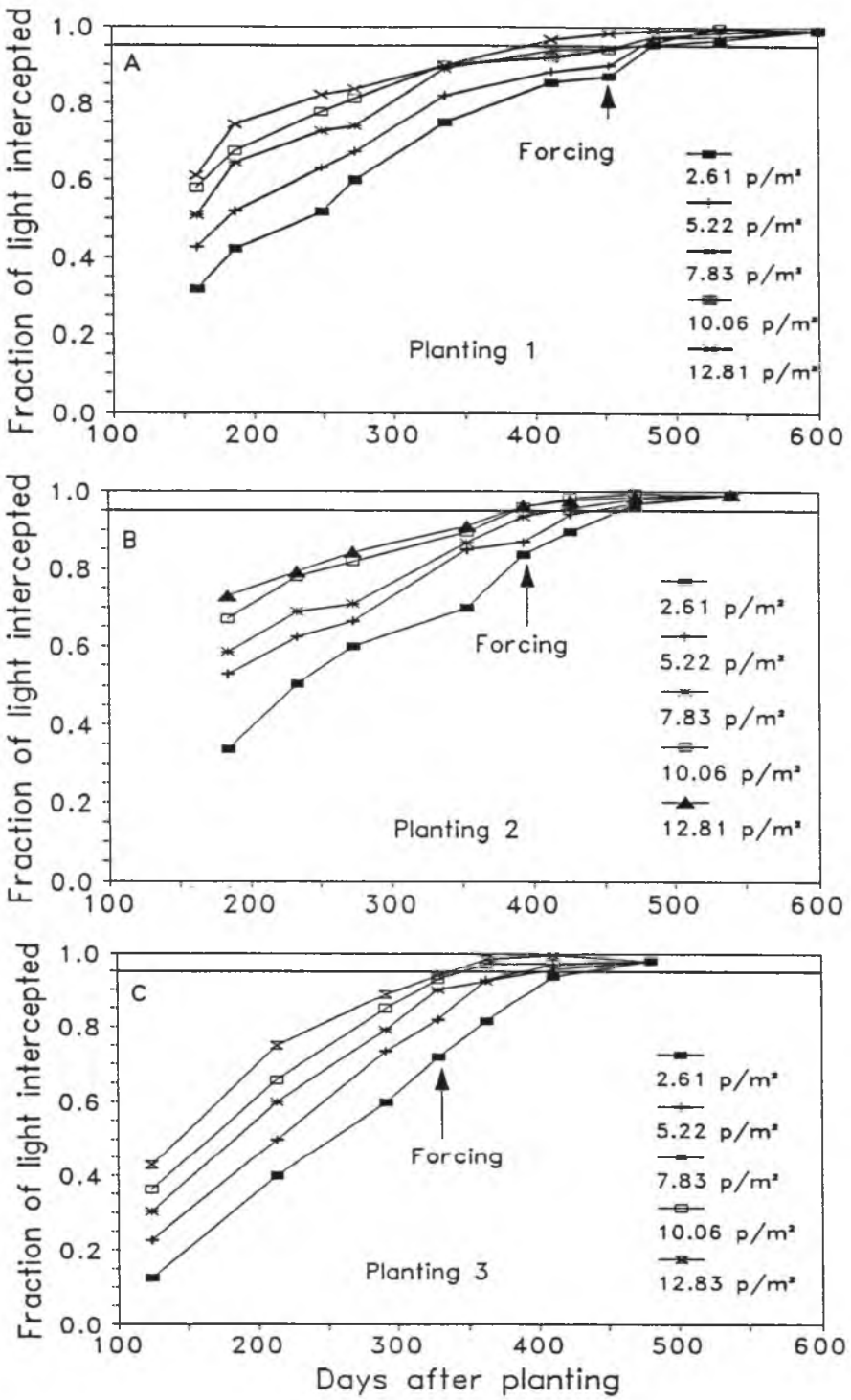


Fig. 3.6 Light interception by pineapple leaf canopies for five plant population densities planted on June 15 (A), August 15 (B), and October 18 (C), 1989. All plants were forced on September 18, 1990.

closure was not reached until about three months after forcing. The time required to reach 0.95 FLI approximately corresponded to the time that maximum LAI was attained. This suggests that when the canopy intercepts most of the available light, any further increase in leaf area would shade lower leaves, causing senescence and resulting in a decrease in LAI.

The fraction of light intercepted was plotted against leaf area index for the three plantings (Fig. 3.7 A, B and C). The light interception and leaf area index data were fitted by an exponential equation. The coefficients of regression, equivalent to the light extinction coefficient of Beer's law were not significantly different among the three plantings. They were 0.59 for PI and 0.58 for the other two plantings. Fleisch (1988) reported a light extinction coefficient of 0.56 for a pineapple canopy. The slopes of the response curves began to decrease at a LAI of between 2 and 2.5 (Fig. 3.7), which occurred at about 200 days after planting at the highest PPDs (Fig. 3.3). Ninety fove percent of light interception was achieved at a LAI of about 5.0, a value somewhat higher than values of 3.0 to 4.0 commonly observed for mesophytic crop plants (Shibles and Weber, 1966; Wells, 1991).

In summary, leaf area per plant and leaf area index increased with time and increasing plant population density. Before about 200 days after planting, leaf area per plant was constant over PPDs and leaf area index was a linear function of PPDs for a given time. Thereafter, leaf area per plant declined and LAI increased curvilinearly as plant population density increased. Maximum LAIs were attained at forcing at the higher PPDs for the June and August plantings. Light interception

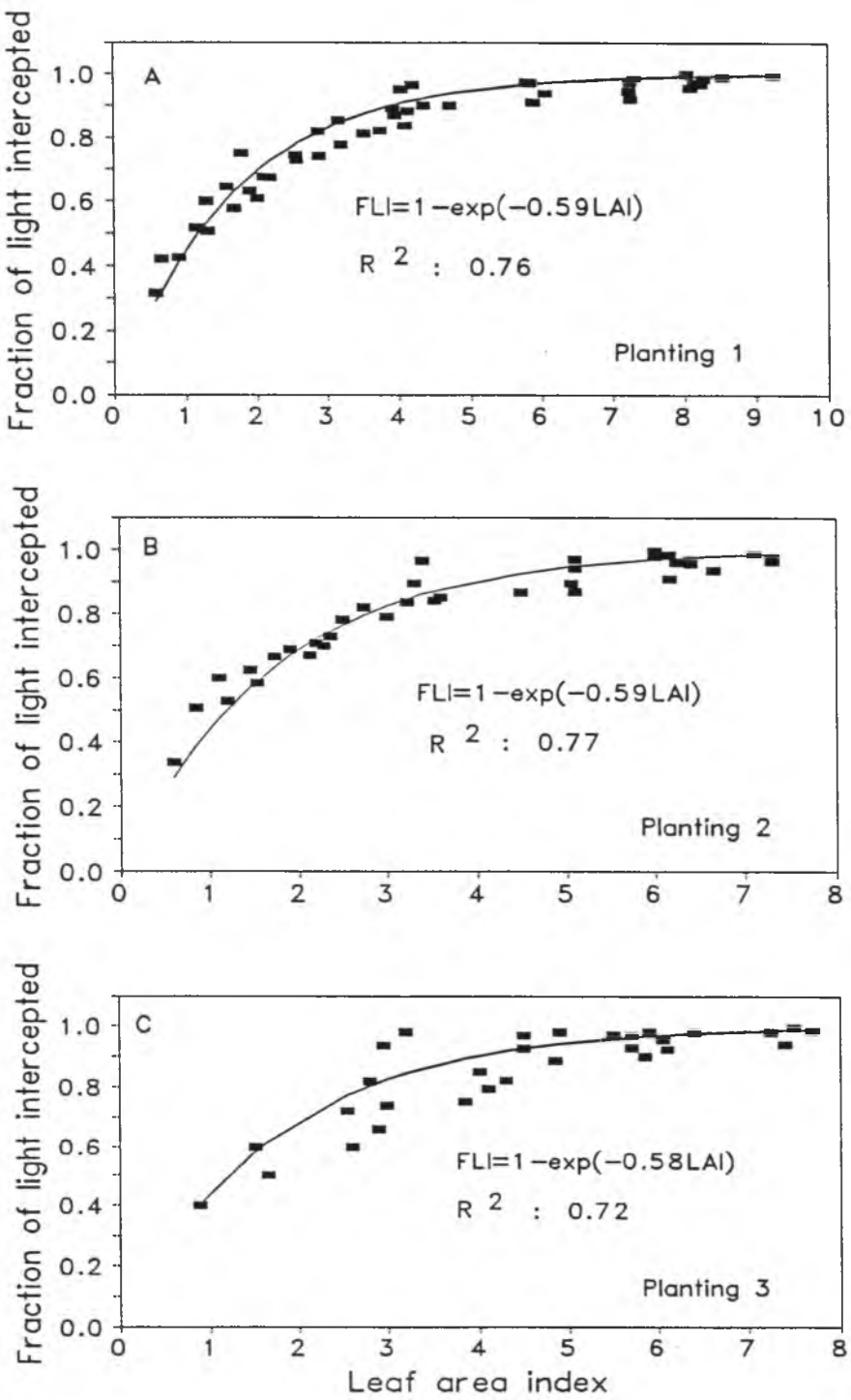


Fig. 3.7 Relationship between canopy light interception and leaf area index for pineapple planted on June 15 (A), August 15 (B), and October 18 (C), 1989. All plants were forced on September 18, 1990.

increased with increasing time and plant population density, but it behaved differently from leaf area per plant and leaf area index in that the relationship between the fraction of light intercepted and LAI was exponential. This relationship and the decline in LAI after a maximum was attained demonstrated that inter-plant competition began to occur by or before 200 days after planting at the highest PPDs, and became more intense after that time.

CHAPTER 4

VEGETATIVE GROWTH AND DRY MATTER PARTITIONING

4.1 INTRODUCTION

In a restricted sense, growth is the result of cell division, enlargement, and differentiation (Gardner et al. 1985), but agronomists generally define growth as an increase in dry matter. Vegetative growth describes all activities associated with leaf initiation and expansion, and the formation of lateral apical meristems that result in branches and a root system (Milthorpe and Moorby, 1986). Vegetative growth of determinate crops ceases when flowering occurs. Parameters commonly used to characterize growth are dry matter accumulation, leaf area, tiller number, plant height and volume. Pineapple growers commonly use plant fresh weight, D-leaf (the youngest fully expanded leaf) weight and length, leaf number and area, and slip and sucker number.

Maximum plant growth is a function of genotype and environment. For a given genotype, maximum growth rate and yield can be obtained by environmental manipulation. The crop environment (or microclimate) can be altered through site selection, tillage, irrigation, drainage, fertilization, pest and disease control, planting date, plant population density, and other cultural practices. Most pineapple production areas are planted with 'Smooth Cayenne', so manipulation of cultural practices is of importance for pineapple growers. Several studies have been done on the effect of plant population density on pineapple growth and yield. None of them

examined the effect of plant population density on dry matter partitioning. Also no results on the effect of plant population density on the vegetative growth and dry matter production of pineapple were found.

Understanding how dry matter is partitioned during the growth of pineapple and the relationship among plant growth parameters, environmental factors and cultural practices is necessary to simulate pineapple growth. For example, the crop growth subroutine in a pineapple growth simulation model likely would calculate dry matter partitioning by balancing photosynthetic supply and plant growth demand. Plant growth demand requires information on the relationships among leaf number, leaf area, leaf weight, and stem weight. Whether those relationships are affected by plant population density is not known. The objectives of the study were to:

1. Examine the response of dry matter accumulation and partitioning to plant population density.
2. Examine the effect of plant population density on D-leaf weight, weight of plant components and total plant weight at the time of forcing.
3. Quantify the relationships among leaf number, leaf area and leaf weight.

4.2 LITERATURE REVIEW

4.2.1. Leaf Growth

The effect of plant population density on plant growth results from two types of competition: interplant (between plants) and intraplant (within a plant). The onset of both types of competition during plant growth varies with the plant population

density. Interplant competition commonly occurs earlier at higher plant population densities than at lower ones, and intraplant competition is more intense at lower plant population densities (Gardner et al. 1985).

Within the range of plant population densities studied in pineapple, no consistent effect of increasing plant population density on vegetative growth has been reported. Data from nineteen unirrigated plant population density trials conducted in Hawaii with Smooth Cayenne pineapple show no consistent effect of plant population density over the range from 9,000 to 26,000 plants per acre on either estimated plant weight or D-leaf weight (Sanford, 1962). Additional data suggested no consistent effect of plant population density on leaf elongation (Sanford, 1962). Sanford (1962) noted that during most of the vegetative growth period, plants are spaced far enough apart even at the highest plant population densities, that they do not compete with each other for light, particularly with regard to the active and developing leaves. Only the older, less active leaves are mutually shaded. However, Dass et al. (1978) reported that the dry mass of the D-leaf decreased significantly as the plant population density of Kew pineapple increased beyond the range of 53,333 to 59,259 plants per hectare. This suggests that at higher densities, interplant competition does occur during the vegetative growth stage.

Conflicting results of the effect of plant population density on growth as expressed in leaf number per plant have been reported. No significant difference in leaf number per plant between plant population densities ranging from 14,826 to 108,722 plants per hectare was observed in Smooth Cayenne, Kew, Sugarloaf, or

Sarawak pineapple over several production areas (Balakrishnan et al. 1978; Chadha et al., 1973; Dass et al., 1978; Ghosh and Medhi, 1981; Gunjate and Limaye, 1977; Norman, 1978; Wang and Chang, 1958, Yoshihara and Hwang, 1957). In other studies, leaf number per plant decreased as plant population density increased from 12,355 to 103,781 plants per hectare (Hwang, 1970; Kwang and Chiu, 1966; Singh et al. 1974; Su, 1957; Wang et al. 1962; Wee, 1969).

The plant height of pineapple was reported to increase with increasing plant population density (Hwang, 1970; Kwang and Chiu, 1966, Wang et al. 1962; Wee, 1969). However, leaf area per plant did not differ significantly across plant population densities ranging from 42,000 to 108,722 plants per hectare (Balakrishnan et al. 1978; Chadha et al. 1973). The inconsistent results may be due to the effect of factors that were not controlled or measured.

4.2.2. Slip and Sucker Production

Initiation and development of vegetative and reproductive organs are vulnerable to photoassimilate and N supply (Patrick, 1988). Assimilate supply to vegetative organs that develop simultaneously with reproductive organs depends on the extent of competition with the reproductive sink. The efficiency of assimilate partitioning to the organs is also determined by the environment the crop experiences during its development.

Light has both quantitative and inductive effects on plant growth and development. For example, total biomass production is strongly correlated with radiation interception by the canopy and the intercepted radiation may act as a

significant determinant of final yield (Milford, et al. 1980). Inductive stimuli, sensed as photoperiod or as alterations in the spectral quality of light in the crop canopy, can cause significant changes in assimilate partitioning, which can lead to increases in crop productivity (Kasperbauer, et al. 1984; Keating, et al. 1985). This may not be true for pineapple, but no data on the subject were found.

As pineapple plant population density increases, interplant competition becomes more intense and net assimilation rate (NAR) would decrease. This would reduce the supply of photosynthate available for the initiation and development of suckers (shoots that develop from buds located on the stem above or below ground level) and slips, which develop on the peduncle or fruit stalk. At plant population densities greater than 42,000 to 62,000 plants per hectare, the average number of slips and suckers produced per plant decreased as plant population density increased while the total number of slips produced per hectare either increased or remained approximately the same (Gadelha, et al. 1980; Dodson, 1968; Cannon, 1957; Gonzalez-Tejera, 1969; Sanford, 1962; Norman, 1978; Wang et al. 1962; Kwang and Chiu, 1966; Wee, 1969; Balakrishnan et al., 1978; Glennie, 1972a, unpublished data).

Glennie (1972, unpublished data) in Australia conducted two trials with 'Smooth Cayenne' pineapple with plant population densities ranging from 12,800 to 214,000 plants per hectare. At plant population densities ranging from 12,800 to 17,300 plants per hectare, the number of suckers per plant was lower but the number of slips (including hapas, which develop on base of the fruit stalk or peduncle) was

higher than at higher plant population densities. The high number of slips and hapas caused plants to lodge. Glennie also found that above 44,5000 plants per hectare, increasing plant population density delayed sucker initiation and growth. Delayed sucker development delays ratoon crop (subsequent crop after harvesting the first or mother plant crop) development. Contrary to the results of Glennie (1972, unpublished data), others found that the number of suckers and slips per plant was not affected by plant population density (Ghosh and Medhi, 1981; Hwang, 1970; Lee, 1977). Su (1957) and Chadha et al. (1973) reported that the number of suckers produced per plant decreased as plants per unit area increased, but the effect of plant population density on slip production was not significant. The inconsistent results may be due to factors other than plant population density such as cultivar, plant size, nutrition, and water. Sanford (1962) reported that the effect of forcing flowering with naphthaleneacetic acid (NAA) had a greater effect on slip production than any effect of plant population density. A decrease in sucker and slip production with increasing plant population density may indicate that the fruit sink demand is greater than that of other developing organs.

4.3 MATERIALS AND METHODS

4.3.1 General Experimental Description

The experimental design and management was described in Chapter 1.

4.3.2 Data Collection and Analysis

4.3.2.1 Data Collection

Beginning about three months after planting until fruit harvesting, plant biomass was measured on plant samples collected approximately once every three months (Table 3.1). Because the number of plants available for sampling was limited, plants were harvested systematically from one end of the beds. At each sampling date, one border plant was discarded in each row from which plants were sampled. For most harvests, four plants were harvested on each sampling date. Two plants were sampled from the two rows in the center bed of three bed plots. In 6 and 12 bed plots, one plant was sampled from each of four rows at each sampling date. Fifteen plants were harvested from each plot at the time of forcing and ten plants at the time of fruit harvesting to reduce sampling error.

The fresh weight of all plants was measured and recorded in the field. Two mid-sized plants from the plot were taken to the laboratory for detailed analysis. The plants were dissected and measurements were made of green leaf area (LA), total leaf fresh and dry weight, weight and area of the youngest fully expanded leaf (the D-leaf (Py et al., 1987)) and stem fresh and dry weight. Green leaf area was defined as the dark area of the dark green and presumably photosynthetically active part of a leaf. The green leaf tissue was separated from the basal pale green and white tissue. Leaf area was measured with a LI-COR LI 3100 area meter. Dry weights were obtained by drying to a constant weight at 70 °C in a forced-draft oven. Because of limited time, only one plant was taken for detailed analysis beginning in March, 1990.

Plant dry matter contents for each plant in the subsample were calculated from tissue fresh and dry weights. The data on dry matter content and leaf area for the two plants was averaged and the results were used to estimate leaf areas and dry tissue mass for the whole-plot sample. Where detailed measurements were taken on only one plant, the data for that plant were used to estimate leaf area and tissue mass for the whole-plot sample.

Mean plant dry weights for each plot were calculated from plant dry matter content and average plant fresh weight of four, fifteen, or ten plants. Mean leaf area, leaf dry weight, and stem dry weight per plot were calculated from subsample data based on the proportion of total plant dry matter partitioned to each of these components. Mean leaves per plant for each plot were obtained from the leaf emergence data. The ratio of leaf area per plant to leaf number was calculated from the leaf area per plant and leaf number obtained on the same date.

4.3.2.2 Statistical Analysis

Statistical analysis was accomplished in two steps:

1. Analysis of Experimental Design

This step only analyzes the effect of the main factors on response variables. In this experiment, the main factors are plant population density and planting date. The response variables to be analyzed were D-leaf area and dry weight, leaf dry weight, stem dry weight, and plant total dry weight at forcing. The analysis of variance procedure SAS ANOVA (SAS Institute, 1985) was used to accomplish this step. Table 4.1 presents the source of variation for the analysis of variance.

Table 4.1 Analysis of variance for the effect of plant population density and planting date on pineapple D-leaf area and dry weight, leaf dry weight, stem dry weight, and plant total dry weight at forcing.

Source of variation	Degree of freedom
Planting date	2
Replication within planting date	6
Plant population density (PPD)	4
Planting date × PPD	8
Experimental error	24
Total	44

2. Analysis of treatment design

This step analyzes the effect of levels of the factors on response variables. Because plant population density is a quantitative factor and planting date was taken to be a qualitative factor for the purposes of this analysis, they were analyzed differently. The former was analyzed by regression while the latter was analyzed by breaking the factor into orthogonal single degree of freedom components. The analysis was accomplished by fitting a model that contained class and continuous variables to the data using the SAS GLM procedure (SAS Institute, 1985) and hand calculation. A polynomial term from first order to higher order was gradually added into the model until the LACKFIT, which is the effect due to lack of fit by the regression, was not significant. A component of planting date was eliminated when it was not significant. Table 4.2 presents the ANOVA table for the combined analysis.

4.3.2.3 Growth Analysis

In order to examine how plant population density and planting date affect pineapple dry matter accumulation and partitioning during vegetative growth,

Table 4.2 Analysis of variance for the effect of treatments on pineapple D-leaf area and dry weight, leaf dry weight, stem dry weight, and plant total dry weight at forcing.

Source of variation	degree of freedom
Planting date (PD)	(2)
PI vs. Others	1
PII vs. PIII	1
Replication within PD	(6)
Plant population density (PPD)	(4)
Linear	1
Quadratic	1
LACKFIT	2
PD × PPD	(8)
(PI vs. others) × Linear	1
(PI vs. others) × Quadratic	1
(PII vs. PIII) × Linear	1
(PII vs. PIII) × Quadratic	1
LACKFIT	4
Experimental Error	(24)
Total	(44)

instantaneous growth attributes were calculated. Data for leaf area per plant, green leaf dry weight, stem dry weight, and total plant weight up to the time of forcing for each treatment were fitted by equations that are the transformation of exponential equations proposed by Potter and Jones (1977) for calculation of dry matter partitioning and as used by Bartholomew (1982) for pineapple, and Tollenaar (1989) for maize.

Leaf area data were fitted by the equation

$$\mathbf{Log_e\, A = Log_e\, A_0 + K_a t} \qquad \mathbf{(4.1)}$$

where Log_e is natural logarithm, A is green leaf area (cm^2 $plant^{-1}$) at time t (day), A_0 is the initial green leaf area (cm^2 $plant^{-1}$), and K_a is the relative growth rate of green

leaf area (cm^2 cm^{-2} day^{-1}).

Green leaf dry weight data were fitted by the equation

$$\mathbf{Log_e\ L = Log_e\ L_0 + K_l t} \qquad \mathbf{(4.2)}$$

where L is green leaf dry weight (g $plant^{-1}$) at time t, L_0 is the initial green leaf dry weight (g $plant^{-1}$), and K_l is the relative growth rate of green leaf (g g^{-1} day^{-1}).

Leaf basal tissue dry weight data were fitted by the equation

$$\mathbf{Log_e\ BL = Log_e\ BL_0 + K_b t} \qquad \mathbf{(4.3)}$$

where BL is basal leaf dry weight (g $plant^{-1}$) at time t, BL_0 is the initial basal leaf dry weight (g $plant^{-1}$), and K_b is the relative growth rate of basal leaf (g g^{-1} day^{-1}).

Stem dry weight data were fitted by the equation

$$\mathbf{Log_e\ S = Log_e\ S_0 + K_s t} \qquad \mathbf{(4.4)}$$

where S is stem dry weight (g $plant^{-1}$) at time t, S_0 is the initial stem dry weight (g $plant^{-1}$), and K_s is relative growth rate of stem (g g^{-1} day^{-1}).

Total plant dry weight data were fitted by the equation

$$\mathbf{Log_e\ W = Log_e\ W_0 + K_w t} \qquad \mathbf{(4.5)}$$

where W is the total dry weight (g $plant^{-1}$) at time t; W_0 is the initial plant dry weight, and K^w is the relative growth rate of plant (RGR) (g g^{-1} day^{-1}).

Instantaneous dry matter partitioning to plant components is expressed as the leaf area partitioning coefficient, leaf weight partitioning coefficient, stem weight partitioning coefficient, and specific leaf area extension. Leaf area partitioning coefficient (LAPC) was defined as the daily increase in leaf area resulting from the daily increase in total dry weight (m^2 day^{-1} kg^{-1} day), i.e., the daily change in leaf

area ratio (leaf area/total plant weight). Leaf weight partitioning coefficient (LWPC) was defined as the proportion of the daily increase in total dry weight that was allocated to the leaf. Leaf basal tissue weight partitioning coefficient (BLWPC) was defined as the proportion of daily increase in total dry weight that was allocated to leaf basal tissue. Stem weight partitioning coefficient (SWPC) was defined as the proportion of the daily increase in total dry weight that was allocated to stem. Specific leaf area expansion (SLAE) was the leaf area per unit weight of new leaf. LAPC, SWPC, and SLAE were derived from the fitted equations above.

By definition, **LAPC=(dA/dt)/(dW/dt),**

LWPC=(dL/dt)/(Dw/dt),

BLWPC=(dBL/dt)/(dW/dt),

SWPC=(dS/dt)/(dW/dt),

SLAE=(dA/dt)/(dL/dt)=LAPC/LWPC.

Because $dLog_eA/dt = dA/(Adt)$ and $dLog_eW/dt=dW/(Wdt)$,

$(dA/dt)/(dW/dt) = (AdLog_eA/dt)/(WdLog_eW/dt)$,

$$LAPC = \frac{K_a A_0 e^{K_a t}}{K_w W_0 e^{K_w t}} \qquad (4.6)$$

$$LWPC = \frac{K_l L_0 e^{K_l t}}{K_w W_0 e^{K_w t}} \quad (4.7)$$

$$BLWPC = \frac{K_{bl} BL_0 e^{K_{bl} t}}{K_{W_0} e^{K_w t}} \quad (4.8)$$

$$SWPC = \frac{K_s S_0 e^{K_s t}}{K_w W_0 e^{K_w t}} \quad (4.9)$$

$$SLAE = \frac{K_a A_0 e^{K_a t}}{K_l L_0 e^{K_l t}} \quad (4.10)$$

To evaluate the effect of PPD and PD on dry matter partitioning to plant components, leaf area ratio (LAR), leaf weight ratio (LWR), leaf basal tissue weight (BLWR), stem weight ratio (SWR), and specific leaf area ratio (SLAR) were calculated from the fitted equations.

The net assimilation rate (NAR), which was defined as dry matter accumulation rate per unit of green leaf area per unit time (Kg m^{-2} day^{-1}) was

calculated by the equation

$$NAR = \frac{K_w W_0 e^{K_w t}}{A_0 e^{K_a t}} \qquad (4.11).$$

The effects of PPD and PD on the derived values RGR, NAR, LAPC, LWPC, BLWPC, SWPC, SLAE, GLAR, BLWR, SWR, and SLAR at 330 and 300 days after planting for PI and PII, respectively, were analyzed statistically using the procedure mentioned above. The time in days after planting selected for analysis represented the midpoint between 200 days after planting when population effects began to be observed and the time of forcing for PI and PII, respectively. Because of limited data from PIII, only PI and PII were analyzed here.

4.4 RESULTS AND DISCUSSION

4.4.1 D-leaf Weight vs. Plant Weight

The pineapple D-leaf has been used as an index leaf for nutrient analysis, leaf water deficiency reading, and plant growth (Py et al., 1987; W.G. Sanford, personal communication). In this study, the relationship between total plant dry weight and D-leaf dry weight was essentially linear for both plantings (Fig. 4.1 A and B) and the two were highly correlated. Total plant dry weight was also highly correlated to D-leaf area (Fig. 4.2 A and B). The results confirmed that D-leaf can be used as an index leaf for plant growth up to the time of forcing for qualitative studies.

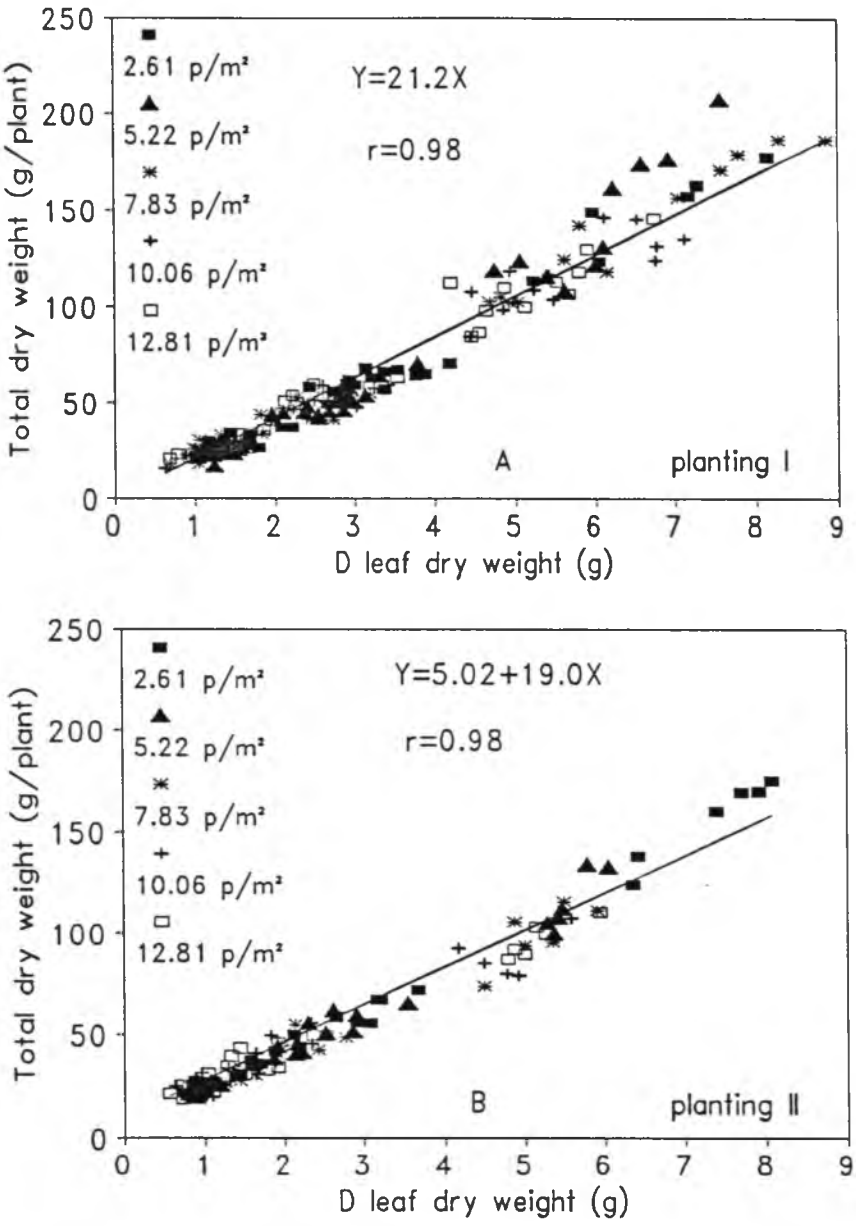


Fig. 4.1 Relationship between total dry weight per plant and D-leaf dry weight up to the time of forcing for pineapple planted June 15 (A) and August 15 (B), 1989.

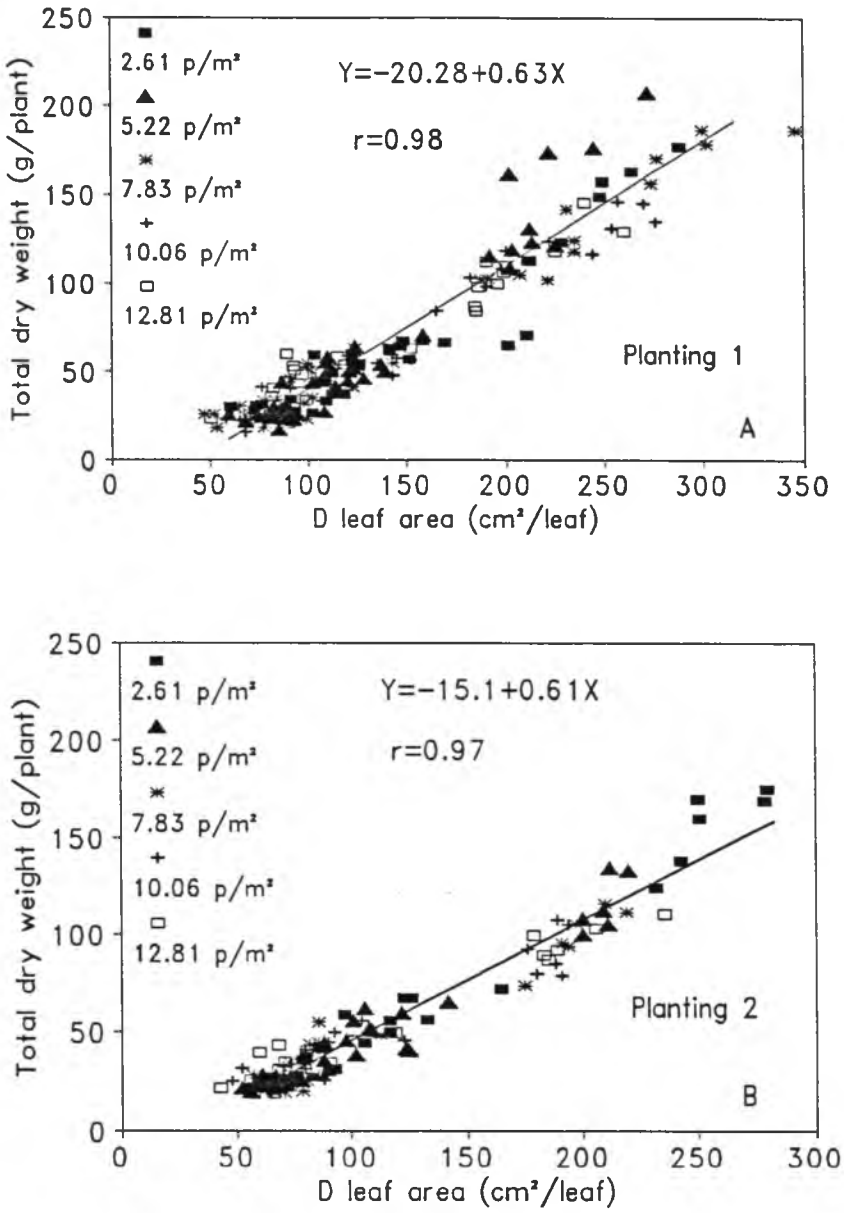


Fig. 4.2 Relationship between total dry weight per plant and D-leaf area up to the time of forcing for pineapple planted June 15 (A) and August 15 (B), 1989.

The effects of PPD and PD on D-leaf area and dry weight at the time of forcing were highly significant (Appendix A.2 and A.3). The interaction of PPD by planting date were also highly significant, indicating that the responses of D-leaf area and dry weight at forcing to PPD are different over different plant ages. The effect of planting date was small relative to the PPD effect. Both D-leaf area and dry weight sampled September 18, the date of forcing, decreased curvilinearly as PPD increased, but the rates of change (or slopes) over plantings were highly significantly different (Fig. 4.3 A and B). The relationships were best fitted by quadratic equations (Table 4.3). This suggests that D-leaf growth was reduced by mutual shading of plants at higher PPDs. These results were similar to those reported by Dass et al. (1978) for 'Kew' pineapple, where D-leaf weight decreased linearly with increasing plant population density.

4.4.2 Dry Matter Accumulation

The increase in mean dry weights of leaf (Fig. 4.4), stem (Fig. 4.5), and total dry weight (Fig. 4.6) per plant over time were constant across plant population densities up to about 200 days after planting. This likely was due to the fact that the leaf canopy had not yet closed so there was little or no inter-plant competition during this period.

Leaf dry weight before forcing increased more rapidly over time at the lower than the higher populations for all plantings (Fig. 4.4 A, B, and C). For PII and PIII, the increase in leaf dry weight ceased by about 100 days (the next sampling period) after forcing. Stem dry weight increased very little during the first 200 days

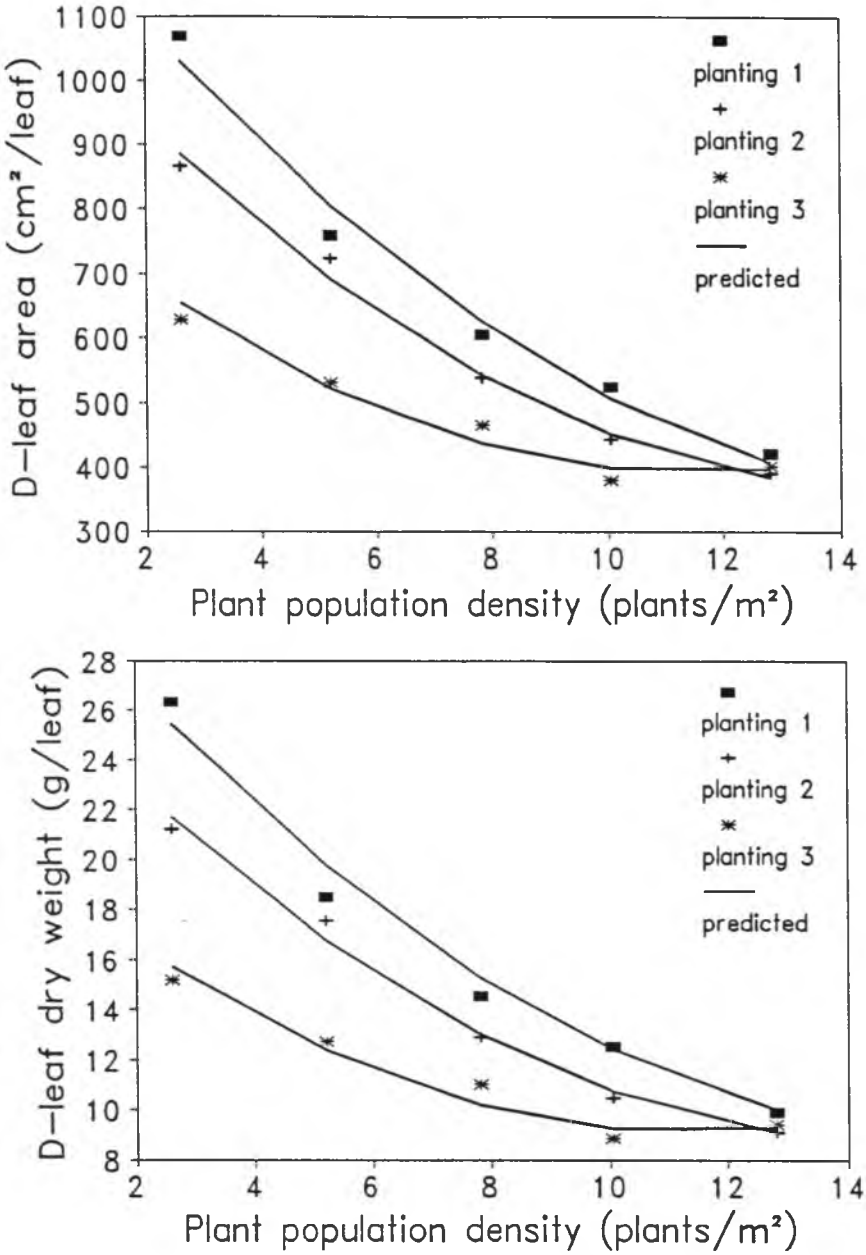


Fig. 4.3 Effect of plant population density on D-leaf area and dry weight at the time of forcing for pineapple planted on June 15, August 15, and October 18, 1989. All Plants were forced on September 18, 1990.

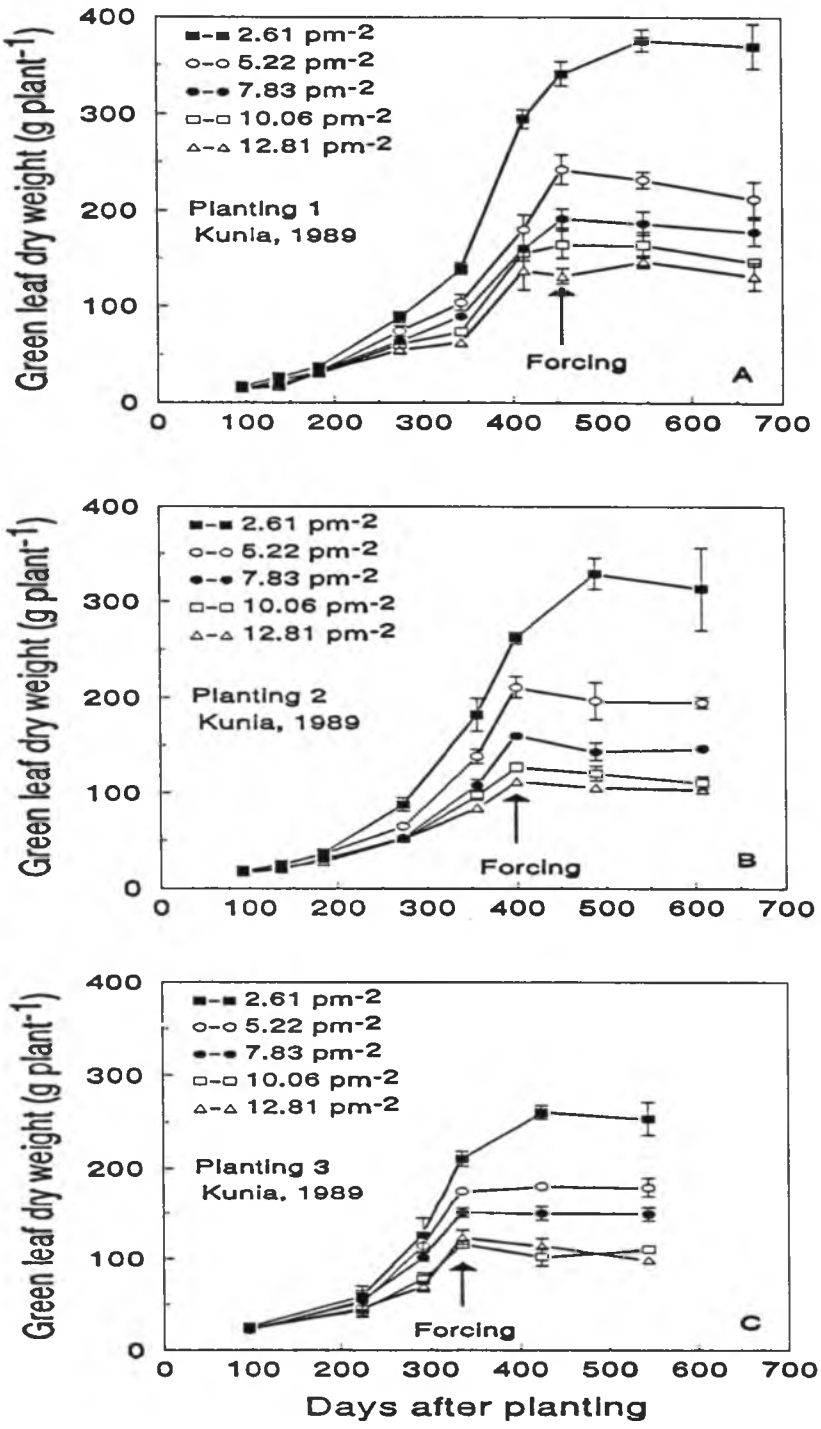


Fig. 4.4 Dry matter accumulation in green leaf tissue of pineapple planted on June 15 (Planting 1), August 15 (Planting 2), and October 18 (Planting 3), 1989. All Plants were forced on September 18, 1990.

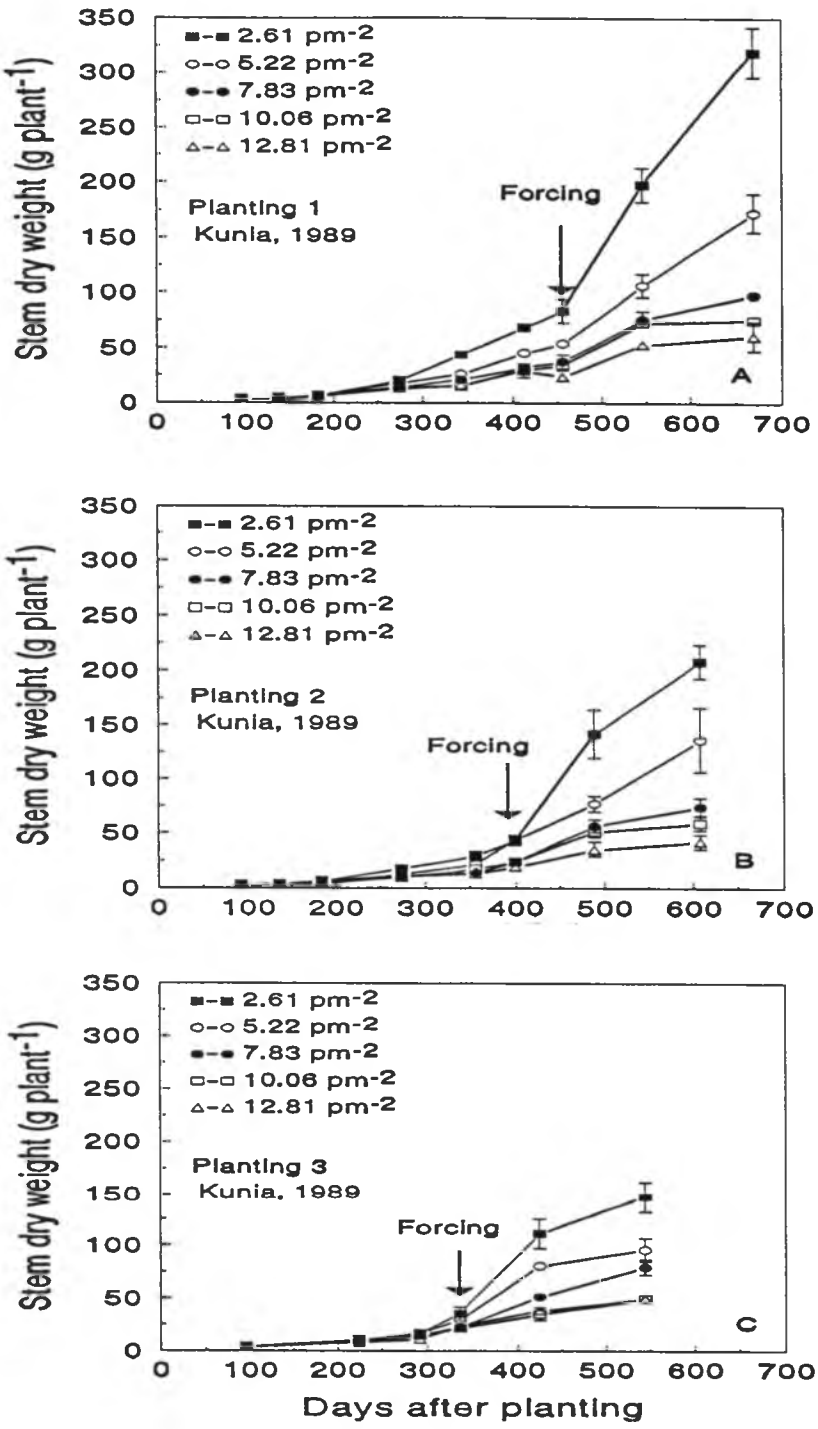


Fig. 4.5 Dry matter accumulation in stem tissue of pineapple planted on June 15 (Planting 1), August 15 (Planting 2), and October 18 (Planting 3), 1989. All Plants were forced on September 18, 1990.

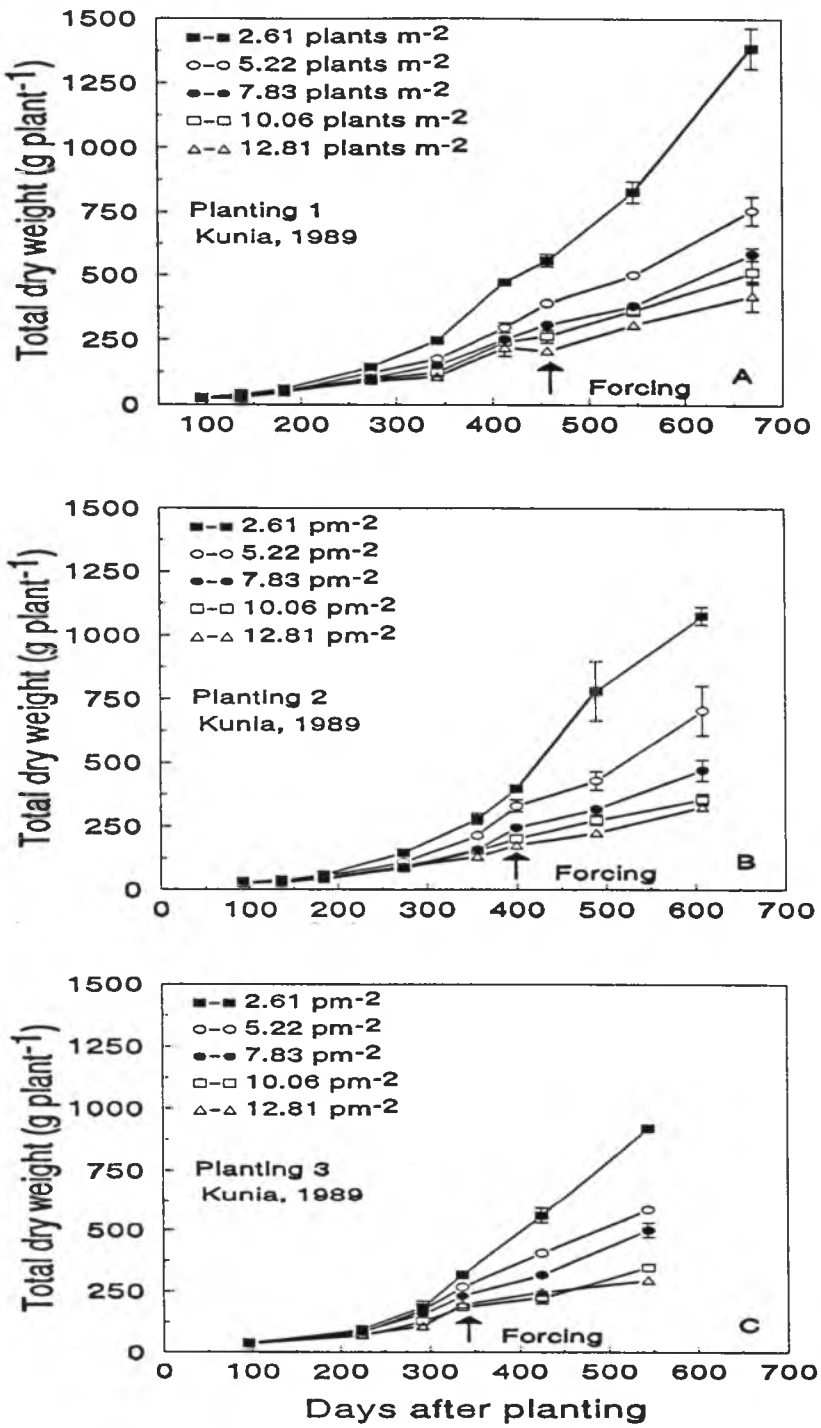


Fig. 4.6 Dry matter accumulation in plant of pineapple planted on June 15 (Planting 1), August 15 (Planting 2), and October 18 (Planting 3), 1989. All Plants were forced on September 18, 1990.

Table 4.3 Regression equations describing the effects of plant population density and planting date on pineapple D-leaf area, D-leaf dry weight, leaf dry weight, stem dry weight and total plant dry weight at forcing within density range from 2.61 to 12.81 plants m^{-2}.

Growth parameter	June 15, 1989	August 15, 1989	October 18, 1989
D-leaf area	$Y=1300-112X+3.3X^2$ †	$Y=1123-100X+3.3X^2$	$Y=829-92X+3.3X^2$
D-leaf dry weight	$Y=32.26-2.84X+0.086X^2$	$Y=27.77-2.56X+0.086X^2$	$Y=20.25-1.96X+0.086X^2$
Leaf dry weight	$Y=419.8-37.47X+1.15X^2$	$Y=344.44-32.8X+1.15X^2$	$Y=279.7-26.9X+1.15X^2$
Stem dry weight	$Y=103.25-10.08X+0.29X^2$	$Y=65.18-7.18X+0.29X^2$	$Y=49.7-5.78X+0.29X^2$
Total dry weight	$Y=682.8-60.5X+1.8X^2$	$Y=528.5-50X+1.8X^2$	$Y=421-40.4X+1.8X^2$

† The results of F-test were presented in Appendix Tables A.2 to A.6.

Y stands for dependent variables leaf area or weight and X stands for the independent variable plant population density.

of the planting (Fig.4.5 A, B, and C) and the dry matter content of stems remained about constant for PI and PII (Fig. 4.7 A and B). After that time, stem dry weights increased slowly up to the time of forcing and rapidly thereafter. Presumably, a carbohydrate surplus was present for accumulation during reproductive development (Fig. 4.7). No consistent effect of plant population density on stem dry matter content was observed.

Plant accumulation of dry matter over time in leaves, stems, and plant paralleled that of leaves and stem (Fig. 4.6 A, B, and C). Plant dry weight (Fig. 4.6 A, B, and C) increased greatly up to forcing. After forcing, leaf initiation ceased, but total plant dry weight increased slightly because of the continued growth of initiated leaves and increases in stem dry weight. Presumably due to intense mutual shading at the higher plant population densities, the increase in plant dry weight was less than it was at the lower plant population densities.

The general shapes of the curves of dry matter accumulation among leaves (Fig. 4.4 A, B, and C), stem (Fig. 4.5 A, B, and C), and plant (Fig. 4.6 A, B, and C) were similar for all three plantings, but the divergence between plant population densities in PII was less than that in PI, and the divergence was least in PIII. The plants in PIII at the time of forcing were four months younger and those in PI, and two months younger than those in PII. The inter-plant competition in PIII would be expected to be less intense than that in PII and PIII.

The analysis of variance for the leaf dry weight, stem dry weight, and total dry weight per plant at forcing (Appendix A.4, A.5, and A.6) show that the main

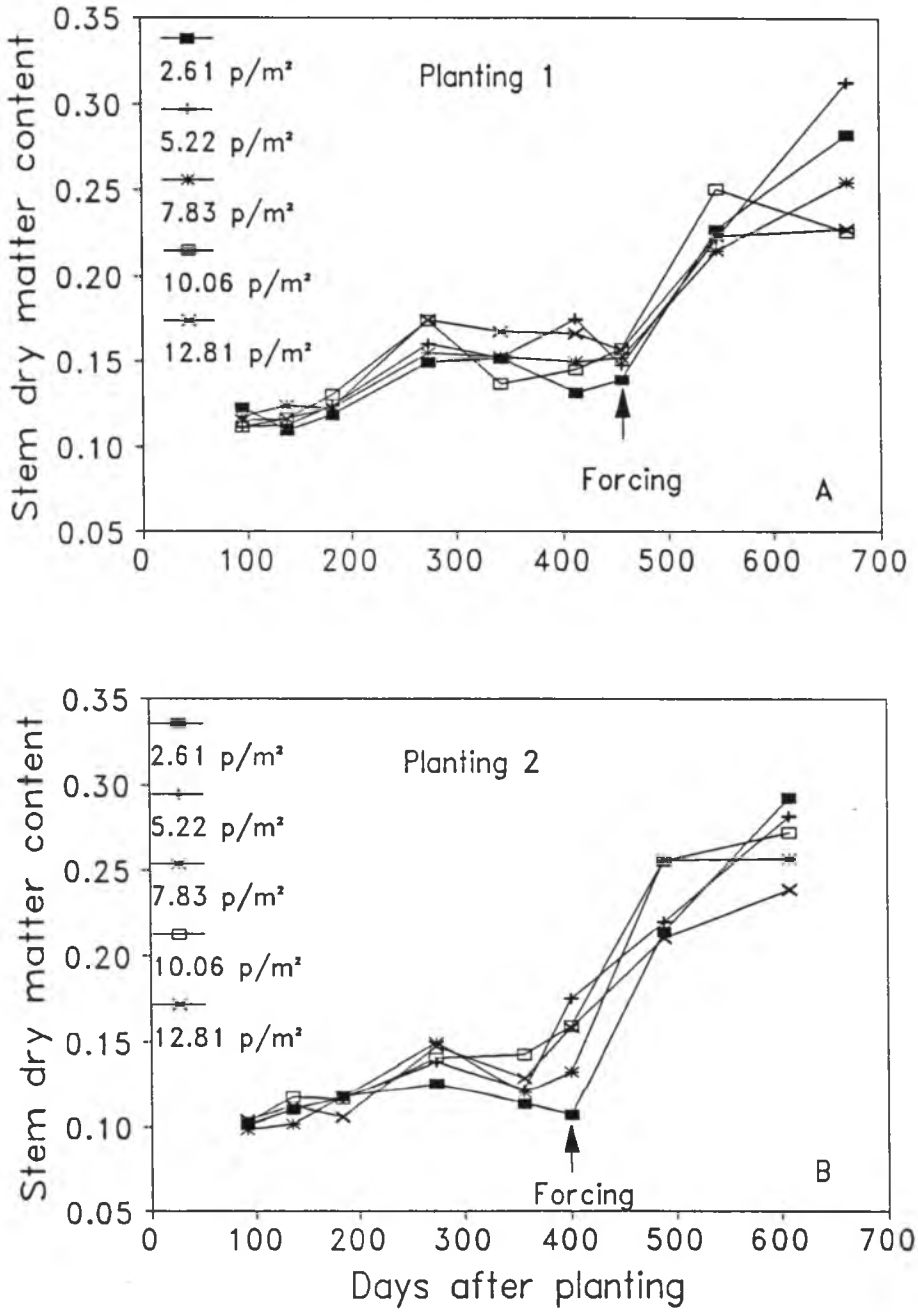


Fig. 4.7 Stem dry matter content of pineapple planted on June 15 (A), and August 15 (B), 1989.

effect of PPD was the most important source of variability. The main effect of PD and the PPD by PD interaction were small relative to the effect of PPD, but all were highly significant. The leaf dry weight, stem dry weight, total dry weight per plant at forcing, decreased curvilinearly as PPD increased (Fig. 4.8), but the rates of decrease over PPDs were significantly different over plantings (Appendix 1.5 to 1.9). The relationships were best fitted by quadratic equations (Table 4.3). The results indicate that inter-plant competition was present during vegetative growth stage at least at the higher PPDs. The significant PPD by PD interaction shows that the degree of competition at each PPD across plantings was different. The results combine data from plants of different ages and competition likely becomes more intense with increasing time after planting.

The increase in green leaf area, green leaf weight, basal leaf weight, stem weight, and total plant weight over time before forcing for each PPD were well-described by exponential equations (Eqn. 4.1 to 4.5). The coefficients of determination for the relationships ranged from 0.96 to 0.999, and all were highly significant. The relative growth rate derived from the fitted equations during vegetative growth decreased linearly with increasing plant population density (Table 4.4). No significant difference in RGR was found between PI and PII (Appendix 1.7).

Total plant weight at any time is a function of initial plant size, relative growth rate, and the duration of growth. The significant difference in plant weight between PI and PII was due primarily to the difference in duration of growth since there was

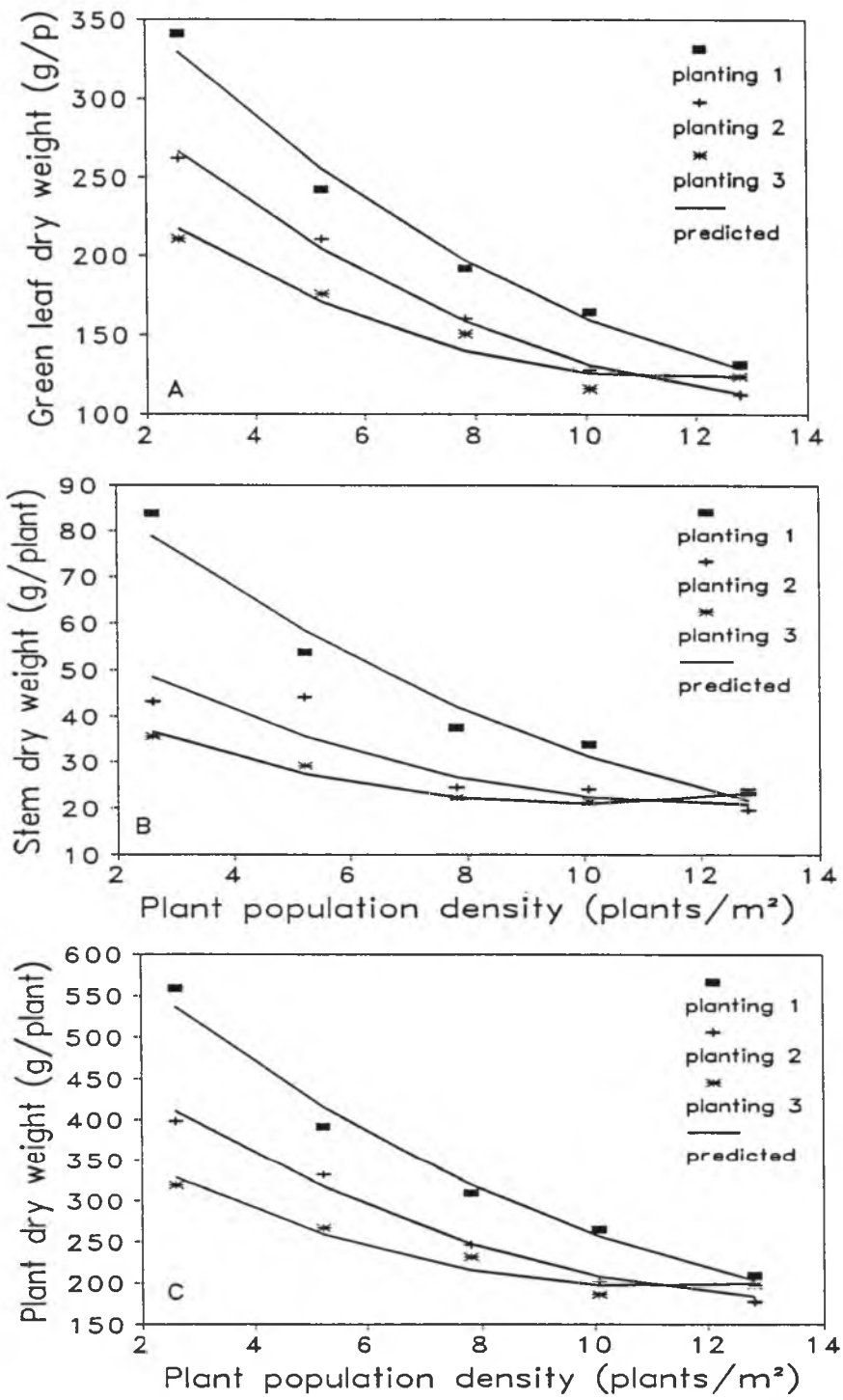


Fig. 4.8 Effect of plant population density on the green leaf dry weight per plant (A), stem dry weight per plant (B), and total dry weight per plant (C) of pineapple planted on June 15 (planting 1), August 15 (planting 2), and October 18, 1989 (planting 3).

Table 4.4 Regression equations describing the effects of plant population density on relative growth rate (RGR), net assimilation rate (NAR), leaf area partitioning coefficient (LAPC), leaf weight partitioning coefficient (LWPC), basal leaf weight partitioning coefficient (BLWPC), stem weight partitioning coefficient (SWPC), and specific leaf expansion (SLAE) that were derived from the fitted growth curves of 'Smooth Cayenne' pineapple planted on June 15 (Planting 1) and August 15 (Planting 2), 1989, respectively.

Parameter	Planting 1 and 2	
RGR ($g\ g^{-1}\ d^{-1}$)	$Y=0.00888-0.000209X$ †	**
NAR ($g\ m^{-2}\ d^{-1}$)	$Y=3.1-0.159X+0.0049X^2$	**
LAPC ($cm^2\ d^{-1}$ g-1 d)	$Y=25.99$	NS
LWPC (Kg d^{-1} Kg^{-1} d)	$Y=0.62$	NS
BLWPC (Kg d^{-1} Kg^{-1} d)	$Y=0.23+0.00215X$	**
SWPC (Kg d^{-1} Kg^{-1} d)	$Y=0.152-0.0019X$	*
SLAE ($cm^2\ d^{-1}$ g-1 d)	$Y=41.3+0.286X$	*

† Y stands for the dependent variables of RGR, NAR, LAPC, LWPC, BLWPC, SWPC, and SLAE. X stands for the independent variable of plant population density.
* and **, respectively, indicates significant at p=0.05 and 0.01; NS indicates not significant.
The results of analysis of variance were presented in Appendix A.7, 8, 9, 10, 11, 12,and 13.

little difference in initial size of planting material. No significant effects of plant population density or planting date were found on LAPC and LWPC while BLWPC and SLAE increased linearly with an increase of PPD but SWPC decreased linearly as PPD increased (Table 4.4). This suggests that during vegetative growth, dry matter partitions more to growing leaves than to stem with increasing plant population density. Net assimilation rate decreased curvilinearly as PPD increased and the relationship was best fitted by a quadratic equation (Table 4.4).

Relative growth rate of pineapple was better correlated with net assimilation rate than it was with the several partitioning coefficients (Table 4.5). This is similar

to the results obtained by Bartholomew (1982) for pineapple grown in the controlled environments. In contrast, the leaf area partitioning (LAP) coefficient was better correlated with relative growth rate for several species having C3 and C4 photosynthetic pathways that were grown in different temperature regimes (Potter and Jones, 1977; Tollenaar, 1989). Potter and Jones (1977) found that LAP coefficients of several plant species were sensitive to temperature while NARs were independent of temperature. Bartholomew (1982) found that leaf area expansion rates of pineapple plants did not vary with temperatures, and the contributing factor to the different NARs was thought to be the leaf display, with thin, drooping leaves of plants grown at warm temperatures having lower NAR.

Table 4.5 Coefficients of correlation (*r*) between pineapple relative growth rate (RGR, g g^{-1} d^{-1}) and leaf area partitioning coefficient (LAPC), green leaf dry weight partitioning coefficient (LWPC), basal leaf tissue dry weight partitioning coefficient (BLWPC), stem dry weight partitioning coefficient (SWPC), specific leaf area expansion (SLAE), and net assimilation rate (NAR) during vegetative growth.

Parameters	RGR	
LAPC	0.33	NS
LWPC	0.012	NS
BLWPC	- 0.47	**
SWPC	0.33	NS
SLAE	- 0.42	*
NAR	0.95	**

* and **, respectively, indicates significant at p=0.05 and 0.01, NS indicates not significant.

In this study, RGR was negatively correlated with the specific leaf area expansion of pineapple (Table 4.5). This inverse relationship may be due to the decline in NAR as green leaves became thinner. Different rates of dry matter accumulation by pineapple over the different PPDs resulted from the effect of PPD on NAR rather than on leaf partitioning coefficients. The decline in NAR with increasing PPD likely was due to reduced light penetrating to shaded leaves at higher PPDs. Reduced light penetration would reduce NAR and total assimilation by individual plants, thus decreasing RGR. A reduction in RGR would then reduce the accumulation of dry matter per plant over time at higher PPDs.

4.4.3 Dry Matter Partitioning

Dry matter accumulation by pineapple plants varied substantially across plant population densities and planting dates, but dry matter partitioning to the components during vegetative growth was similar among the treatments (Fig. 4.9). The proportion of dry matter partitioned to green leaf tissue, basal leaf tissue, and stem was constant up to the time of forcing (Fig. 4.10). The fluctuation in the ratios of green leaf dry weight, basal leaf tissue dry weight to the total dry weight at about 340 days after planting for PI and 280 days for PII was most likely due to the effect of herbicide application. Leaf yellowing was observed during the period. After forcing, most dry matter was partitioned to inflorescence and stem. Also, a comparison of Fig. 4.10 A and C for PI and D and F for PII shows that more dry matter was partitioned to the stem after forcing in lower than in higher PPDs.

Leaf area ratio (LAR) at midpoint of the vegetative growth period was affected

by both planting date and PPD (Appendix A.14). The mean LAR over PPDs for PI was higher than that for PII. LAR increased linearly as PPD increased in both plantings and both had the same slope (Table 4.6). Specific leaf area ratio (SLAR) was not influenced by planting date, but significantly influenced by PPD (Appendix A.15). SLAR increased linearly as the PPD increased (Table 4.6). The ratios LWR, BLWR, and SWR at the mid-point of the vegetative growth period were not affected by PPD, but affected by PD (Appendix A.16, A.17, A.18).

Table 4.6 Regression equations describing the effects of plant population density and planting date on leaf area ratio (LAR), green leaf weight ratio (LWR), basal leaf weight ratio (BLWR), stem weight ratio (SWR), and specific leaf area ratio (SLAR) of pineapple at 330 and 300 days after planting for Plants planted on June 15 (PI), and August 15 (PII), 1989, respectively.

Parameter	June 15, 1989 (PI)		August 15, 1989 (PII)	
LAR	Y=30.33+0.323X †	**	Y=31.87+0.323X	**
LWR	Y=0.61	**	Y=0.63	**
BLWR	Y=0.252	*	Y=0.258	*
SWR	Y=0.145	**	Y=0.111	**
SLAR	Y=50.3+0.51X	**	Y=50.3+0.51X	**

† Y stands for the dependent variables of LAR, LWR, BLWR, SWR, and SLAR.
X stands for independent variable of plant population density.
* and **, respectively, indicates significant at p=0.05 and 0.01, NS indicates not significant.

The difference in LWR, BLWR, and SWR between the two plantings was most likely due to the different ages of the plants (plants in PII were two months younger than in PI). Because is the product of LWR and SLAR, the difference in LAR was due to the difference in SLAR.

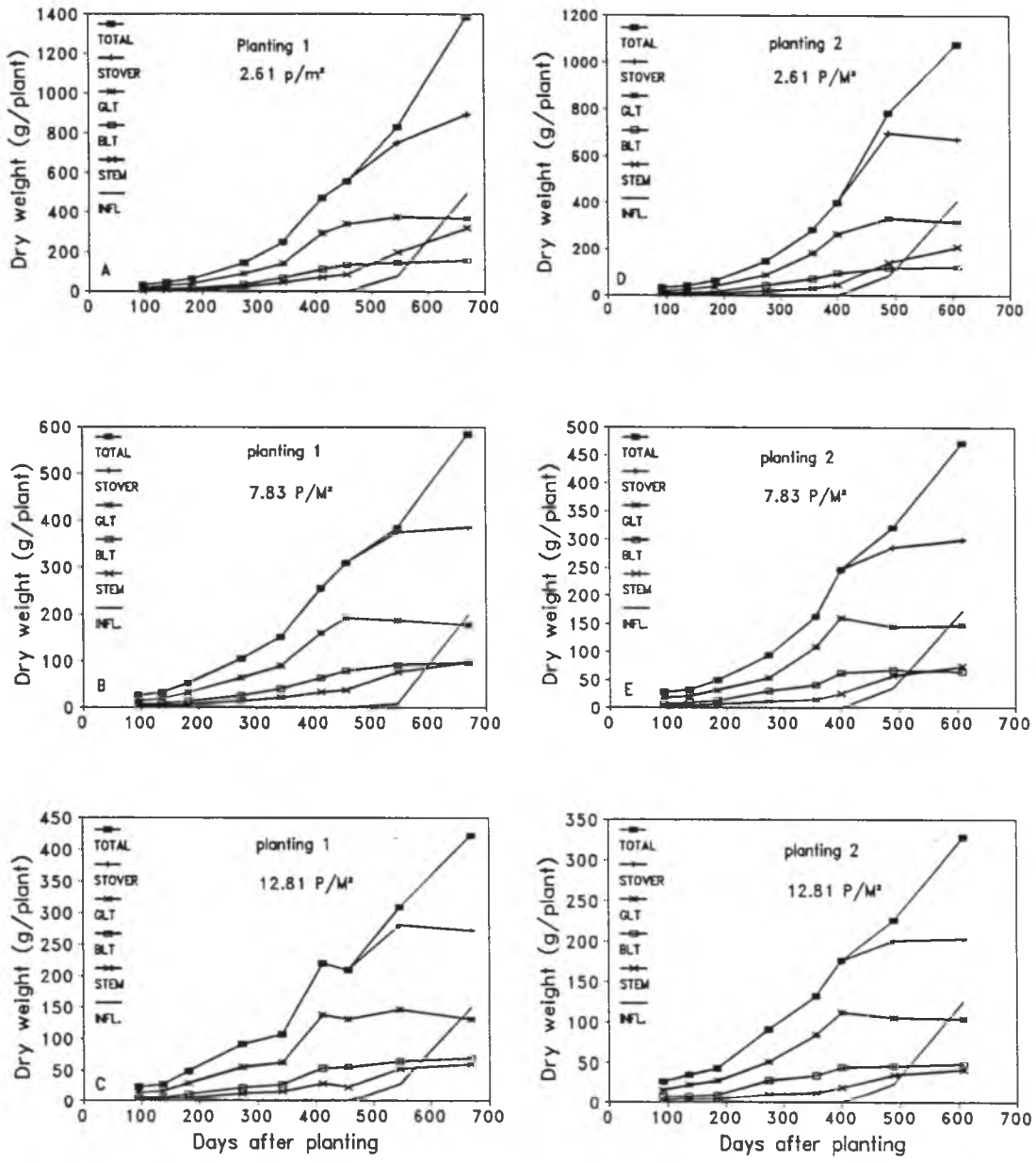


Fig. 4.9 Dry matter accumulated by the plant (TOTAL), leaf plus stem (STOVER), green leaf (GLT), basal leaf (BLT), stem, and inflorescence (INFL)of pineapple planted at three plant population densities June 15 and August 15, 1989. All plants were forced on September 15, 1990.

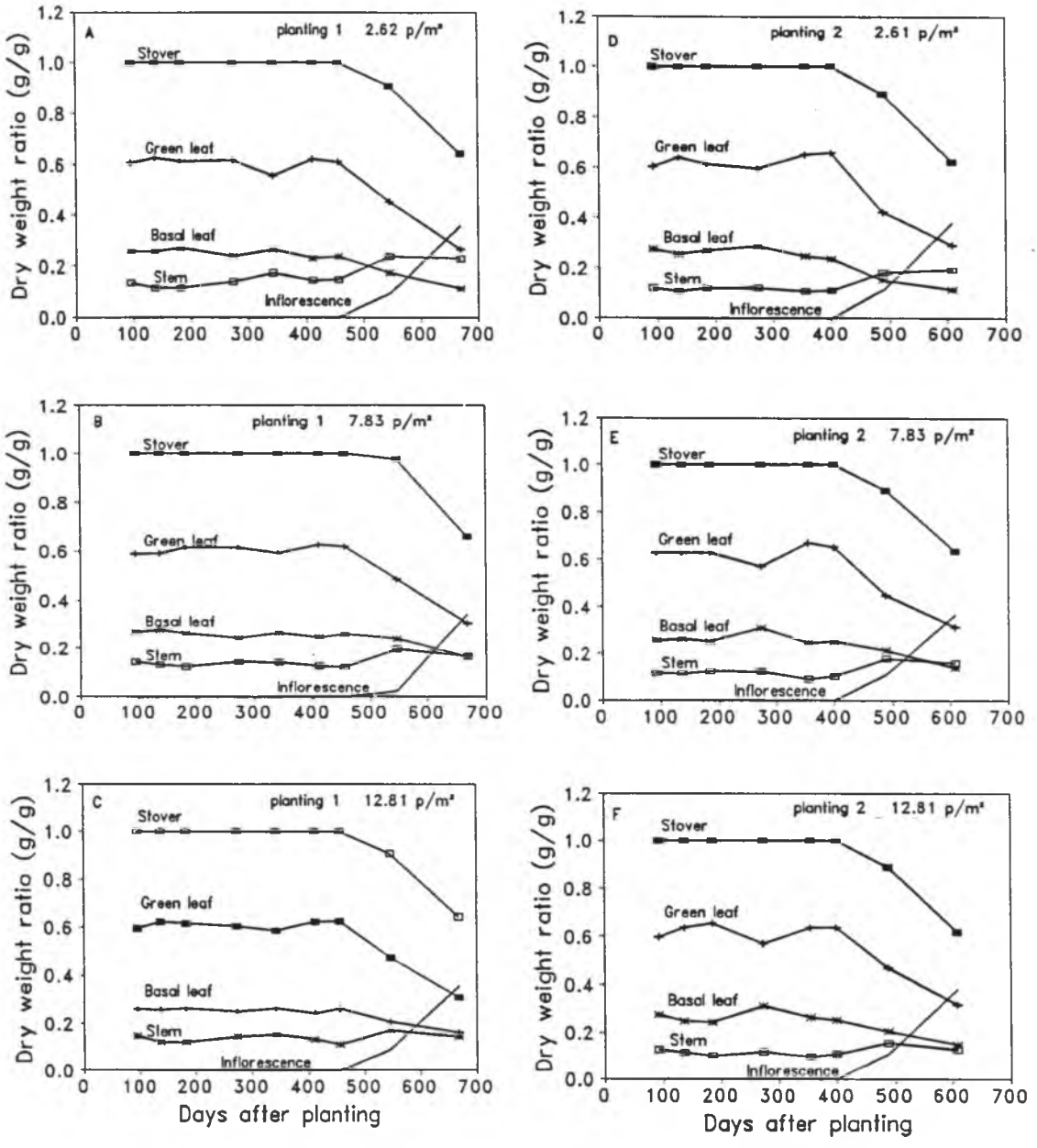


Fig. 4.10 Ratios of plant component (stover=stem plus green and basal leaf) dry weights to total dry weight for pineapple planted at three plant populations on June 15 and August 15, 1989. All plants were forced on September 18, 1990.

The effects of PPD and PD on dry matter partitioning to reproductive organs and stem during reproductive development were examined using the dry weight ratios of inflorescence and stem to total dry weight at the time of fruit harvest. The stem weight ratio at harvest (HSWR) decreased linearly as PPD increased and the relationship was affected by planting date and their interaction (Table 4.7; Appendix A.19).

Table 4.7 Regression equations describing the effects of planting date and plant population density on stem-whole plant dry weight ratio (HSWR) and fresh fruit-whole plant dry weight ratio (HFWR) at fruit harvest for pineapple planted on three dates and forced September 18, 1990.

Planting Date	HSWR		HFWR	
June 15, 1989	$Y = 0.263 - 0.0102X$	**	$Y=0.188+0.024X-0.001X^2$	**
August 15, 1989	$Y = 0.188 - 0.0033X$	**	$Y=0.236+0.021X-0.001X^2$	**
October 18 1989	$Y = 0.188 - 0.0033X$	**	$Y=0.236+0.021x-0.001X^2$	**

Y stands for the dependent variables HSWR, HFWR.
X stands for the independent variable plant population density.
* and **, respectively, indicates significant at p=0.05 and 0.01, NS indicates not significant.

At the two lower PPDs, HSWR in PI was significantly higher than those for PII and PIII, but no significant difference was found among plantings at higher PPDs (Fig. 4.11). The data show that dry matter partitioning to stem was influenced by plant size. When a plant reaches a certain size dry matter is partitioned to the stem.

The effects of PPD and PD on fresh fruit-whole plant dry weight ratio at harvest (HFWR) were significant (Table 4.7 and Appendix 1.20). The mean HFWR across PPDs in PI was less than that in PII or PIII; there was no significant difference

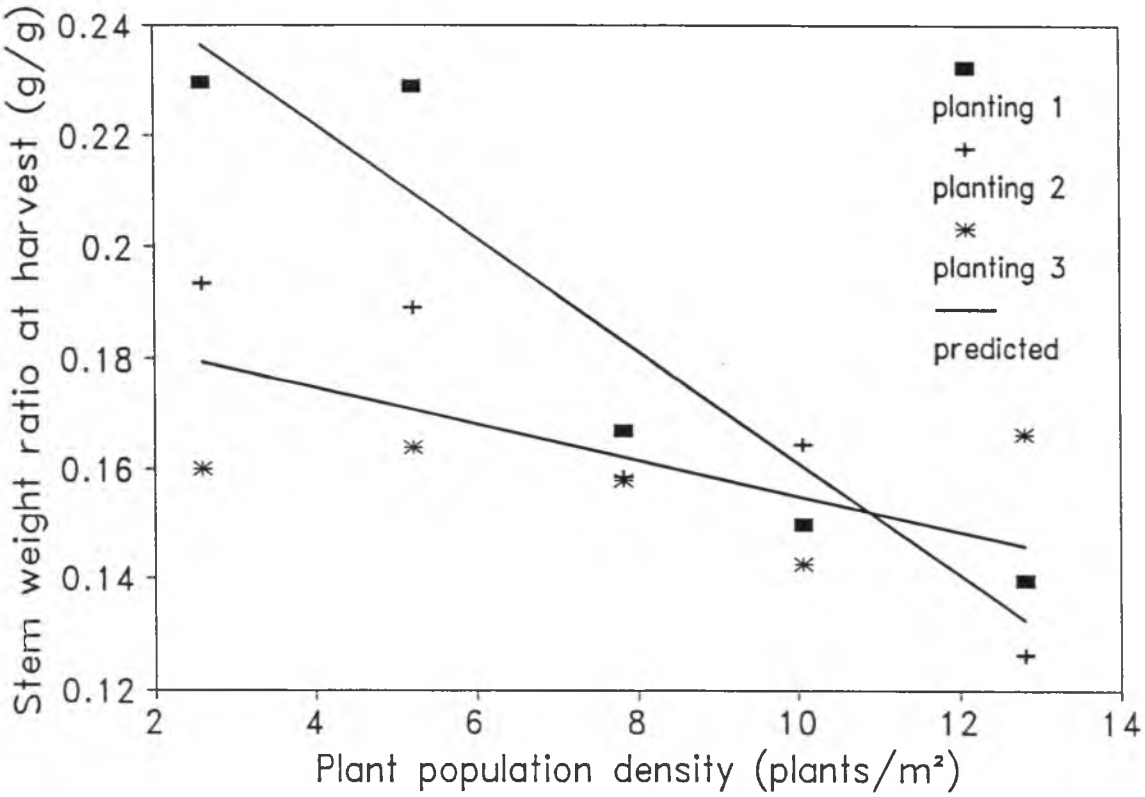


Fig. 4.11 Effect of plant population density on the ratio stem dry weight per plant to total plant dry weight at fruit harvest for pineapple planted on June 15 (planting 1), August 15 (planting 2, and October 18, 1989 (planting 3).

in HFWR across PPDs between PII and PIII. HFWR increased curvilinearly with increasing PPD and the relationships were best fitted by quadratic equations (Table 4.7). Dry matter partitioning to fruits was more efficient in small than in large plants, presumably because the mutual shading associated with the more intense competition at the higher PPDs reduced the substrate available for both storage and fruit development. The evidence suggests that the fruit has priority over the stem when resources are limited.

4.4.4 Relationship between Leaf Area and Leaf Number per Plant

The ratio leaf area-leaf number per plant (LANR), which reflects the increase in area per leaf as leaf number increases, increased with time up to about the time of forcing and then declined (Fig. 4.12). The LANR at the lowest PPD was consistently higher than those at other PPDs over time. There were no consistent differences in LANR among other PPDs. When the LANRs up to the time of forcing were plotted against the number of leaves per plant, a linear relationship was obtained (Fig. 4.13). The variability accounted for by the linear model was 92 percent. The relationship was highly significant and was not affected by PPD. This relationship allows the calculation of daily growth of green leaf area up to the time of forcing from leaf number and daily fraction of leaf in the pineapple growth model, but it needs to be tested for other environments.

In summary, dry matter accumulation of 'Smooth Cayenne' pineapple varied substantially over plant population densities and planting dates. This was due to the difference in initial size of plant, the duration of growth, and the decline in net

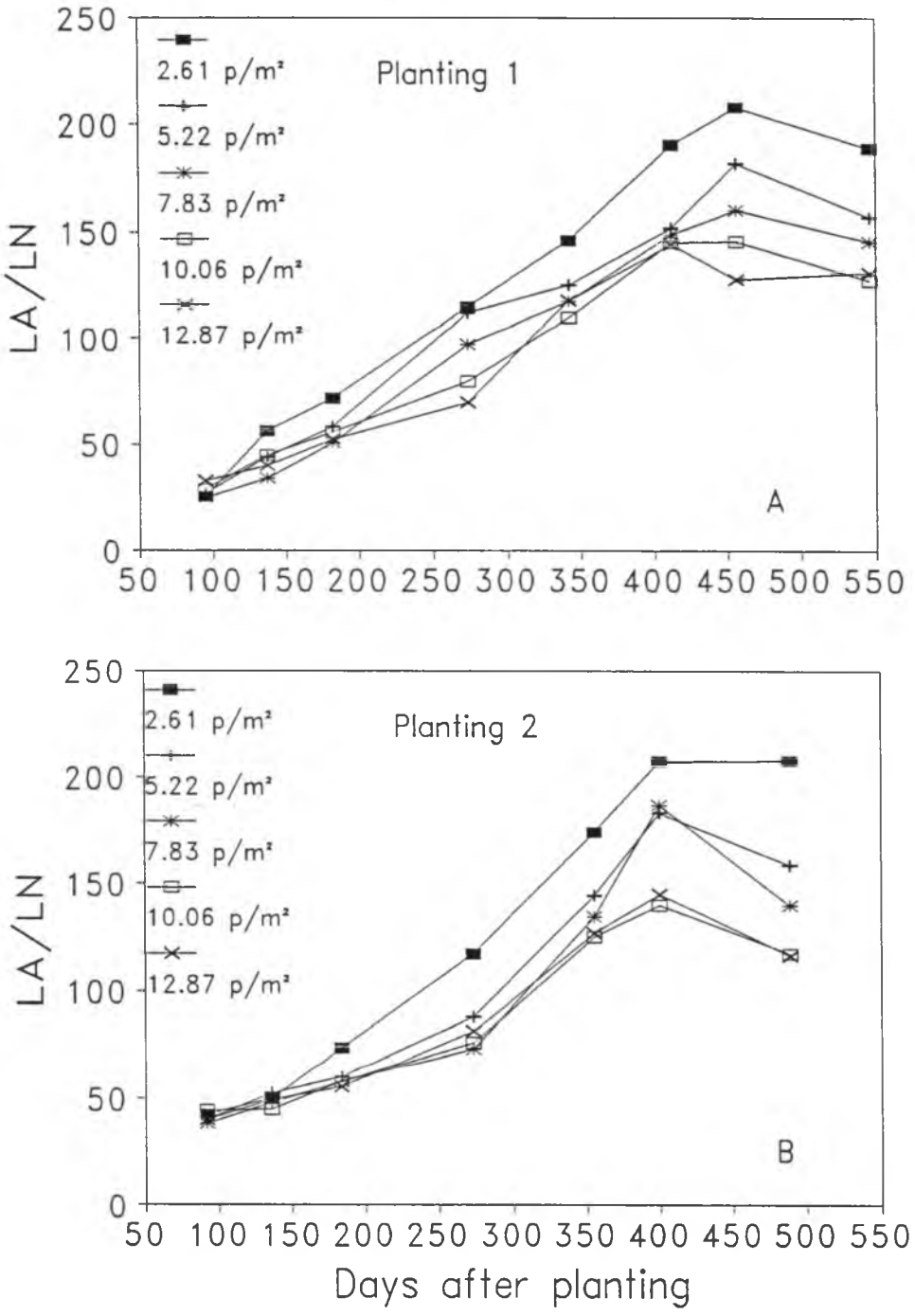


Fig. 4.12 Green leaf area (LA)-leaf number (LN) per plant for pineapple planted on June 15 (A), and August 15 (B), 1989.

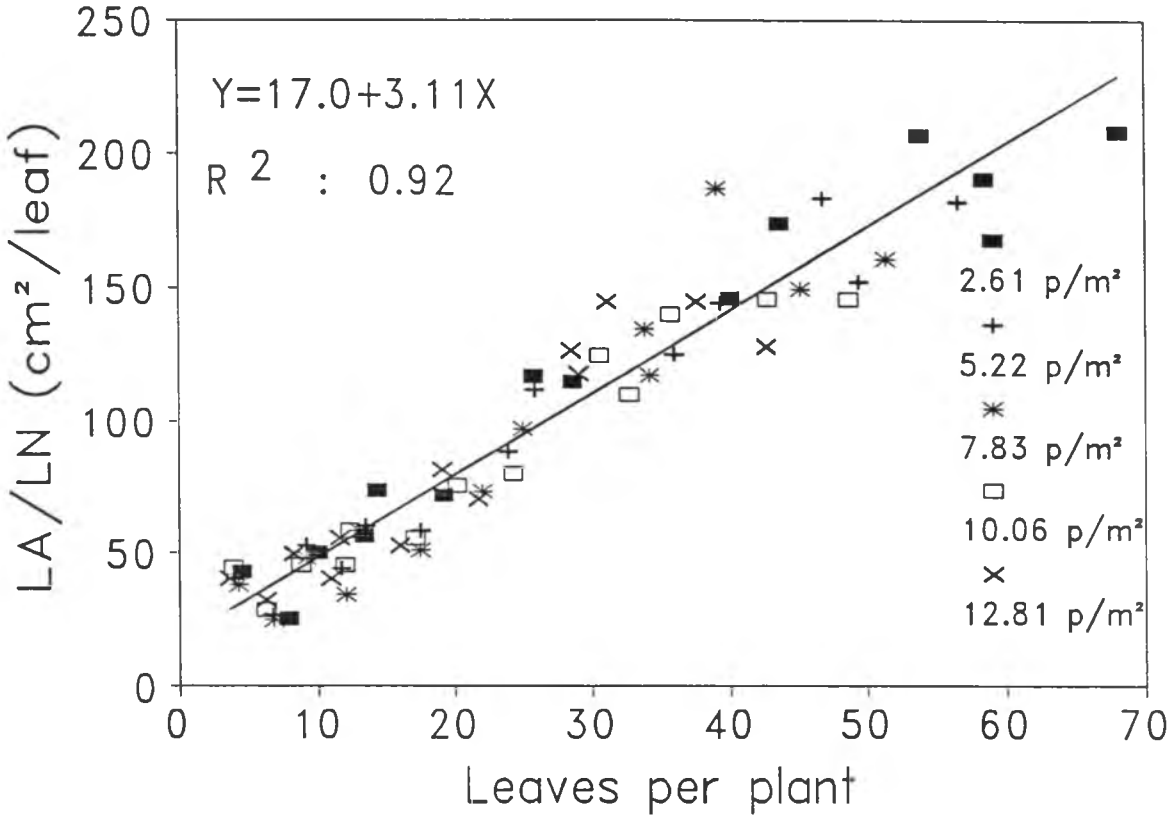


Fig. 4.13 Relationship between the ratio green leaf area per plant (LA)-leaf number per plant (LN) and leaf number up to the time of forcing for pineapple planted June 15 and August 15, 1989 at five plant population densities.

assimilation rate during vegetative growth as plant population increased. Dry matter was partitioned more to leaves during the vegetative stage and the more to inflorescence and stem during reproductive development. The proportion of dry matter partitioned to leaves and stem during vegetative growth was not significantly affected by plant population densities. The proportion of dry matter partitioned to stem at fruit harvest decreased linearly as plant population density increased and as planting was delayed. Dry matter partitioning to fruits increased curvilinearly as increased plant population density and as planting was delayed. The D-leaf area and dry weight, dry weights of green leaf, stem, and plant at forcing decreased curvilinearly as plant population density increased, and the relationships were influenced consistently by planting dates. The ratio green leaf area per plant to leaf number per plant up to the time of forcing was highly correlated with leaf number per plant, and the relationship was not influenced by PPDs and planting dates.

CHAPTER 5

REPRODUCTIVE DEVELOPMENT AND YIELD

5.1 INTRODUCTION

Plant population densities that result in inter-plant competition reduce vegetative growth per plant of 'Smooth Cayenne' pineapple (Chapter 4). Plant competition would become more intense during reproductive development as a result of further increase in dry matter per plant in a fixed area. The amount of light intercepted by a plant during the early period of reproductive development influences the pineapple fruit weight (Sanford, unpublished data). Thus, plant competition for sunlight due to increasing plant population density would be expected to decrease average fruit weight. Sanford (unpublished data) found that harvest date of pineapple fruits was delayed and fruit harvest duration increased with increasing PPD. It is often observed that fruits mature earlier at the edge of a field and fruits in south-facing rows in the northern hemisphere mature earlier than those in north-facing rows. It is therefore hypothesized that for a given cultivar, variation in fruit development rate is due at least in part to the variation in fruit exposure to sunlight at a given location. Both plant population density and plant size within a PPD are likely to cause variation in fruit exposure to sunlight. Information on how PPD and plant size within a PPD affects pineapple fruit development rate is necessary to be able to accurately simulate pineapple fruit development and predict fruit harvest date.

Knowing how plant population density and plant size at forcing within a plant

population density influence fruit weight and the distribution of fruit sizes will improve the ability to predict their effects on economic fruit yield of pineapple. No data were found in the literature on the effects of plant population density and plant size within a plant population density and their interaction on reproductive development, fruit yield, and fruit size distribution.

The objectives of the study were to:

1. Examine effects of plant population density and planting date on the rate of fruit development, average fruit weight, fruit yield, and fruit size distribution.
2. Examine effects of PPD on fruit quality.

5.2 LITERATURE REVIEW

5.2.1 Plant Fruiting

The percentage of plants producing a fruit (fruiting percentage) directly influences the yield of pineapple. The fruiting percentage of 'Smooth Cayenne' pineapple permitted to flower naturally decreased as plant population density increased in both plant and ratoon crops (Kwang and Chiu, 1966). Similar results were obtained when 'Sarawak' (Lee, 1977), 'Kew' (Gunjate and Limaye, 1977), 'Smooth Cayenne' (Wang and Chang, 1959) and 'Singapore Spanish' (Wee, 1969) clones of pineapple plant crops were forced into flower. Contrary to the above results, there was no significant effect of plant population density on the fruiting percentage of 'Smooth Cayenne' pineapple in Taiwan (Hwang, 1970; Su, 1957).

Because the susceptibility of pineapple to natural flower induction is influenced by the size of the plant (Cooper, 1942; Das et al., 1965; Py, 1958), the cultivar, and environmental conditions (Bartholomew and Kadzimin, 1977), variation in the percentage of natural flowering across densities could be due to many factors. Variation in fruiting percentage of forced plants could be due to the difficulty in uniformly treating all plants with the growth regulator as plant population increases and to variation in susceptibility to the growth regulator due to differential growth rates caused by crowding. Plant competition for light may also reduce the fruiting percentage.

5.2.2 Time of Fruit Harvest

The time and duration of flowering and harvesting are affected by cultivar, environment, and plant population density. In four trials conducted in Hawaii where plant population density ranged from 43,000 to 64,245 plants per hectare, harvest was delayed as plant population density increased, with only minor exceptions regardless of whether flower initiation was forced or natural (Sanford, 1962b). He also reported that the total period required to complete the harvest usually increased with increasing plant population density. Similar results were obtained in Australia (Jordan, 1977; Glennie, 1972a) and in Ghana (Norman, 1978). The differences in time of fruit harvest and time span of harvest with different plant population densities may result from the effect of plant population density on the microclimate around the fruits.

Contrary to the above results, Singh et al. (1974), and Chadha et al. (1973) found that fruits matured earlier at higher than at lower plant population densities, and

there was no significant effect of plant population density on harvest duration. Chadha et al. (1973) also found that at higher plant population densities, plants flowered and completed flowering earlier than those at lower plant population densities. Balakrishanan et al. (1978) reported that there was no significant difference in duration of plant crops among plant densities from 44,477 to 111,200 plants per hectare. These contrary results from India may be due to uncontrolled or uncharacterized factors such as water stress or nutrient stress that masked the effect of plant population density.

5.2.3 Plant Crop Fruit Yield

1. Average fruit weight

For a given plant population density, the average yield per plant directly influences the total yield per unit area. Seeds per plant of subterranean clover decreased progressively with increasing PPD (Donald, 1954). Duncan (1958) found that grain yield per plant of maize from several experiments decreased exponentially with increasing PPD. Holliday (1960a and b) reported that grain yield of wheat per plant decreased curvilinearly with increasing PPD and the relationship between the reciprocal of the yield and PPD was described by a quadratic expression. The curvilinear relationship between yield per plant and PPD has been suggested to be due to intense intra-plant competition at lower PPDs and intense inter-plant competition at higher PPDs (Donald, 1963).

Above a certain plant population density, the average fruit weight of pineapple decreased as plant population density increased (Sanford, 1962b; Bartholomew and

Paull, 1986). Analysis of data from many plant population density trials reported in the literature (Table 5.1) shows fruit weight decreases linearly as plant population density increases and other similar results have also been reported (Sanford, 1965; Kwang and Chiu, 1966; Wang and Chang, 1958a and b; Mitchell and Nicholson, 1965; Ghosh and Medhi, 1981; Gunjate and Limaye, 1977). The decrease in fruit weight for every 1000 plants per hectare increase is function of the clone or cultivar and environmental factors (Table 5.1). In Hawaii, for 'Smooth Cayenne', there was a loss of approximately 20 grams in average fruit weight for every increase of a thousand plants per hectare, in Australia, the loss was about 12 grams, and in Swaziland it was about 6 grams. For a given location and cultivar, the smaller the decrease in fruit weight per increase of 1,000 plants per hectare; the higher the plant population density required for maximum yield. The decrease in average fruit weight with increasing plant population density results from decreased light interception by individual plants during the reproductive period.

Defoliation experiments conducted by Sideris and Krauss (1936, unpublished data) and Sanford (personal communication) in Hawaii demonstrated that carbohydrates needed during the fruit development period did not come from stored carbohydrates but from carbohydrates currently produced in the leaves as the result of photosynthesis. Another experiment, also conducted in Hawaii (Sanford, unpublished data), confirmed this observation. In this experiment, which was planted at 54,114 plants per hectare, plants were forced to flower 13 months after planting. Treatments consisted of removing every other plant at two week intervals from the time of

Table 5.1 Relationships between average fruit weight of pineapple and plant population densities. Linear regression equations were calculated from data in the literature.

Variety or cultivar	Location	Plant density range((1000 plants ha^{-1})	Regression (Kg)	R^2	Fruit weight drop‡	Reference
Smooth Cayenne	Hawaii	32.37 - 43.00	Y=3.14-2.02E-05X	0.99	20.21	Sanford, 1962b
		43.00 - 64.24	Y=2.26-8.08E-06X	0.99	8.08	Sanford, 1962b
		43.00 - 64.24	Y=3.06-1.84E-05X	0.99	18.37	Sanford, 1962b
		43.00 - 64.24	Y=2.52-1.3E-05X	0.99	13.04	Sanford, 1962b
		43.00 - 64.24	Y=3.09-2.2E-05X	0.97	22.05	Sanford, 1962b
		43.00 - 64.24	Y=3.04-2.0E-05X	0.98	20.21	Sanford, 1962b
		43.00 - 64.24	Y=2.84-1.5E-0.5X	0.99	15.25	Sanford, 1962b
		36.82 - 51.64	Y=2.25-1.76E-05X	0.94	17.64	Sanford, 1962b
	Beerwah, Australia	11.86 - 215.2	Y=2.28-8.45E-06X	0.91	4.45	Glennie, 1972a
		11.86 - 120.8	Y=2.42-1.23E-05X	0.97	12.31	Glennie, 1972a
		25.94 - 120.8	Y=2.35-1.1E-05X	0.98	11.02	Glennie, 1972b
		26.93 - 98.84	Y=2.33-1.27E-05X	0.94	12.68	Glennie, 1972b
	Taiwan	40.03 - 57.08	Y=1.38-5.51E-06X	0.94	5.51	Hwang, 1970
		34.30 - 50.01	Y=1.72-5.88E-06X	0.97	5.88	
	Taiwan †	34.30 - 50.01	Y=1.61-6.43E-06X	0.90	6.43	
	Malkerns Swaziland	43.00 - 100.4	Y=2.05-6.43E-06X	0.94	6.43	Dodson, 1968
Sarawak	Kelang, Malaysia	59.08 - 177.2	Y=2.5-2.02E-06X	0.94	20.21	Lee, 1977
Kew	Bangalore, India	50.83 - 105.6	Y=1.81-4.41E-06X	0.72	4.41	Dass et al. 1978
Giant Kew	Basti, India	12.35 - 49.42	Y=0.69-2.57E-06X	0.79	2.57	Singh et al. 1974
Sugarloaf	Kumasi, Ghana	17.00 - 157.0	Y=1.59-8.82E-06X	0.93	8.82	Norman, 1978
PR-167	Manati, Puerto Rico	77.43 - 147.3	Y=2.06-7.53E-06X	0.96	7.53	Ramires and Gandia, 1982
Red Spanish		14.95 - 54.14	Y=1.92-7.9E-06X	0.87	7.90	Gonzalez-Tejera, 1969
Singapore Spanish	Johore, Malaysia	28.70 - 104.4	Y=1.16-3.49E-06X	0.88	3.49	Wee, 1969

† Collar of slip clone of Smooth Cayenne.

‡ Decrease in average fruit weight for each increase in plant population density of 1000 plants.

forcing to 28 weeks after forcing plant removal reduced plant population density to 27,057 plants per hectare. The increase in average fruit weight because of removal of every other plant at forcing was 540.26 gram (1.19 pounds), a value very close to the predicted gain of 499.4 gram (1.10 pounds) based on the linear relationship between PPD and average fruit weight (Table 5.1) established in earlier studies (Sanford, 1962). Sanford (unpublished data) also found that the number of eyes per long spiral was determined in the first two weeks after forcing. Since the final fruit weight is a product of the total number of eyes per fruit and average eye weight, the sunlight conditions during the early period of fruit development are important in influencing average fruit weight.

For a given plant population density, average fruit weight is a function of controllable factors such as agronomic practices and less controllable factors such as climate. Among those factors, irradiance and air temperature are the major factors affecting the average fruit weight (Sanford, unpublished data). Fields where plants produce high average plant crop fruit weights could sustain higher plant population densities.

Some evidence suggests that the decrease in fruit weight with increasing plant population density may also be due to a limiting supply of nutrients. Su (1957) examined the interaction between plant population density and fertilizer level on fruit yield of 'Smooth Cayenne' pineapple at plant densities of 26,410 to 42,251 plants per hectare. He found that when fertilizer was applied on a unit area basis, average fruit weight decreased as plant population density increased. If fertilizer was applied on a

per plant basis, there was no significant effect of plant population density on average fruit weight. He concluded that the decrease in fruit weight, seemingly due to the close spacing of plants, was due to the decrease in the amount of fertilizer available to each plant. However, Wee (1969) demonstrated that even when fertilizer was applied on per plant basis, mean fruit weight of 'Singapore Spanish' pineapple still decreased as plant population density increased from 27,182 to 106,252 per hectare.

A number of studies did not show any effect of plant population density on average fruit weight (Cardinali and Andersen, 1971; Ramirez and Tejera, 1983; Wang and Chang, 1961; Samuels and Gonzalez-Tejera, 1976; Balakrishnan et al. 1978). The plant densities in the foregoing studies ranged from about 9,884 to 51,890 plants per hectare and the lack of an effect may have been due to the lower plant population densities (Cardinali and Andersen, 1971), or to other factors such as water stress, or insect pests and diseases.

2. Fruit yield per unit area

Holliday (1960a and b) suggested that there were essentially two basic biological relationships between yield and plant population density: asymptotic and parabolic. In the former, yield rises to a maximum with increasing plant population density, and is then relatively constant at high plant population densities. In the latter relationship, yield rises to a maximum but then declines at high PPDs. Holliday (1960b) also suggested that yield that consisted of vegetative parts of the crop or total dry matter conformed to an asymptotic relationship while reproductive forms of yield conformed to the parabolic relationship. Polynomial, exponential, geometric and

reciprocal equations have been used to describe the parabolic relationship of reproductive yield to plant population density (Willey and Heath, 1969). Among the equations, reciprocal equations were shown to "offer the best possibilities of being able to describe yield/density relationships accurately and meaningfully" (Willey and Heath).

The relationship between pineapple fruit yield and plant population density has been found to be parabolic and asymptotic (Dodson, 1968; Lee, 1977; Wee, 1969). The fruit yield of 'Smooth Cayenne' pineapple in Swaziland increased with an increase of plant population density, to a maximum at 56,832 plants ha^{-1}, and then declined (Dodson, 1968). In Malaysia, fruit yield of 'Sarawak' pineapple reached a maximum at a plant population density of 53,795 plants ha^{-1} and then declined with increasing PPD (Lee, 1977) while the yield of 'Singapore Spanish' pineapple leveled off at 71,757 plants ha^{-1} (Wee, 1969). The asymptotic relationship was likely due to the fact that the yield was the weight of all fruits, including unmarketable fruits. The results suggest that there would be a critical PPD beyond which PPD can become too high because there is insufficient photosynthate to sustain maintenance respiration and requirements for fruit growth. This has been demonstrated in other crops (Donald, 1963). The fruit yield data for pineapple also suggest that the critical PPD is influenced by genotype and environment.

In Australia, the yield of 'Smooth Cayenne' pineapple fruit increased with increasing plant population density but did not reach a maximum even at a plant population density of 215,221 plants ha^{-1} (Glennie, 1972a and 1972b). Similar results

were reported in other countries within the range of PPDs studied (Singh et al. 1974; Dass et al. 1978; Ghosh and Medhi, 1981; Chadha et al. 1973; Balakrishnan et al. 1978; Wang and Chang, 1958a and b; Yoshihara and Hwang, 1957; Norman, 1978; Gonzalez-Tejera, 1969; Hwang, 1970; Kwang and Chiu, 1966; Gunjate and Limaye, 1976; Mitchell and Nicholson, 1965; Wang and Chang, 1957; Wang et al. 1962; Su, 1957; Ramirez and Gandia, 1976 and 1982; Ramirez and Tejera, 1983). This relationship could be explained by two reasons: first, fruit yield consists of all fruits, and Glennie (1972a) commented that most fruits at the highest PPD were not marketable. Second, the plant population density range in some of the studies was too narrow and low, for example, 12,350 to 49,420 (Singh et al., 1974), 14,950 to 54,140 (Gonzalez-Tejera, 1969), 40,030 to 57,080 plants ha^{-1} (Hwang, 1970).

Sanford (1961) demonstrated that actual gains in Mg ha^{-1} per 1000 plant increment were influenced by average fruit weight, and the lower the average fruit weight the lower the PPD at which a yield plateau occurs.

It is important to note that the critical plant population density, which is the minimum plant population density that produces highest yield, is not the optimal plant population density, at which highest profit is obtained. If one only looks at yield, increased plant population density might decrease net profit (Wassman, 1978). Optimal plant population density is determined by fruit yield, fruit size, and fruit quality. Determination of the best fruit size is based on the requirements of the end users. For the fresh market, consumer preferences are most important whereas for the cannery, high recovery of fruit slices is important.

5.2.4 Plant Crop Fruit Characteristics and Recovery

Average fruit weight, fruit shape, and fruit size are important in determining the optimal plant population density both for fresh market and for the cannery (W.G. Sanford, personal communication). The effect of plant population density on average fruit weight was reviewed in section 5.2.2. Fruit shape of pineapple is an important determinant of recovery of slices in the cannery. Tapered fruits produce more slices with shell adhering to them and thus reduce slice recovery per fruit. In some plant population density studies, fruit was less tapered as fruit size decreased with increasing PPD (Sanford, personal communication; Gunjade and Limaye, 1977) whereas no significant effect of plant population density on fruit shape was found in others (Chadha et al. 1973; Ghosh and Medhi, 1981).

Fruit size, expressed as maximum diameter, is an important index for fruits intended for processing in the cannery and it is closely related to average fruit weight (Sanford, personal communication). Fruit diameter became smaller when plant population density increased (Hwang, 1970; Kwang and Chiu, 1966; Su, 1957).

The effects of plant population density on internal fruit characteristics of 'Smooth Cayenne' pineapple have been intensively studied at the Pineapple Research Institute in Hawaii (Sanford, 1962a and b, 1963 and 1965). Fruit translucence and esters decreased, whereas titratable acids, total soluble solids, and flesh pigment increased as plant population density increased. Similar results for acid content (Dodson, 1968; Wee, 1969) and sugar content (Gonzelez-Tejera, 1969) were obtained while one study showed that acid content decreased with increasing plant population

density (Gonzelez-Tejera, 1969). Other studies show no significant effect of plant population density on fruit acidity, sugar content or pH of juice (Dass et al. 1978; Ramirez and Gonzalez-Tejera, 1983; Ramirez and Gandia, 1982; Ghosh and Medhi, 1981).

Slice recovery of fruit also is influenced by PPD. Number of cases of fancy slices per Mg of fruits decreased substantially as plant population density increased in several trials where PPD ranged from 43,000 to 64,240 plants ha^{-1} (Sanford, 1963 and 1965). The loss of fancy slices was about 11 percent at 54,300 plants ha^{-1} and 31 percent at 64,200 plants ha^{-1} over that at 43,000 plants ha^{-1}. Cases of choice slices increased slightly, and standard slices showed a large increase. Total cases per Mg was not consistently affected by plant population density. In terms of cases of slices per hectare, fancy slice recovery remained approximately constant as plant population density increased while choice, standard, and total slices all increased up to a plant population density of 64,254 plants ha^{-1} (Sanford, 1962a and b, 1963, 1965).

5.2.5 Ratoon Crop

Few studies have examined the effect of plant population density on the growth and yield of the first ratoon crop. As mentioned in Chapter 3, average sucker number per plant decreased as plant population density increased whereas suckers per unit area either increased or did not change. Sanford (1963) found that in Hawaii first ratoon average fruit weights decreased only slightly with increasing plant population density, but numbers of fruit were substantially increased resulting in a large increase in tonnage. Results from Taiwan (Kwang and Chiu, 1966), Puerto

Rico (Ramirez and Gandia, 1982) showed that average fruit weights of ratoon crops were not affected by plant densities while fruit yield per unit area increased as plant population density increased. Dodson (1967) reported that ratoon fruit set and average fruit length and fruit weight decreased significantly while ratoon fruit yield was not affected by increasing plant population. Wee (1969) in Malaysia found that ratoon fruit yield, average fruit weight, and number of fruits harvested were not influenced by increasing plant population density but percentage of plants fruiting decreased from 112 to 29 percent as plant population density increased from 28,703 to 104,373 plants per ha. Kwang and Chiu (1966) also reported that the percentage of fruiting plants decreased with increasing PPD in the ratoon. The effect of PPD on ratoon fruit recovery are the same as those reported for plant crop fruit (Sanford, unpublished data).

5.2.6 Effect of Plant Size on Fruit Weight

The bulk of dry matter gain by the harvested portion is supplied as photoassimilate, principally as a single oligosaccharide (sucrose, sorbitol, stachyose, raffinose), the type depending on the plant species (Patrick, 1988). Though assimilate partitioning is influenced by partitioning of root-assimilated mineral ions and the environment around crops, within a given environment, for determinant crops, the size of the plant at the time of floral differentiation determines the yield of the harvested portion of the plant (Patrick, 1988).

Average fruit weight of pineapple is highly correlated with plant size at floral differentiation. Van Overbeek (1946) found that the average fruit weight of

'Cabezona' pineapple was highly and significantly correlated with the number of leaves per plant from plants (either natural or forced) grown in both poor and excellent conditions. Fruit weight was also highly correlated with plant weight, estimated leaf mass, and D-leaf weight at the time of floral initiation (Gaillard, 1969; Py and Lossois, 1962; Py et al., 1987; Tan and Wee, 1973; Mitchell, 1962; Malezieux, 1986). Without showing any data, Glennie (1972b) commented that the low average fruit mass and sucker production at higher densities was directly related to the small size of the plant at flower induction.

Pineapple plant crop fruit weight is also positively correlated with the size of planting material used to establish the crop (slips or crowns) (Bartholomew and Kadzimin, 1977; Sanford, unpublished data). This might be because at any given planting time and plant population density, plant weight at the time of floral differentiation is positively correlated with the size of planting material. It would be expected that this relationship would hold during the entire period of plant crop development (Sanford, personal communication). It is important to note that the relationships between average fruit weight and plant size or size of planting materials are influenced by the times of planting and of forcing (Gaillard, 1969; Sanford, personal communication).

5.3 MATERIALS AND METHODS

5.3.1 General Experimental Description

The general experimental design and field management practices were described in Chapter one.

5.3.2 Data Collection and Analysis

Data on fruit weight and fruit size distribution based on maximum fruit diameter were collected on a minimum of 55 fruit from each plot. Every fruit in the designated harvest area in each plot was harvested, beginning when the fruit shell was 30 to 50 percent of yellow. Fruit harvesting was started March 25 and ended May 17, 1991 and the harvesting interval was one week. Dates of harvest for each treatment in each planting are shown in the results section. Every fruit was picked whether it was ripe or not when 95% of fruits in a plot had been harvested. The fruits were sorted into size-categories based on standard industry diameters. These categories and their respective diameters were 2.5T (>13.65 cm), 2T (≤ 13.65 and >10.8 cm), 1T (≤ 10.8 and >9.5 cm), and S1T (<9.5 cm). Fruits and crowns in each category were bulked and weighed separately. In addition, 10 plants with fruits were harvested at random from each plot to determine total plant dry weight, fruit dry weight, total soluble solids and acid content. Total soluble solids was determined with a hand refractometer while acid content was determined by titrating an aliquot of juice extracted from a longitudinal section cut from the center of each fruit.

The harvest date was defined as the date when 10% of the fruits were harvested (Fleisch and Bartholomew, 1987). The date of physiological maturity for each treatment was defined as the date when 90% of fruits were harvested.

Fruit development rate (D, day^{-1}) was defined as the reciprocal of the time (t, day) from forcing to physiological maturity.

Average fruit weight was defined as the mean weight of all sizes of fruits

without crowns. Average fresh fruit weight was defined as the mean weight of all sizes of fruits with crowns to conform to industry practice of marketing fresh fruit with their tops.

Fruit yield was the total weight of fruits without crowns per unit area, and fresh fruit yield was the total weight of fruits with crowns per unit area. The fruit yield (Mg ha^{-1}) and fresh fruit yield were calculated as follows, assuming that every plant produced a fruit.

Fruit Yield(Mg ha^{-1})=Average fruit weight (kg)*PPD*10

Fresh fruit yield=Average fresh fruit weight (kg)*PPD*10.

5.3.3 Statistical Analysis

1. Analysis of experimental design

Initially, the effect of the main factors on response variables was analyzed. In this experiment, the main factors were plant population density and planting date. The response variables analyzed were fruit development rate, and the reciprocal of average fruit and fresh fruit weights. Analysis of variance was computed by SAS ANOVA procedure (SAS Institute, 1985). Table 5.2 presents source of variation for the analysis of variance.

2. Analysis among treatments

To further explore the effect of treatments on response variables, differences between levels of treatments were evaluated. Because plant population density is a quantitative factor and planting date was taken to be a qualitative factor for the purposes of this study, they were analyzed differently. The former was analyzed

Table 5.2 Analysis of variance table for the main effects of planting date and plant population density on pineapple fruit data.

Source of variation	Degree of freedom
Planting date	2
Replication within planting date	6
Plant population density (PPD)	4
Planting date × PPD	8
Experimental error	24
Total	44

using regression while the latter was analyzed by breaking the factor into orthogonal single degree of freedom components. For the fruit development rate, the analysis was accomplished by fitting a model that contained class and continuous variables to the data using SAS GLM procedure (SAS Institute, 1985) and hand calculation. Polynomial terms from first order to higher order were added into the model stepwise until the LACKFIT, which is the effect due to lack of fit by the regression, was not significant ($p > 0.05$). A component of planting date was eliminated when it was not significant. For the average fruit weight, the analysis was accomplished by fitting an asymptotic model (the reciprocal of the mean fruit yield as a linear function of plant population density) (Holliday, 1960b) to the data. Table 5.3 presents the analysis of variance table.

In addition, the cumulative percentage of fruits in the size categories 2.5T, 2.5T+2T, and 2.5T+2T+1T were regressed against PPD for each planting using the SAS GLM procedure (SAS Institute, 1985).

Analysis of variance for soluble solids, acid content, and pH of fruits of planting one was performed using the SAS ANOVA procedure (SAS Institute, 1985).

Table 5.3 Analysis of variance table for the evaluation of treatment effects on pineapple fruit data.

Source of variation	degree of freedom
Planting date (PD)	(2)
PI vs. Others	1
PII vs. PIII	1
Replication within PD	(6)
Plant population density (PPD)	(4)
Linear	1
Quadratic	1
LACKFIT	2
PD × PPD	(8)
(PI vs. others) × Linear	1
(PI vs. others) × Quadratic	1
(PII vs. PIII) × Linear	1
(PII vs. PIII) × Quadratic	1
LACKFIT	4
Experimental Error	(24)
Total	(44)

5.4 RESULTS AND DISCUSSION

5.4.1 Time of Fruit Harvest

The dates of the fruit harvest rounds and the number of fruits harvested for each plant population density in each round are presented in Table 5.4. Fruit harvest in this experiment started on March 25, 1992 and it lasted about two months. The fruit harvest peak (the highest number of fruits in each round or 50 percent of cumulative fruits harvested in each progressive harvest round) was delayed by increasing plant population density, but was not affected by planting dates (Table 5.4, Fig. 5.1). The duration of harvest was not affected by plant population density except for the June 15 planting where the duration of fruit harvest increased with increasing plant population density. The extended harvest duration for the June 15 planting

Table 5.4 Dates of the fruit harvest rounds and number of fruits harvested on each round for densities of 2.61 (A), 5.22 (B), 7.83 (C), 10.06 (D), and 12.81 (E) plants m^{-2} of pineapple planted on June 15 (PI), August 15 (PII), and October 18 (PIII), 1989. All plants were forced on September 18, 1990.

Date of	PI					PII					PIII				
harvest	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
03-25-91	13†	10	10	18	3	-	-	-	-	-	-	-	-	-	-
04-02-91	15	8	5	3	3	45	6	-	-	-	86	8	-	-	-
04-08-91	68	18	2	5	2	109	35	18	-	-	93	21	3	-	-
04-15-91	61	37	11	4	1	73	42	33	3	-	47	31	33	-	-
04-23-91	58	63	31	16	7	34	84	71	39	20	30	94	85	52	40
04-30-91	-‡	55	58	27	55	23	45	65	59	52	3	40	52	55	75
05-07-91	-	9	41	36	63	-	16	38	55	84	-	18	28	36	79
05-14-91	-	1	13	38	51	-	8	9	33	67	-	-	6	31	50
05-17-91	-	-	4	18	48	-	-	-	12	36	-	-	7	23	27

† Fruit numbers are the total of three replications.

‡ - indicates no fruit was harvested.

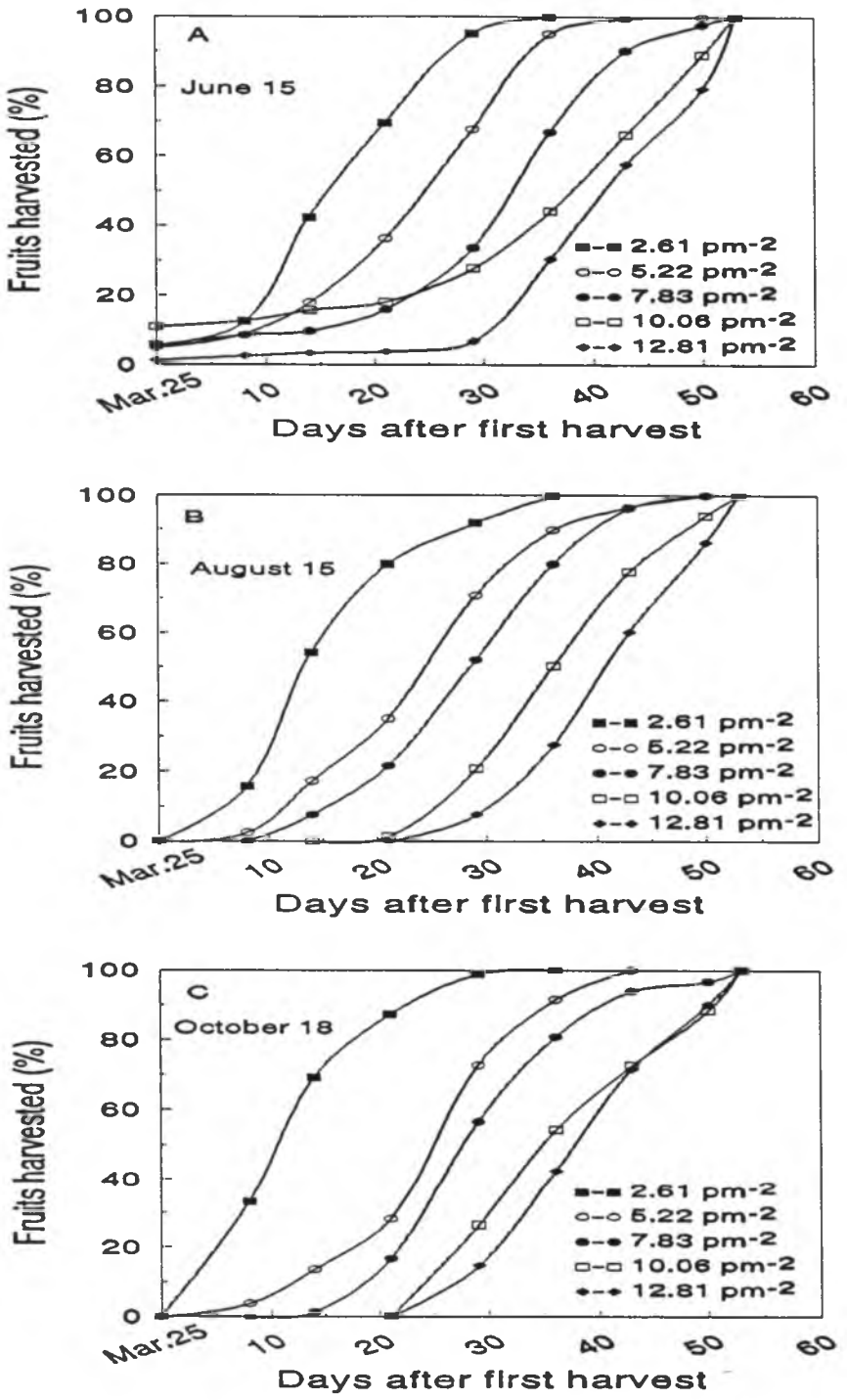


Fig. 5.1 Cumulative percentage of fruits harvested for pineapple planted on June 15 (A), August 15 (B), and October 18 (C), 1989. All plants were forced on September 18, 1990. The first round of fruit harvest was on March 25, 1991.

was due to natural flower differentiation before forcing. At forcing, plants in the June 15 planting were 14 months old, and because of their large size were more susceptible to natural flowering than plants in other plantings.

To further examine the relationship between fruit development and plant population density, analysis of variance for fruit development rate was performed. The fruit development rate, the reciprocal of days from forcing to fruit harvest date or physiological maturity, was not significantly influenced by planting dates, but was significantly influenced by plant population density (Appendix A.21 and A.22). A lower fruit development rate increases the time from forcing to fruit harvest date. Fruit development rate from forcing to harvest date declined linearly as plant population density increased (Fig. 5.2) while fruit development rate between forcing and fruit physiological maturity date declined curvilinearly (Fig. 5.3) as PPD increased from 2.61 to 12.81 plants m^{-2}. The latter relationship was well fitted by a quadratic equation (Fig. 5.3). These results were similar to those obtained by Sanford (1962), Jordan (1977), Glennie (1972a), and Norman (1978). The decrease in fruit development rate was assumed to be due to a decrease in average fruit temperature caused by the increased mutual shading at the higher populations. Fruits were well exposed at the two lowest populations, but at high populations, leaves were forced upright and fruits were less well exposed. Fruit exposure to sunlight is assumed to be important because as was noted earlier, fruits matured earliest at the edge of the field, and in south-facing rows presumably due to better exposure. There was no significant effect of planting date on fruit development rate. Fruit exposure

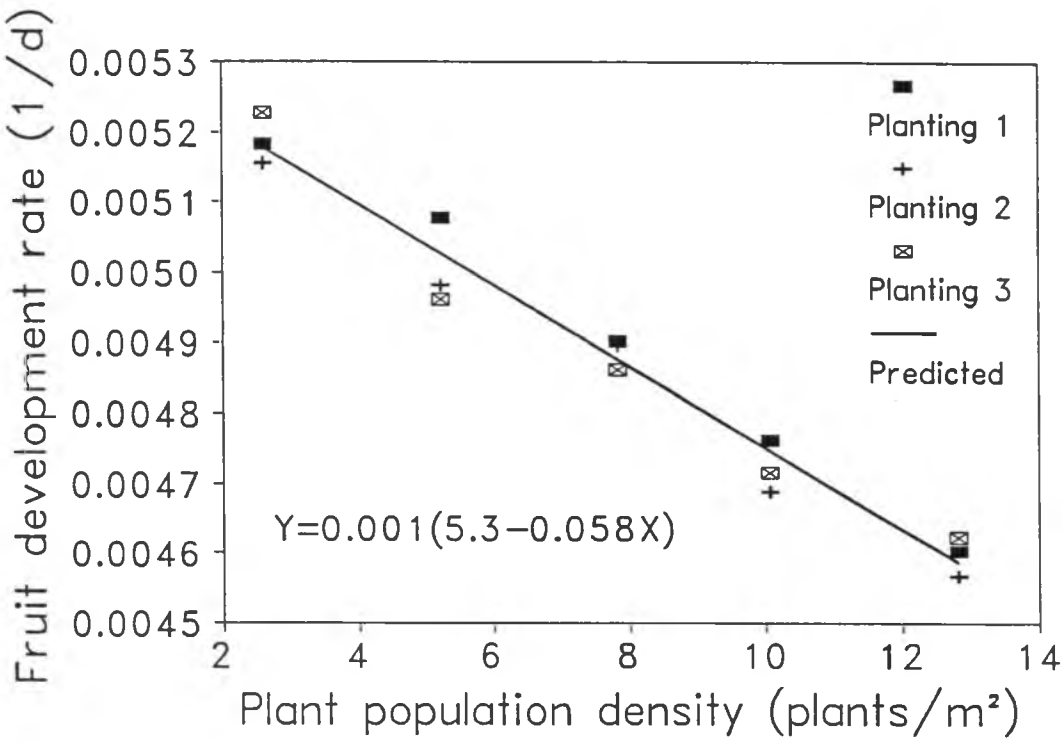


Fig. 5.2 Effect of plant population density (plants m^{-2}) on fruit development rate (d^{-1}) between forcing and fruit harvest (10% ripe fruits) for pineapple planted in June (Planting 1), August (Planting 2), and October (Planting 3), 1989 and forced in September, 1990.

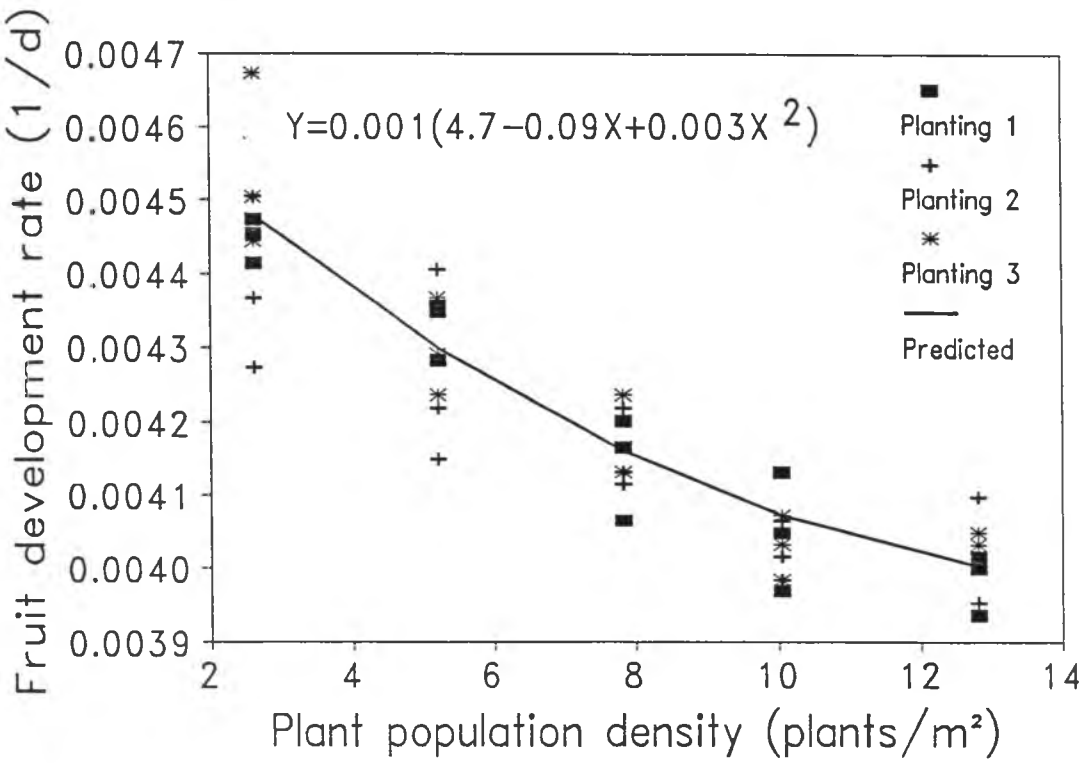


Fig. 5.3 Effect of plant population density (plants m^{-2}) on fruit development rate (d^{-1}) between forcing and physiological maturity (95 % ripe fruits) for pineapple planted in June (Planting 1), August (Planting 2), and October (Planting 3), 1989 and forced in September, 1990.

might be expected to be greater on smaller plants, but the effect, if any, was too small to detect in this study.

Crop development rate was reported to be a function of air temperature and photoperiod for rice (*Oryza sativa* L.), where ontogenetic development rate from sowing to flowering was a function of daily photoperiod and daily temperature (Horie et al., 1986). Similar results were obtained in studies of plant development rate of soybean [*Glycine max* (L.) Merr.] (Sinclair, et al., 1991). Fleisch and Bartholomew (1986) developed a heat unit model to predict inflorescence development rate of pineapple using modified growing degree days. In this study, where plants were grown in the same conditions, photoperiod and air temperature were the same. The difference in fruit development rate due to plant population presumably was due to changes in the microclimate around the plant caused by the plant population density.

5.4.2 Average Fruit Weight

Average fruit weight (without crown) and fresh fruit weight (with crown) were significantly affected by both plant population density and planting date (Appendix A.23 and A.24). Plant population density was the largest source of variation. The interaction between PPD and planting date was significant. Average fruit weight and fresh fruit weight declined curvilinearly as PPD increased (Fig. 5.4), and the relationship was well described by reciprocal equations (Table 5.5).

The reciprocal equations can be written in a general form:

$$\frac{1}{w} = a + b\rho$$

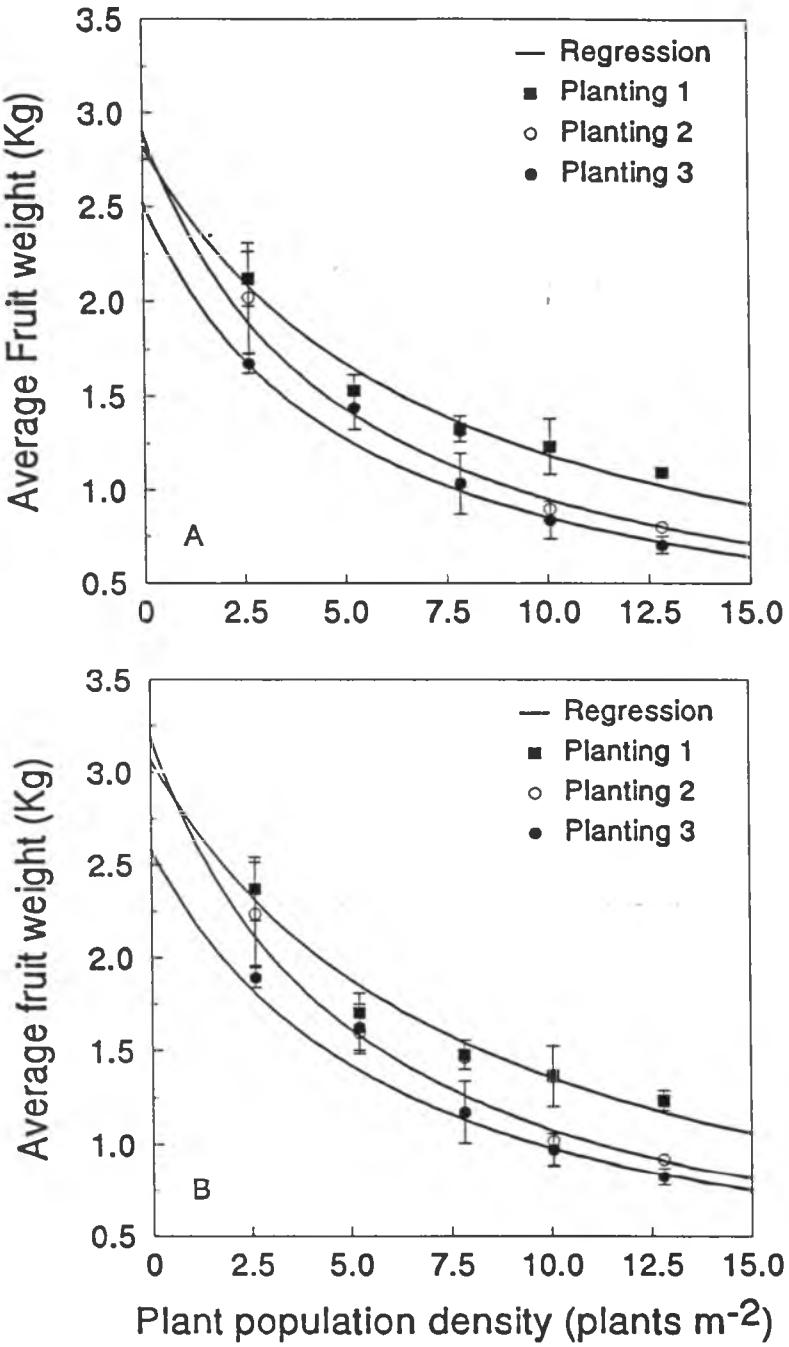


Fig. 5.4 Relationship between average fruit weight (Kg) without (A) and with (B) crowns and plant population density (plants m^{-2}) for pineapple planted in June, August and October, 1989 and forced in September, 1990.

or on a yield per area basis as

$$y = \frac{\rho}{a + b\rho}$$

where w is yield per plant, y is yield per area, ρ is plant population density, and a and b are constants.

Table 5.5 Regression equations describing the effects of plant population density on average fruit (without crown) and fresh fruit (with crown) weight for of pineapple planted in June(1), August (2), and October (3), 1989. All plants were forced in September, 1990.

Planting	Average Fruit Weight (kg)	R^2	Average Fresh Fruit Weight (kg)	R^2
1	$Y^{-1} = 0.354 + 0.0486X$	0.89	$Y^{-1} = 0.326 + 0.041X$	0.87
2	$Y^{-1} = 0.345 + 0.0705X$	0.91	$Y^{-1} = 0.314 + 0.061X$	0.91
3	$Y^{-1} = 0.397 + 0.0775X$	0.91	$Y^{-1} = 0.388 + 0.063X$	0.90

Willey and Heath (1969) argued that a and b were meaningful factors. The parameter b was indicative of environmental potential and a was indicative of genetic potential, because as ρ increases, y approaches the value of b^{-1}; as ρ tends to zero, w tends to a^{-1}. The values of a in this study for both average fruit and fresh fruit weight were different among plantings (Table 5.5) but they can not be interpreted as indicators of genetic potential, because plants were forced by application of ethylene at different ages. However, the differences in a among plantings were small, indicating that even plants in a competition free situation tend to produce a constant fruit size when plants reach a certain size. The values of b in this study (Table 5.5)

were very interesting. The later the planting, the lower the value of b, although the difference between b values for the August and October plantings was small. This indicated that June planting potentially produced greater yield than other plantings because the plants were forced at larger size. Holliday (1960b) rewrote the reciprocal equation into:

$$w = A \cdot \frac{1}{1 + Ab\rho}$$

where A is a^{-1} the "apparent maximum" yield per plant and all other parameters were as defined previously. He termed the expression $1/(1+Ab\rho)$ the "competition function". The yield per plant is, therefore, the product of the potential of the plant (A) and the forces of competition that are acting upon it $[1/(1+Ab\rho)]$. Plotting the "competition function" against ρ (Fig. 5.5), illustrates the differences in slope change in slope with density among the plantings. Dry matter partitioning to fruits was less efficient in larger plants than it was in smaller ones. If all plants had the same efficiency in partitioning dry matter to fruits, the "competition function" curves theoretically would be the same. The decrease in efficiency of dry matter partitioning as plant size increased is also illustrated in Fig. 5.6.

The decrease in average fruit weight with increasing plant population density was due to the increase in competition for sunlight. Defoliation experiments conducted by Sideris and Krauss (1936) and Sanford (personal communication) in Hawaii demonstrated that carbohydrates required for fruit development did not

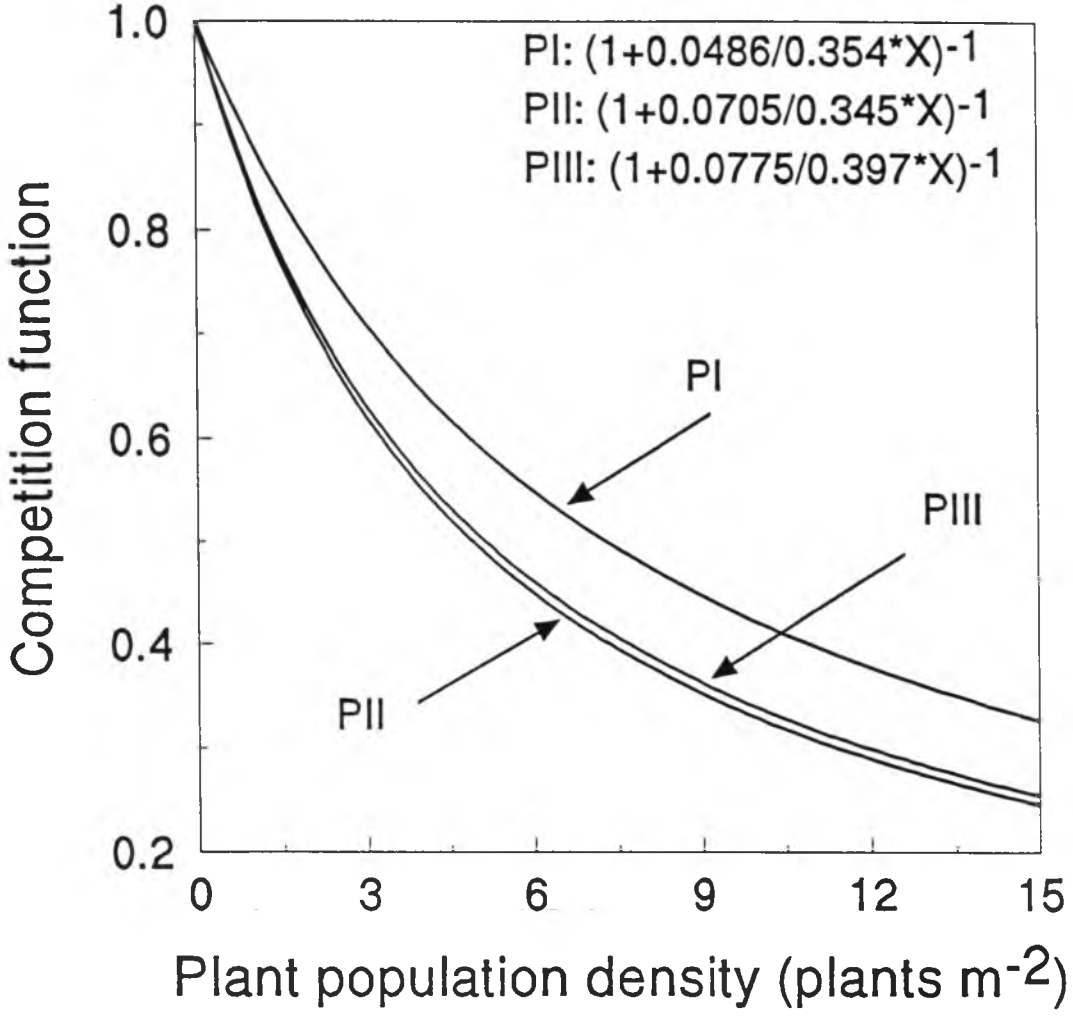


Fig. 5.5 "Competition function" (1/(1+*(b/a)**X)) derived from the fruit-density relationship for pineapple planted at Kunia, Hawaii on June 15 (PI), August 15 (PII), and October 18 (PIII), 1989. All plants were forced on September 18, 1990. *a* and *b* are the intercept and slope of a reciprocal equation of average fruit weight over density.

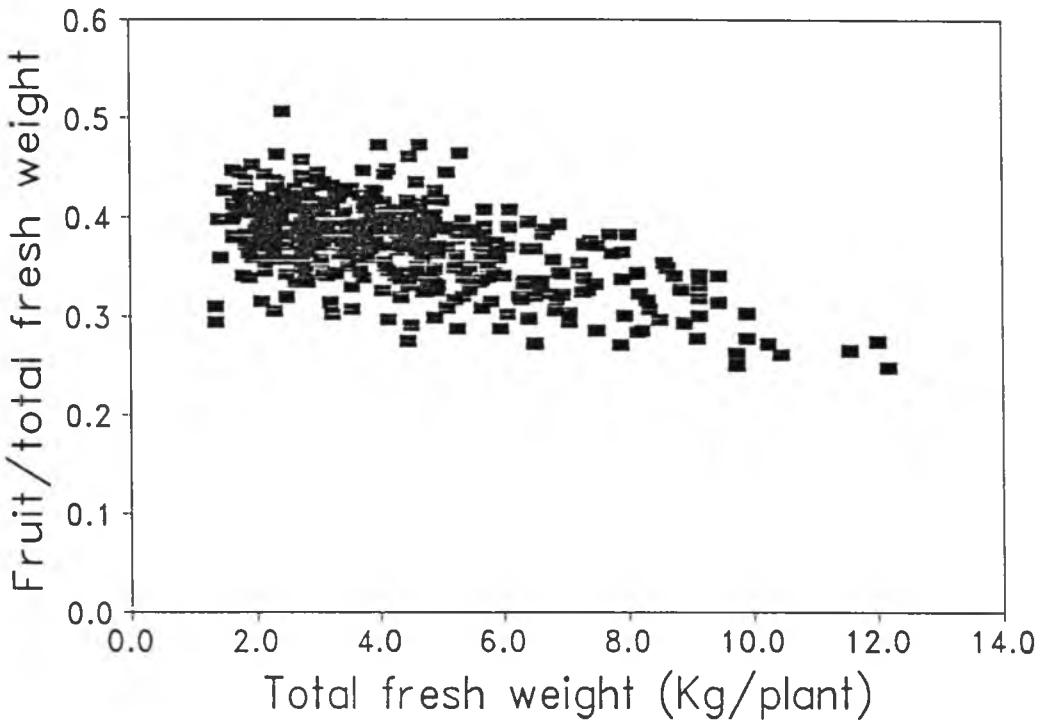


Fig. 5.6 Plot of fruit-total plant fresh weight ratio against total plant fresh weight of pineapple planted at Kunia, Hawaii in 1989.

come from stored reserves but from current photosynthesis. The relationship between PPD and yield per plant was similar to those results obtained for clover (Donald, 1954), maize (Duncan, 1958), and wheat (Holliday, 1960a and b).

Other studies of the effects of PPD on fruit yield resulted in negative linear relationships between average fruit weight and plant population density (Sanford, 1962 and 1965; Glennie, 1972a and 1972b; Hwang, 1970; Kwang and Chiu, 1966; Dodson, 1968; Lee, 1977; Dass et al., 1978; Norman, 1978; Ramirez and Gandia, 1982; Gonzalez-Tejera, 1969; Wee, 1969; Wang and Chang, 1958; Mitchell and Nicholson, 1965; Ghosh and Medhi, 1981; and Gunjate and Limaye, 1977). The linearity of the relationship might be due to the lower populations and narrower range of densities used in some of the studies; exceptions were those of Glennie (1972a and b), Dodson (1968), Lee (1977), and Wee (1969).

5.4.3 Fruit Size Distribution

Fruit size was measured to evaluate the effects of size and plant population density on this measure of fruit quality. Large (2.5T) and medium (2T) sized fruits have higher value than smaller ones because they are suitable for use as fresh fruit or for canning as slices. Smaller fruit have a lesser value because they are suitable only for processing into lower value products such as chunks, crushed pineapple, or juice. The percentage of 2.5T fruits decreased curvilinearly while the percentage of 2T fruits increased and then decreased as PPD increased (Fig. 5.7). The percentage of 1T and S1T fruits increased as PPD increased. The slope of the curve in each size category was different. In order to quantitatively calculate the fruit yield distribution

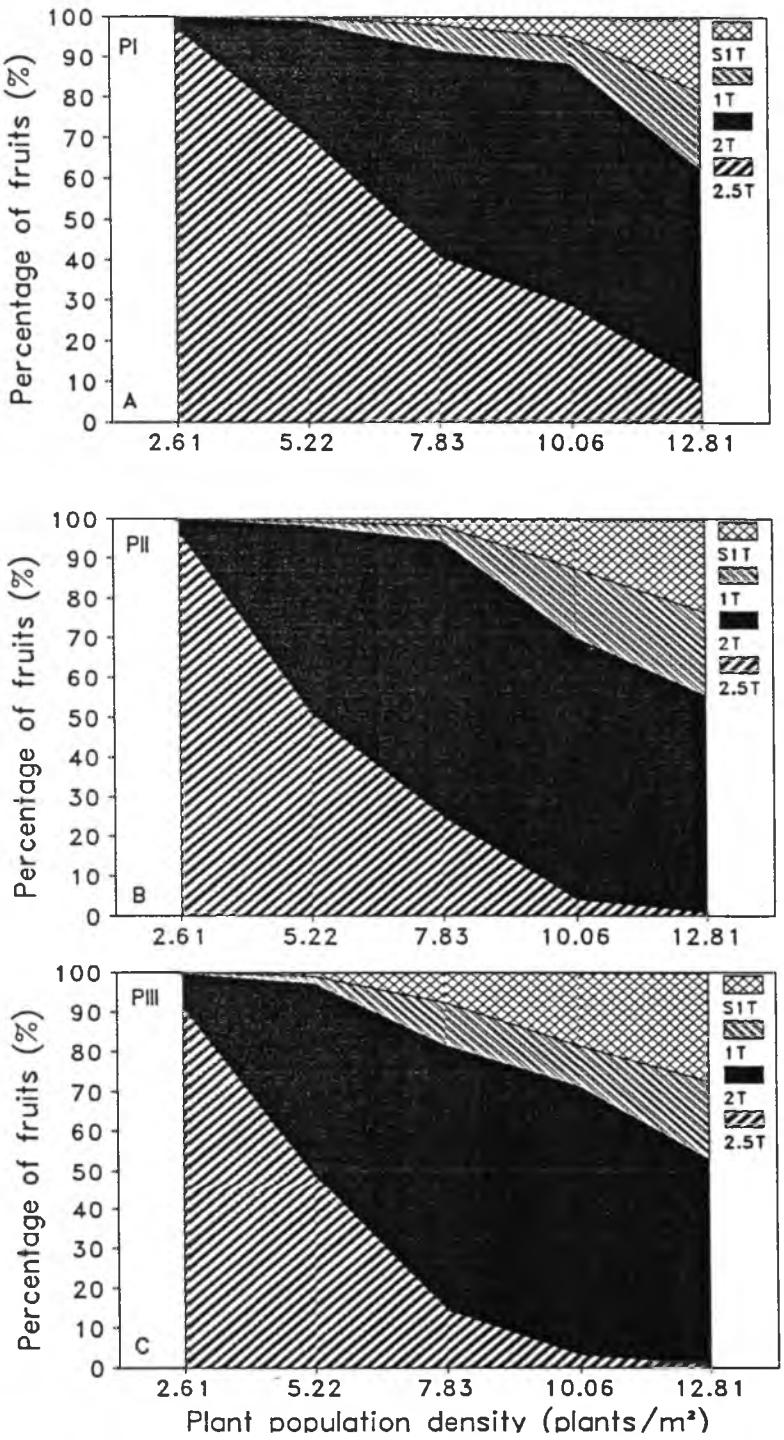


Fig. 5.7 Fruit size distribution by plant population density for 'Smooth Cayenne' pineapple planted on June 15 (PI), August 15 (PII), and October 18 (PIII), 1989, and forced on September 18, 1990. Fruit size categories are 2.5T (>13.65 cm), 2T (≤13.65 cm and >10.8 cm), 1T (≤10.8 cm and >9.5 cm), and S1T (<9.5 cm).

for each size category across PPD, the relationships between the cumulative percentage of fruits in the categories 2.5T, 2T, 1T, and S1T and PPD were obtained using regression techniques. The quadratic equations were well fitted to the data (Table 5.6). The variation accounted for by the equations ranged from 0.956 to 0.999. The relationship between percentage 2T or 1T fruits was obtained by subtracting two successive equations.

Plants within a PPD decreased in size at the later planting dates and plants within a planting date decreased in size with increasing PPD. Plant size at flower induction or at harvest is highly correlated with fruit weight (Gaillard, 1969; Py and Lossois, 1962; Py et al. 1987; Tan and Wee, 1973; Mitchell, 1962; Malezieux, 1986) and that was also the case in this experiment (Fig. 5.8).

Table 5.6 Regression equations describing fruit size distribution as a function of plant population density for three plantings of pineapple. All plants were forced in September, 1990.

Planting Date	Fruit Size †	Cumulative % of Fruits	R^2
June 15	2.5T	$Y=131.9-3.93X+0.34X^2$	0.996 **
	2.5T+2T	$Y= 90.8+4.49X-0.52X^2$	0.964 **
	2.5T+2T+1T	$Y= 93.6+3.03X-0.31X^2$	0.972 **
August 15	2.5T	$Y=153.2-24.37X+0.97X^2$	0.997 **
	2.5T+2T	$Y= 96.2+ 3.01X-0.49X^2$	0.956 **
	2.5T+2T+1T	$Y=94.87+ 2.74X-0.33X^2$	0.980 **
October 18	2.5T	$Y=152.1-25.99X+1.11X^2$	0.999 **
	2.5T+2T	$Y=103.1- 0.13X-0.30X^2$	0.991 **
	2.5T+2T+1T	$Y=100.8+ 0.57X-0.22X^2$	0.983 **

† Fruit categories were designated from largest to smallest diameter, based on industry practices as 2.5T (>13.65 cm), 2T (≤13.65 and >10.8 cm), 1T (≤10.8 and >9.5 cm), and S1T (<9.5 cm).
Y stands for the cumulative percentage of fruits in the different size categories.
X Stands for plant population density (plants m^2).
** indicates highly significant at 0.001 probability level.

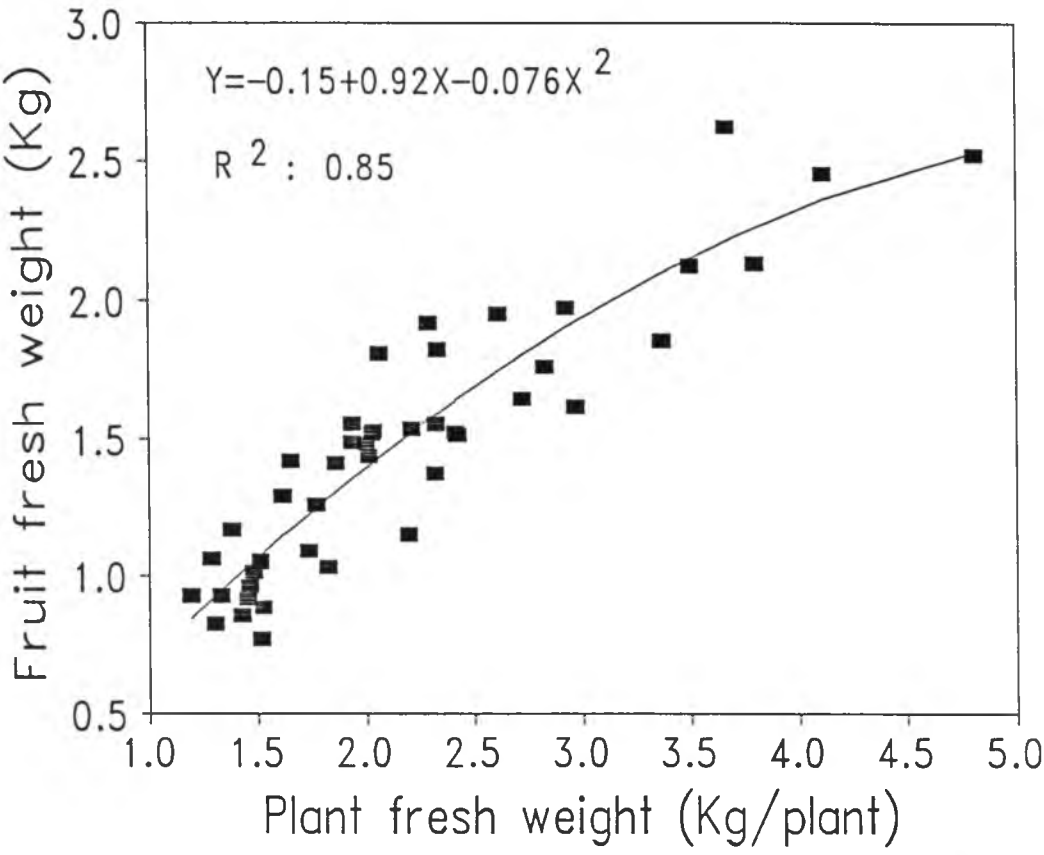


Fig. 5.8 Relationship between fruit fresh weight (fruit plus crown) and plant fresh weight at forcing for 'Smooth Cayenne' pineapple.

Fruit fresh weight (including crowns) was highly and positively correlated with total plant fresh weight at the time of forcing (Fig. 5.8) and their relationship was well described by a quadratic equation. The results were similar to those obtained by Gaillard (1969), Py and Lossois (1962), Py and Tisseau (1965), Tan and Wee (1973), Mitchell (1962), Malezieux (1986), where fruit weight was highly correlated with plant weight, estimated leaf mass, and D-leaf weight at the time of floral initiation.

The fact that variation in fruit weight occurred in a predictable manner, indicates that it should be possible to develop a model that can predict economic fruit yield if the plant population density at planting and plant size at forcing are known.

5.4.4 Fruit Yield per Unit Area

Total fruit yield of pineapple per unit area in this study was asymptotically related to plant population (Fig. 5.9) and the asymptotic relationship was well described by reciprocal equations (Table 5.7), which were derived from the reciprocal equations for average fruit weight and density relationship.

Table 5.7 Reciprocal equations describing the effect of plant population density on fruit (without crowns) and fresh fruit (with crowns) yield for three plantings of pineapple.

Planting Date	Fruit Yield (Mg ha^{-1})	Fresh Fruit Yield (Mg ha^{-1})
June 15	$Y=10X*(0.354+0.0486X)^{-1}$	$Y=10X*(0.326+0.041X)^{-1}$
August 15	$Y=10X*(0.345+0.0705X)^{-1}$	$Y=10X*(0.0314+0.061X^{-1}$
October 18	$Y=10X*(0.397+0.0775X)^{-1}$	$Y=10X*(0.388+0.067X)^{-1}$

Y stands for yield and X for plant population density.

Fruit yield (Fig. 5.9) as described above is the total yield of all fruits. At the higher PPDs, many fruits would have a lower value because of their small size. It is

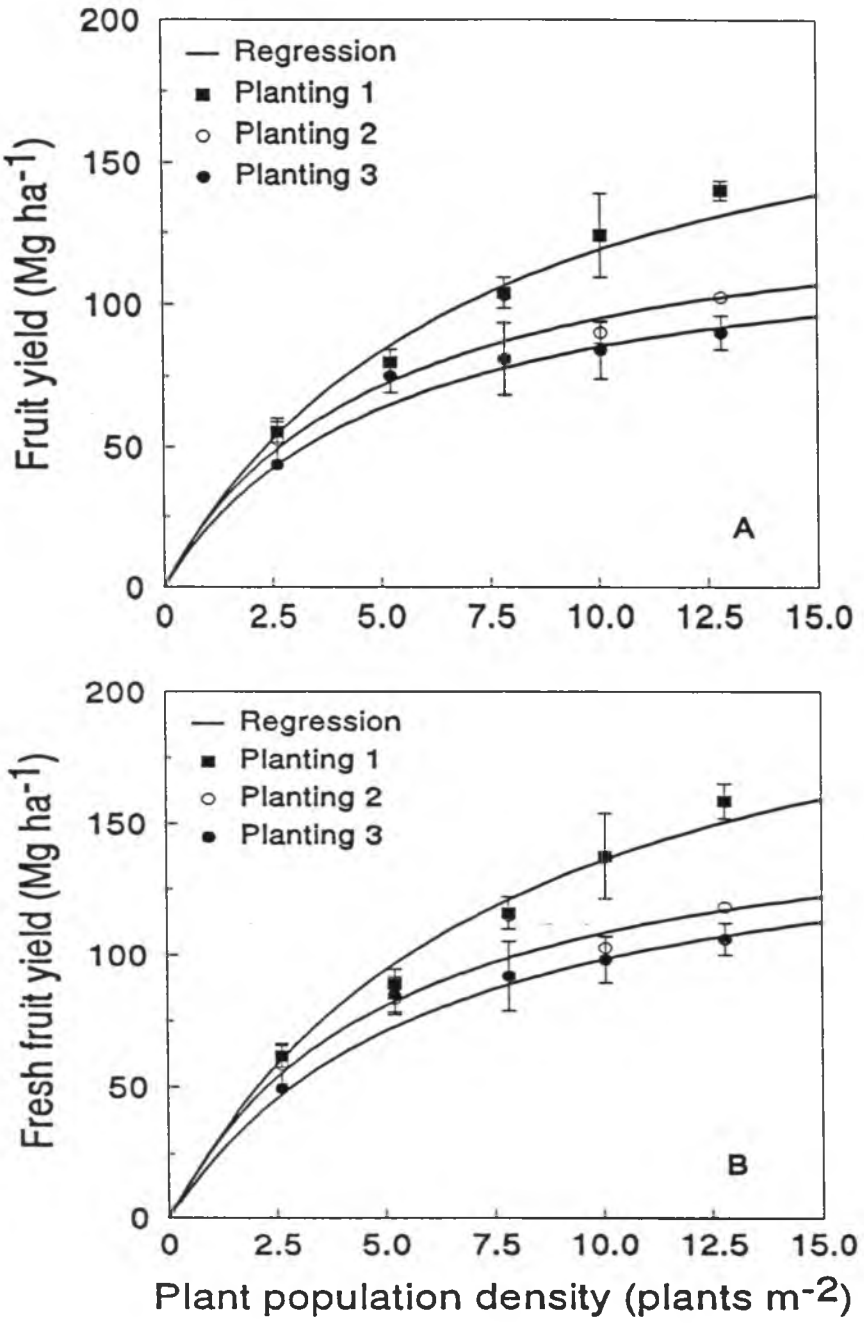


Fig. 5.9 Relationship between fruit yield with (A) and without (B) crowns and plant population density (plants m^{-2}) for 'Smooth Cayenne' pineapple planted on June 15 (Planting 1), August 15 (Planting 2) and October 18 (Planting 3), 1989 and forced on September 18, 1990.

interesting to look at fruit yield distribution by size as a function of PPD. Fruit yield by size category is a function of average fruit weight, PPD, and the fraction of a particular size of fruits and is described by the equation

$$\mathbf{FY_{size} = FY_{tot} \bullet f\ (FOF)} \qquad \mathbf{(5.3)}$$

where FY_{size} is fruit yield (Mg ha^{-1}) of a designated size, FY_{tot} is total fruit yield (tons ha^{-1}), FOF is the fraction of the total fruits for that designated size, and *f* is the sign of the function.

As was noted in Section 5.4.3, fruit size distribution is a function of PPD as is FOF (Table 5.3), thus

$$\mathbf{FOF = f\ (PPD)\ \ and} \qquad \mathbf{(5.4)}$$

$$\mathbf{FY_{tot} = f\ (PPD)} \qquad \mathbf{(5.5).}$$

Fruit yields and fresh fruit yields (tons ha^{-1}) were then calculated for the size categories 2.5T, 2.5T+2T, and 2.5T+2T+1T for all plantings using equations 5.3, 5.4, and 5.5. Fruit and fresh fruit yields for each designated size for all plantings were then plotted against PPD (Fig. 5.10 and 5.11). In PI, the yield of 2.5T was highest at a PPD of 4 plants m^{-2}, and then declined (Fig. 5.10 A). The yield of 2.5T plus 2T fruits increased curvilinearly with increasing PPD until reaching a PPD of 9 plants m^{-2}, then leveled off, and declined at a PPD of 10. The yield of 2.5T plus 2T plus 1T fruits increased curvilinearly with increasing PPD and leveled off at a PPD of 10 plants m^{-2}. Maximum fruit yield for each designated size of fruits occurred at a lower PPD in PII than in PI, and at a lower PPD in PIII than in PII (Fig. 5.10 A, B,

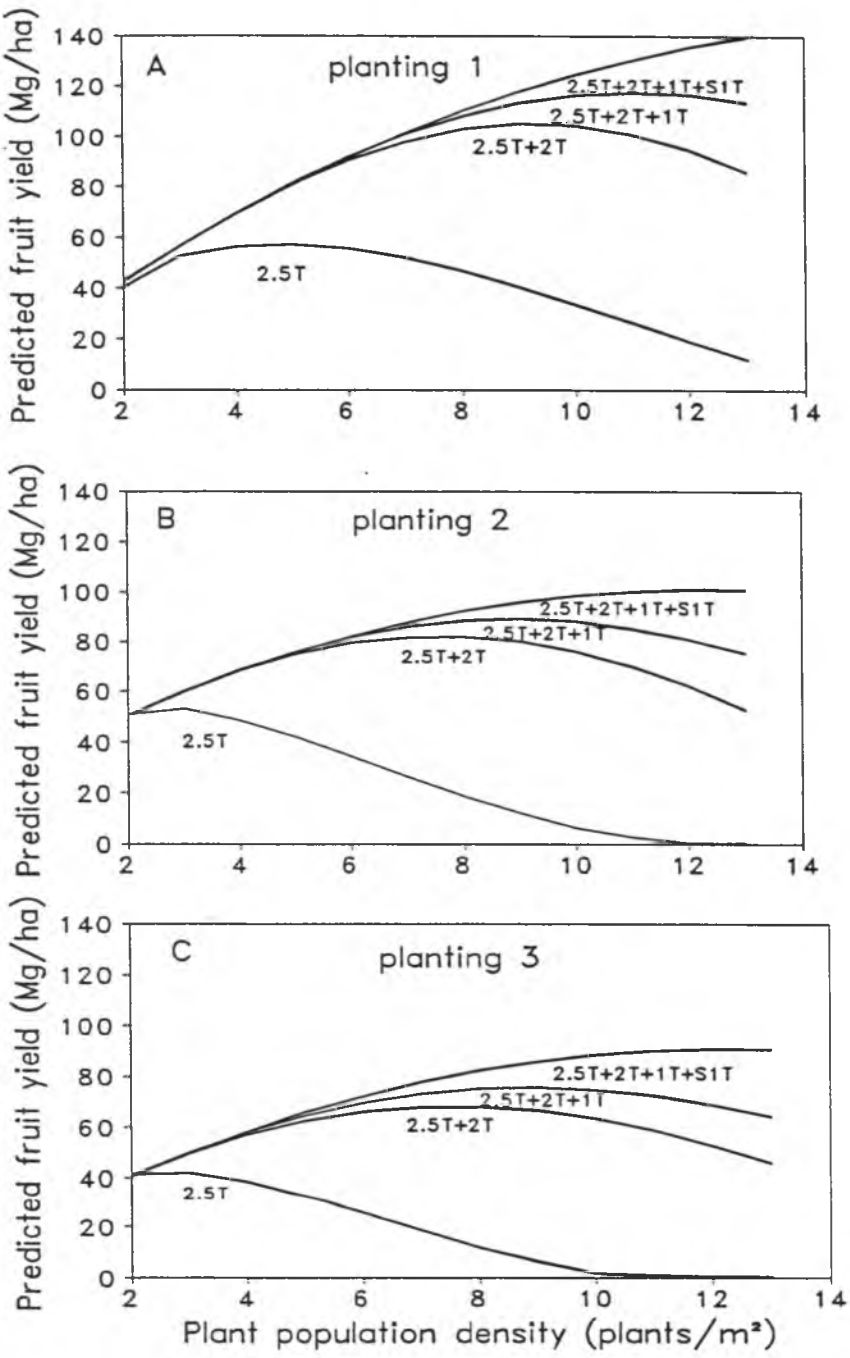


Fig. 5.10 Predicted fruit yield (fruit without crowns) from the relationship between plant population density and fruit size distribution for 'Smooth Cayenne' pineapple planted on June 15 (A), August 15 (B), and October 18 (C), 1989, and forced on September 18, 1990. Fruit size categories were designated from largest to smallest diameter as 2.5T (>13.65 cm), 2T (≤13.65 and >10.8 cm), 1T (≤10.8 and >9.5 cm), and S1T (≤9.5 cm).

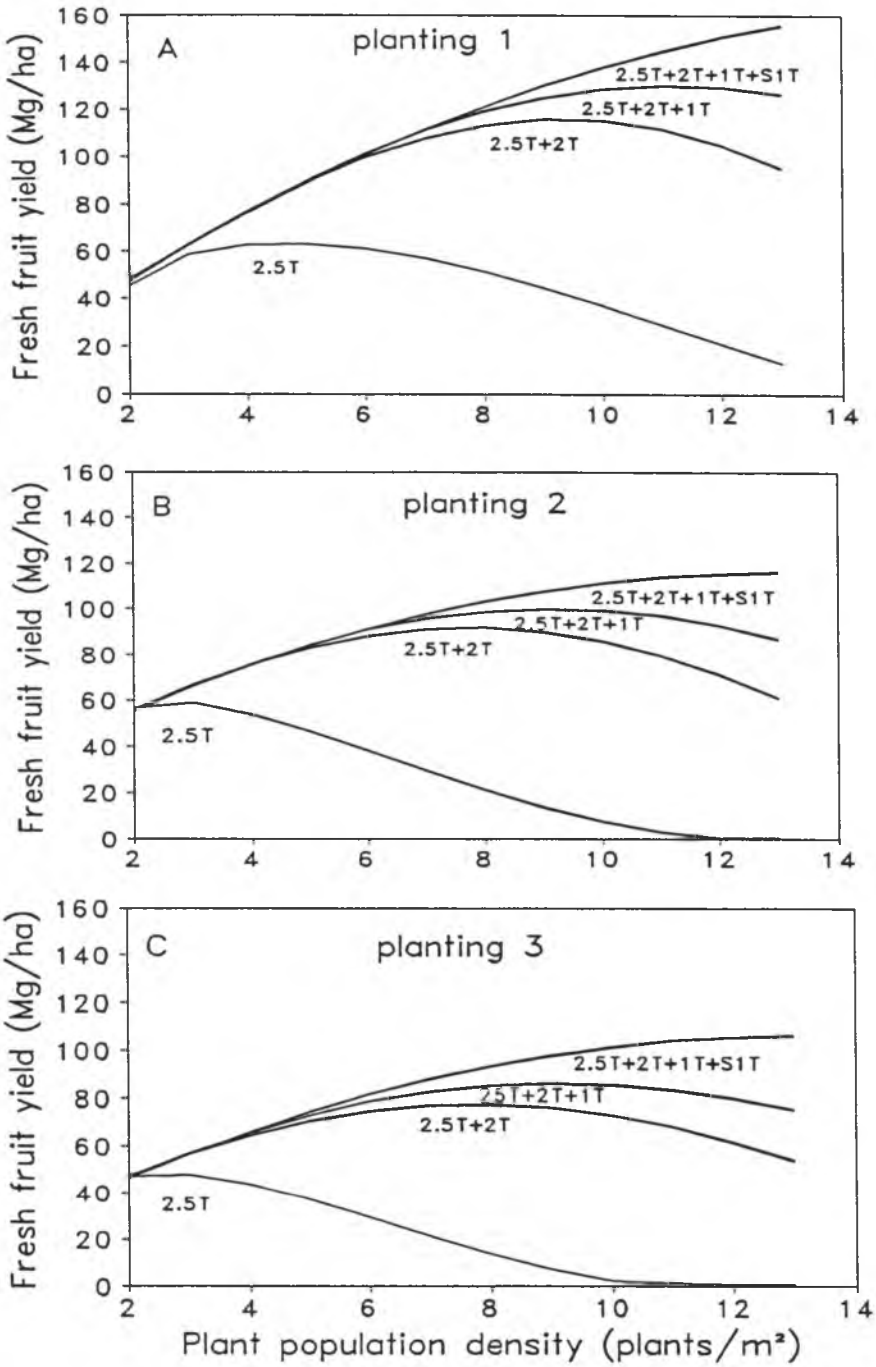


Fig. 5.11 Predicted fresh fruit yield (fruit with crowns) from the relationship between plant population density and fruit size distribution for 'Smooth Cayenne' pineapple planted on June 15 (A), August 15 (B), and October 18 (C), 1989, and forced on September 18, 1990. Fruit size categories were designated from largest to smallest diameter as 2.5T (>13.65 cm), 2T (≤13.65 and >10.8 cm), 1T (≤10.8 and >9.5 cm), and S1T (≤9.5 cm).

and C). Similar results were obtained for fresh fruit yield distribution (Fig. 5.11). This analysis provides information making it possible to determine the optimal plant population density, and plant size at the time of forcing.

5.4.5 Fruit Quality

Total soluble solids, titratable acidity, and pH of fruit juice in PI were measured. The effects of PPD on total soluble solids, titratable acidity, and pH of the fruit juice in PI were not significant (Table 5.8).

Table 5.8 Effects of plant population density (PPD) on total soluble solids, titratable acidity, and pH of pineapple fruit juice. Data were from planting 1 which was planted in June, 1989, forced in September, 1990, and harvested during April and May, 1991.

PPD ($p\ m^{-2}$)	Soluble solids (°Brix)	Titratable acidity (*mmol* H^+/100*ml* juice)	pH
2.61	15.29	2.66	3.41
5.22	15.85	2.56	3.37
7.83	15.64	2.43	3.40
10.06	15.07	2.58	3.36
12.81	15.61	2.74	3.35

The results were similar to those obtained by Dass et al. (1978), Ramirez and Gonzalez-Tejera(1983), Ramirez and Gandia (1982), and Ghosh and Medhi (1981) but contrary to those of Sanford (1962, 1963, and 1965), Dodson (1968), Wee (1969), and Gonzelez-Tejera (1969), where total soluble solids and acidity increased with increasing PPD. The effect of PPD on fruit quality might be masked by the climate effect. That might result in inconsistent results from many population density trials. No data on fruit quality were collected for PII and PIII because of lack of a evidence of an effect of PPD on fruit quality in PI.

In summary, fruit development rate was not significantly affected by plant size within a plant population density (planting date) but declined as plant population density increased. Average fruit weight decreased significantly with increasing PPD and decreasing plant size within a PPD (planting date). The interaction effect was significant. The larger the plants at the time of forcing, the larger the average fruit weight, because fruit weight was highly correlated with plant weight. Plants at lower PPD and earlier plantings produced more 2.5T fruits and fewer 1T and S1T fruits. The fruit yield per unit area increased curvilinearly with increasing PPD and the relationship was asymptotic. The relationship between economic yield, which depends on fruit size and PPD, was parabolic. The yield of large fruits within a PD increased with increasing PPD, reached a maximum and then declined. The later the planting date, the smaller the average plant size at forcing, and the lower the yield. Fruit quality in terms of soluble solids, and titratable acidity of juice was not significantly influenced by plant population density. It was concluded that fruit development rate was influenced not only by air temperature and time but also by plant population density. Plant population density should be considered in any simulation model of pineapple fruit growth and development.

PART III. SIMULATION OF PINEAPPLE GROWTH, DEVELOPMENT AND YIELD

INTRODUCTION

In part I, the response of leaf emergence, canopy development, growth, fruit development and yield of pineapple to plant population density and plant size at forcing were characterized. Typically, such research would end with the hope that the results would be useful to other researchers. Here, the plan was to integrate the results into a model that could simulate the processes of plant growth, development and yield. Such a model could simulate the effect of plant population density and plant size at forcing on pineapple growth, development and yield in some Hawaii environments and should minimize the need to conduct similar field experiments.

Modeling pineapple development has been attempted (Medcalf, 1949; Fleisch and Bartholomew, 1987). As early as 1949, Medcalf developed an air temperature growth unit (ATGU) model to predict the harvest peak of pineapple fruits in advance of harvest using historical climatological data. By his method, air temperature was divided into five degree increments and the total amount of time that the plant would spend in each range was summed up. Each total then was multiplied by its respective weighting factor (corresponding to the effectiveness of this temperature range in promoting leaf elongation) to obtain the ATGU over a certain period of time. However, industry researchers indicate that the model was not able to accurately predict the harvest date ($\pm$ 2 weeks from actual date).

Recently, Bartholomew and his colleagues (personal communication) initiated a series of experiments on Oahu, Hawaii in 1983, and on Maui, Hawaii in 1984 and

1985 for the purpose of pineapple modeling. Fleisch and Bartholomew (1987) developed a heat unit model to predict pineapple inflorescence development using actual meteorological data. The model used different basal temperatures to calculate growing degree hours (GDH) accumulated for each phase of development. The GDH accumulated during the day and night were calculated separately using different sets of weighting factors. The GDH model was more accurate than the ATGU model (Fleisch and Bartholomew, 1987), but it was not applicable to the variety of environments in Hawaii in which pineapple is grown. Fleisch (1988) later modified the heat unit model developed in 1987 to use growing degree days (GDD) computed from daily minimum and maximum air temperature. The model predicted inflorescence development with a precision similar to the GDH model. However, its primary advantages are ease of data collection and calculation and compatibility with the IBSNAT (1988) minimum data set.

The stages of inflorescence development of pineapple in the models (both GDH and GDD) were defined based on inflorescence morphology rather than physiology. The models are, therefore, not easily incorporated into a mechanistic model where dry matter accumulation and partitioning to the developing inflorescence is based on physiology.

Using the field data collected previously, Fleisch (1988) developed a regression model to predict leaf area from total plant dry weight and average air temperature between successive harvests. One problem with the model is the use of average air temperature because the effect of air temperature on leaf elongation is

nonlinear (Sanford, 1962). Another problem is that the model could not directly predict leaf area development.

Fleisch (1988) also developed three simulation models for predicting biomass accumulation of pineapple during vegetative growth. One model was strictly statistical. It predicted biomass accumulation from a relationship between plant weight, daily mean air temperature, and plant relative growth rate. The other two models were semi-empirical. First, the models estimated green leaf area from a given plant weight and air temperature at time t_0. Second, the models estimated the amount of light intercepted by the leaf area for a given plant density at time t_0. Third, the models estimated plant growth rate between time t_0 and t_1 and biomass at time t_1. The models accurately predicted biomass accumulation during the vegetative growth period. Limitations of the models are that they are not mechanistic, and they do not simulate many important processes such as photosynthesis and dry matter partitioning among plant parts. The empirical nature of the models makes further development, testing, and validation difficult.

Comprehensive simulation models of plant growth have been developed in recent years for cotton (Jones, et al., 1980), soybean (Wilkerson et al., 1983), beans (Hoogenboom, et al.,1991), maize (Jones and Kiniry, 1986) and wheat (Godwin et al., 1984). The Crop-Environment Resource Synthesis Maize model (CERES-MAIZE) is a model that simulates maize growth, development and yield. The model takes into account the following processes:

1) phenological development, especially as affected by genetics and weather;

2) extension growth of leaves, stems, and roots;

3) biomass accumulation and partitioning, especially among vegetative and reproductive organs;

4) soil water balance and water use by the crop;

5) soil nitrogen transformations, uptake by the crop, and partitioning among plant parts.

CERES-Maize is a process-oriented model that calculates daily growth increment. It has been well tested in many countries and its model structure has been adopted for other crops such as wheat, rice, barley, sorghum, millet (IBSNAT, 1990) and potato (Hodges, 1991). However, the CERES models simulate only at a population level. They do not deal with interaction between factors and competition with other crops or other organisms such as diseases and pests on the community level (Jones and Kiniry, 1986).

A community level cropping system simulation model (CROPSYS) for intercropping of maize and soybean has been developed by Caldwell and his colleagues (Caldwell, personal communication). The model has the hierarchical structure of an agricultural system, and is amenable to further development, testing and validation.

The objective of this study was to adopt the CERES-Maize model structure, to integrate data from the pineapple literature and from field experiments to develop a more comprehensive and process-based simulation model of pineapple growth, development and fruit yield. The model would be developed so it could be

incorporated into CROPSYS to provide a framework for further development, testing and validation. The model was named ALOHA-Pineapple by Goro Uehara where ALOHA is an acronym that stands for Assessments of Local Options for Hawaii Agriculture.

CHAPTER 6

MODEL DESCRIPTIONS

6.1 CROP PHENOLOGY AND MODEL GROWTH PHASES

Characterizing the phenology of crop growth and development is a key step in accurately simulating crop phenological events and dry matter partitioning. No scale of pineapple growth and development was found in the published literature. The phenological scale adopted here was constructed based on latent events identified from the growth data and flower phenology defined by Bartholomew (1977) and Fleisch and Bartholomew (1987) and further refined here. The schematic phenology of pineapple growth is presented in Fig. 6.1. Pineapple phenological development is characterized by single vegetative and reproductive phases and ten growing stages represented by V1, V2, V3, V4, R1, R2, R3, R4, R5, and R6, where V designates a vegetative phase and R designates a reproductive phase. The stages are defined as:

V1: root initiation.

V2: leaf initiation and emergence of the first new leaf.

V3: end of zero net stem growth; dry matter partitioning is mostly to new growing leaves and roots between V2 and V3.

V4: a prolonged period of vegetative growth.

R1: termination of leaf initiation by exogenous application of a growth regulator, decreasing leaf and root growth, beginning transition to reproductive growth.

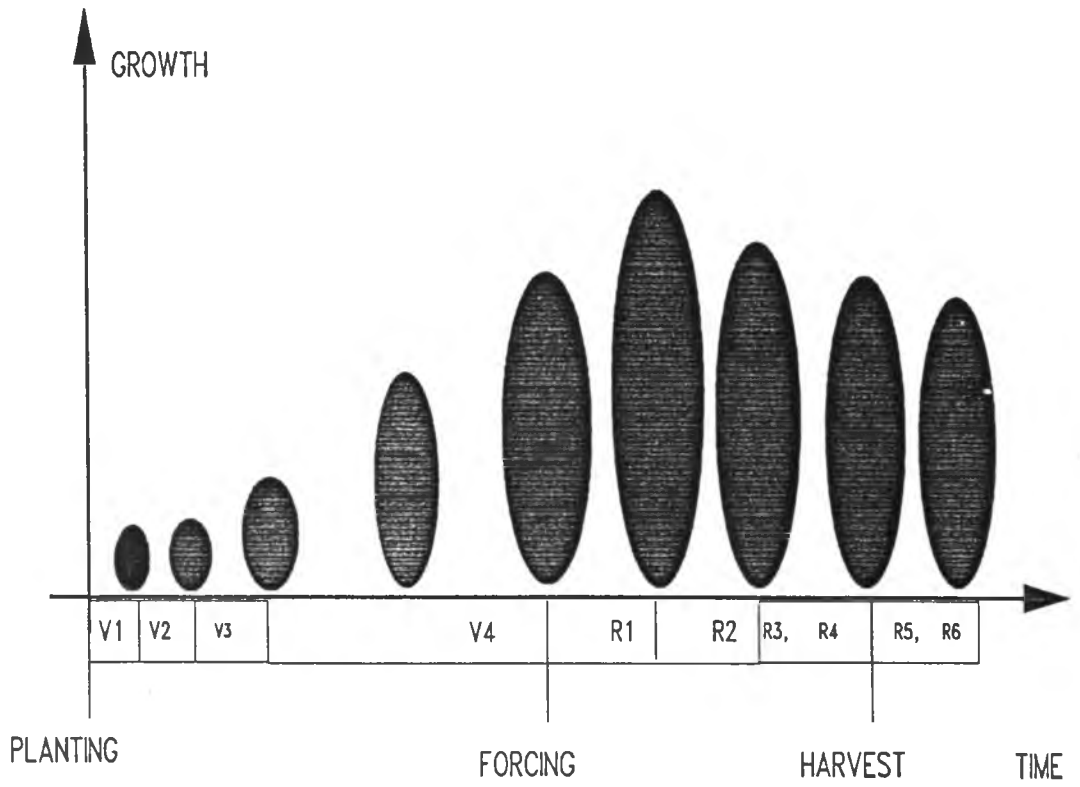


Fig. 6.1 Schematic phenology of pineapple vegetative (V1 - V4) and reproductive (R1 - R6) growth and canopy development.

R2: the end of floret initiation; sepal primordia fully enclose the petals of the youngest flower primordia; leaves already initiated continue to enlarge.

R3: beginning of flowering; leaf growth ceases.

R4: end of flowering; suckers on larger plants initiated.

R5: end of fruitlet growth.

R6: fruit maturation, and sucker growth, if initiated.

Only some of above phenological phases were used to develop the model (ALOHA-Pineapple) because not all stages have been adequately characterized. The phases modeled represent plant growth intervals defined by distinct morphological or physiological events based on the growth stages (Table 6.1). For programming purposes, all phases used in the model were given an identifying integer (ISTAGE), including the phase before planting, and the numbering of phases is circular.

No attempt was made to simulate development of the ratoon crop. Its phenology would be simular to that of the mother plant crop except that most ratoon shoots do not develop an independent root system.

6.2 MODEL SUBROUTINE STRUCTURE

ALOHA-Pineapple was derived from CERES-Maize Version 2.1. The model subroutine structure is similar to that of CERES-Maize (Fig. 6.2) (Jones and Kiniry, 1986; Kiniry, 1991). The major changes in the model are subroutines for phenological development (PHENOL), phase initiation (PHASEI) and growth (GROSUB). One subroutine PINEAPPLEPARAMETER was added to input

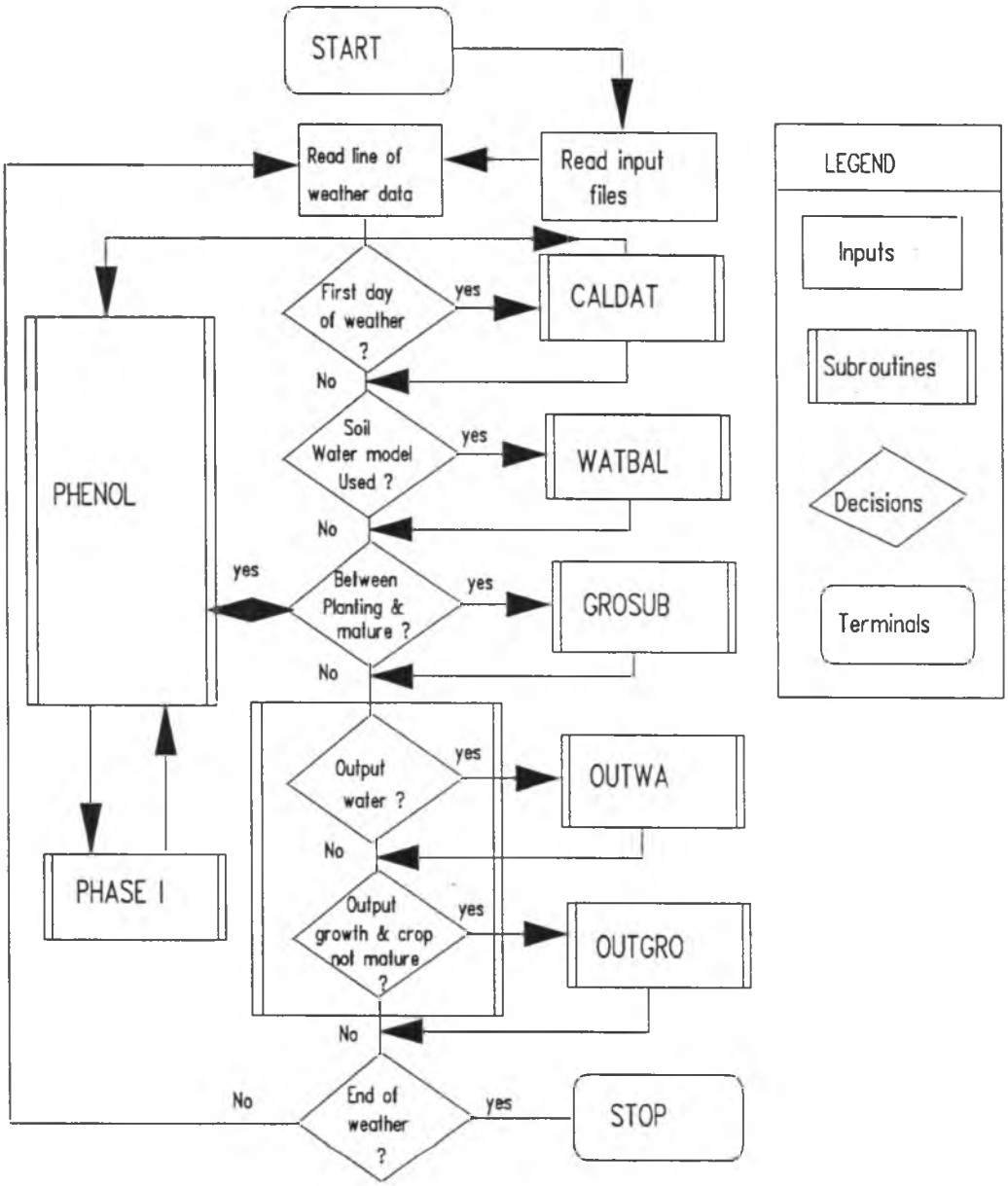


Fig. 6.2 Simplified flow chart of the ALOHA-Pineapple model. CALDAT is a subroutine for converting the day of year to calendar date. WATBAL is a subroutine for calculating the soil water balance. OUTWA and OUTGRO are the subroutines to output water balance and growth data, respectively.

parameters that are different from those used by CERES-Maize. The input and output formats were also modified. Only the three subroutines PHENOL, PHASEI and GROSUB are described here in detail.

Table 6.1 The phenological phases (ISTAGE) used in the ALOHA-Pineapple.

ISTAGE	Phase description
7	Prior to planting
8	Planting to root initiation
9	Root initiation to emergence of first new leaf
1	First new leaf emergence to end of zero net stem growth
2	End of zero net stem growth to time of forcing
3	Forcing to end of floret initiation
4	End of floret initiation to first open flower
5	First open flower to beginning fruit harvest (10% fruits with shell one-third yellow, shell color 1 of Py et al. 1987)
6	Fruit harvesting to physiological maturity (90% fruits harvested)

The model operates on a daily incrementing loop, which is executed until the end of the weather data (Fig.6.2). The model was written in Microsoft FORTRAN and run through the DSSAT (IBSNAT, 1989) shell but it can be run alone.

6.2.1 Model Input

The model requires the following minimum input data for soil and crop parameters and weather. The rationale for the selection and use of the plant-related

parameters will be discussed later.

1. Soil layer and irrigation information (Jones and Kiniry, 1986).
2. Initial weight of plant material (crowns) and plant population density.
3. Cultivar parameters:
   a. P2: cumulative growing degree days from forcing to end of floret initiation;
   b. P3: cumulative growing degree days from end of floret initiation to opening of first flower;
   c. P4: cumulative growing degree days from opening of first flower to fruit harvest:
   d. P5: cumulative growing degree days from fruit harvest to physiological maturity;
   e. G2: potential fruitlet (eye) number, genetic coefficient;
   f. G3: maximum rate of dry matter partitioning to fruitlets (g d^{-1} eye^{-1}).
4. Condition parameters:
   a. P1: cumulative growing degree days from emergence of the first new the leaf to end of zero net stem growth;
   b. P6: cumulative growing degree days from root initiation to emergence of first new leaf;
   c. P7: cumulative growing degree days from emergence of first new leaf to the beginning of interplant competition (plant population density restricts vegetative growth). This is an emperical parameter that only

serves the purpose of calculating leaf emergence, no biological meaning was applied here.

5. Decision variable: total plant weight at the time of forcing (PlantSize).
6. Weather: daily maximum air temperature (TEMPMX), daily minimum air temperature (TEMPMN), daily total solar radiation (SOLRAD), and daily precipitation (RAIN).

6.2.2 Subroutine PHENOL

The subroutine PHENOL simulates pineapple phenological development. The information flow chart for PHENOL is presented in Fig. 6.3. Pineapple phenological development is determined mainly by thermal time because there is no evidence pineapple is sensitive to photoperiod (Chapter 1; Shiroma, 1972; Fleisch and Bartholomew, 1988). Because a plant population density greater than 25,000 plants ha^{-1} can increase the thermal time required to reach a particular phenological stage the model calculates thermal time from air temperature, and thermal time is then modified by a factor that accounts for the effect of plant population density (Chapter 1 and Chapter 4). The model was developed assuming that flowering will be forced, with forcing date determined by the decision variable PlantSize.

Depending on the phases, subroutine PHENOL uses calendar day, daily thermal time (DTT) (or growing degree-day) or total biomass per plant to determine the end of each phenological phase (Fig. 6.3). PHENOL begins by calculating daily thermal time. Daily thermal time is calculated differently depending on the phenological phase. Leaf emergence rate is linearly related to accumulated DTT

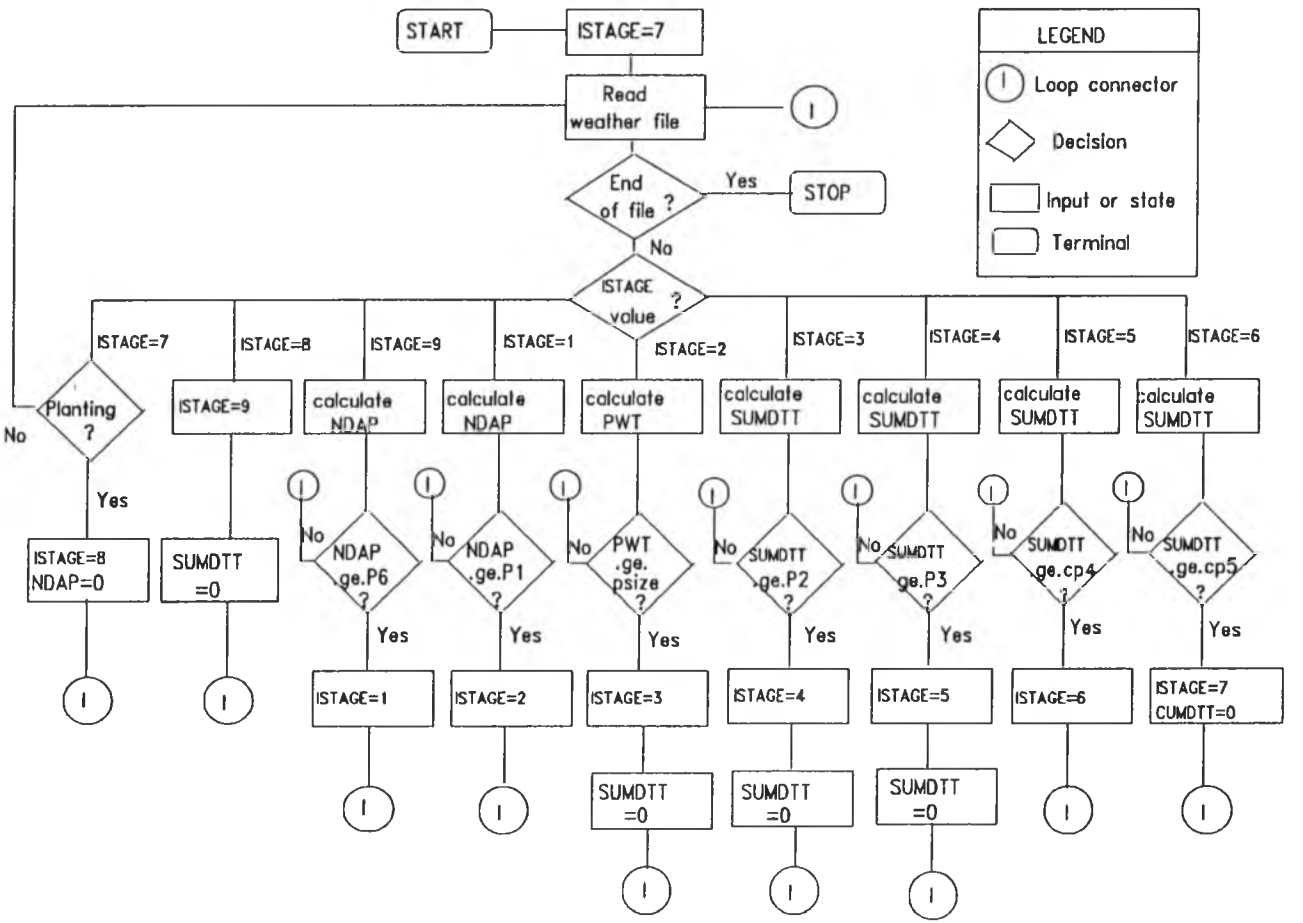


Fig. 6.3 Flow chart of the pineapple phenology model in ALOHA-Pineapple. The acronyms are NDAP, days after planting, SUMDTT, cumulative thermal time, PWT, total plant weight, and ISTAGE is phenological stage. P1 to P6 are model parameters and cp4 and cp5 correct the parameters p4 and p5 for the effect of plant population.

while the relationship between accumulated DTT and inflorescence development rate is nonlinear (Chapter 1; Fleisch, 1988).

Different base temperatures (Tbase) were used to calculate DTT in different model growth stages. A Tbase of 16.0 °C was used during the vegetative phase. The value was derived from leaf emergence data under Hawaii field conditions (Chapter 1). Tbases of 6.25, 12.5, and 4.0 °C were used for ISTAGE 3, 4, and 5 and 6, respectively. The values were derived from inflorescence development data obtained in the field at different locations in Hawaii (Fleisch, 1988).

Daily thermal time was calculated from the mean daily temperature (TEMPM), which was calculated from the daily maximum (TEMPMX) and minimum temperature (TEMPMN) by the equation

DTT = TEMPM - Tbase, if TEMPM > Tbase.

During the vegetative phase, DTT is set to zero if daily maximum temperature (TEMPMX) is less than Tbase. If TEMPMX is greater than and TEMPMN is less than Tbase or if TEMPMX exceeds 34 °C, DTT is modified by TTMP, which is the mean of eight interpolations of air temperature calculated using the three-hour temperature correction factor (TMFAC(I)) (Jones and Kiniry, 1986). TTMP is calculated by the equation

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

During the reproductive phase (ISTAGE≥3), DTT is modified by a multiplier (Table 6.2), to correct for the apparent nonlinearity between air temperature and inflorescence development rate (Fleisch, 1988).

Table 6.2 Multipliers and their corresponding temperature ranges used to account for the nonlinearity between air temperature and inflorescence development rate (Fleisch, 1988).

Temperature ranges	Multiplier
11 - 13	2.03
13 - 15	1.21
15 - 17	1.09
17 - 19	1.03
19 - 21	1.00
21 - 23	0.99
23 - 25	1.00
25 - 27	1.01
27 - 29	1.03
29 - 31	1.06
31 - 33	1.08
> 33	1.11

ISTAGE 7: Preplanting

The model is initialized with ISTAGE 7. When the subroutine PHENOL is called planting date is written. Then PHENOL calls subroutine PHASEI to update development-related variables and set a day counter, number of days after planting (NDAP), to zero.

ISTAGE 8: Planting to Root Initiation

Root initiation defined, as day of emergence of the first root, is determined by soil water content. It is assumed that if soil water content is near field capacity, roots are initiated. When root initiation occurs, the date and related information are recorded and PHASEI is called to update development-related variables.

ISTAGE 9: Root Initiation to Emergence of First New Leaf

The first new leaf is the first leaf that emerges after planting. It is the starting point for the calculation of number of leaves emerged and leaf production after

planting. Soil water status, planting material, and air temperature are the factors thought to influence this event. Because there are no data available to make it possible to predict when this event occurs, a parameter (P6), the cumulative growing degree days after planting (SUMDTT), is used to predict the date of emergence of the first new leaf. Using days after planting is easier for model calibration. When SUMDTT is greater than or equal to P6, the first new leaf emerges. Then the date of the event and related information are written and PHASEI is called to update development-related variables.

ISTAGE 1: Emergence of First New Leaf to End of Zero Net Stem Growth

This stage is defined so stem growth can be calculated. Approximately 25 percent of the dry biomass of the crown is stem (unpublished data). Measurements of pineapple growth indicate that for some unknown period after planting, there is no gain in stem dry weight, and in fact a loss is more likely. The loss in stem dry matter would be due to the energy and substrates required for root growth and respiration for mintenance. A parameter P1, which is the cumulative growing degree days since emergence of the first new leaf, is used to determine the end of zero net stem growth. The value of parameter P1 was derived by calibrating the model to the growth data. When SUMDTT is greater than or equal to (P1+P6), the end of the stage occurs. The date of the event and related information are written and PHASEI is called to update development-related variables.

During ISTAGE 1, number of leaves emerged is predicted by DTT, modified as appropriate by plant population density (Chapter 1). The procedure used will be

described in subroutine GROSUB.

ISTAGE 2: End of Zero Net Stem Growth to Forcing

Natural flowering of pineapple occurs sporadically during the winter months. In Hawaii, and in most environments where pineapple is grown (Py et al., 1987), the crop can be forced to flower by growth regulating chemicals every month of the year. The model simulates only the forced flowering pineapple because it is assumed this represents the most common practice. Data in the literature indicate that fruit yield is related to total plant weight at the time of forcing (Chapter 4). A parameter (PLANTSIZE), which is determined by the user, is used to predict the time of forcing. When the total above-ground plant weight (TOTALPLANTWT), is greater than or equal to PLANTSIZE, forcing occurs, the forcing date is recorded and PHASEI is called to update development-related variables.

ISTAGE 3: Forcing to End of Floret Initiation

The definitions of the phenological stages of fruit development from forcing to maturity and the determination of stages come partially from the heat unit model of Fleisch and Bartholomew (1987). During ISTAGE 3, leaf initiation ends but leaf emergence and leaf expansion continue. The end of leaf growth has not yet been determined but it occurs by the end of ISTAGE 4. The duration of ISTAGE 3 is strongly influenced by air temperature and Fleisch and Bartholomew (1987) reported that day and night air temperature and the difference between them were important. At this stage of development, the model only utilizes cumulative growing degree days modified as indicated in Table 6.2. Plant size, or more specifically the amount of

light intercepted per plant during this stage, is assumed to be important in determining fruitlet number and potential fruit size of pineapple (Py et al., 1987; W.G. Sanford, personal communication; Chapter 5). Because quantitative information on the relationship between plant physiology and morphology and eye number is lacking for pineapple, the CERES-Maize procedure was followed here. The duration of the stage (IDURP) and biomass (SUMP) accumulated during the stage determine the number of fruitlets per fruit. Then the average photosynthesis rate per plant (PhotosynEye) and number of eyes (GPP) are calculated. The equations

PhotosynEye = SUMP*1000/IDURP*3.5/5.0 and

GPP = G2*PhotosynEye*/7200+50,

were adopted from CERES-Maize and calibrated to the fruit data collected from Maui, Hawaii (D. Bartholomew, unpublished data).

The term G2 is a cultivar related parameter (or genetic coefficient) for maximum number of eyes per fruit, which is assumed to be constant for a specific cultivar. For 'Smooth Cayenne' pineapple, it was set to 200 eyes per fruit by a prior calibration.

A cultivar-related parameter (or genetic coefficient), P2, which is the cumulative growing degree days since forcing, is used to determine the end of the stage. When SUMDTT, which is set to 0 at forcing and calculated with a base temperature of 6.25 °C (Fleisch, 1988), is greater than or equal to P2, the end of the stage occurs. Then the date of the event and related information is written and PHASEI is called to update development-related variables.

ISTAGE 4: End of Floret Initiation to Opening of First Flower

The end of this stage occurs at anthesis of the first flower at the base of the fruit, thus the stage is defined only by morphology. Leaf growth is assumed to cease at the end of this stage. A cultivar-related parameter (or genetic coefficient), P3, which is cumulative growing degree days since sepals closed on youngest flowers, is used to determine the end of the stage. When SUMDTT, which is calculated with a base temperature of 12.5 °C (Fleisch, 1988), is greater than or equal to P3, the end of the stage occurs. Maximum LAI is set to the actual LAI at this time. Finally, the date of the event is written and PHASEI is called to update development-related variables.

ISTAGE 5: Opening of First Flower to Fruit Harvest

Fruit harvest is defined as the time when the shell of ten percent of the fruits is one-third yellow (shell color 1, Py, et al. 1987). It is the beginning of fruit harvesting. The date of fruit harvest is determined by a cultivar-related parameter (or genetic coefficient), P4, which is cumulative growing degree days since opening of the first flower. Because fruit development rate during this stage was affected by plant population density (Chapter 4), P4 was modified to CP4 to correct for the effects of plant population density. When SUMDTT, which is calculated with a base temperature of 4.0 °C (Fleisch, 1988), is greater than or equal to CP4, fruit harvest occurs.

The equation used is

CP4 = P4+(PLANTS-8.0)*2.4*20.95)

where PLANTS is plant population density. The equation was derived from the fruit data collected from Kunia, Hawaii (Chapter 4).

The fruit is assumed to reach a maximum weight at the end of the stage. When the date of fruit harvest occurs, fruit yield (Kg ha^{-1} fresh weight), which is assumed to have a moisture content of 85%, is calculated. Fruit eye weight (g eye^{-1}), and number of eyes per square meter are also calculated. It is assumed that these terms would have some value in model calibration and validation. Finally, PHASEI is called to update development-related variables.

ISTAGE 6: Fruit Harvest to Physiological Maturity

Physiological maturity is defined as the time when 90 percent of fruits have been harvested. The date of physiological maturity is determined by a cultivar-related parameter (CP5), which is cumulative growing degree days calculated with a base temperature of 4.0 (Fleisch, 1988) and for the effect of plant population density. The equation used to calculate DTT for this stage is

$$\mathbf{CP5 = P4 + P5 + (3.15*(PLANTS-8.0) - 0.254*(PLANTS-8.0)^2*20.95),}$$

where P5 is cumulative growing degree days since Fruit Harvest. The coefficients of the equation were derived from the fruit data collected at Kunia, Hawaii (Chapter 4). When SUMDTT, which is set to 0 at the end of ISTAGE 4, is greater than or equal to CP5, physiological maturity occurs. PHASEI is called and a simulation cycle counter (IRET) is updated to 1.

6.2.3 Subroutine PHASEI

This subroutine updates growing stages when a stage is completed and

initializes or resets some important variables at the beginning of a stage. For example, initial crown weight, leaf weight, stem weight, and leaf area, which are assumed to be important factors affecting plant growth, are initialized at the time of planting. Base temperature and SUMDTT are reset in the specified phases (Fig. 6.3). The subroutine PHASEI is called by subroutine PHENOL when each stage is completed (Fig. 6.2).

6.2.4 Subroutine GROSUB

The description of the subroutine GROSUB is summarized in Fig. 6.4. This subroutine calculates leaf area development, light interception, photosynthesis, and partitioning of biomass to various parts of the plant. Calculation of plant growth is balanced by the carbohydrate supply and demand for new growth. The amount of carbohydrate synthesized is assumed to be proportional to light interception per unit land area, which is determined by leaf area index. The partitioning of biomass into various growing organs in the plant is done using a priority system.

It is assumed that before emergence of the first new leaf, leaf growth of the crown is equal to biomass lost due to senescence, respiration and root growth. So biomass is calculated beginning at the time of first new leaf emergence.

A. Carbohydrate Supply

GROSUB simulates carbohydrate for a day as follows:

1. Calculate photosynthetically active radiation (PAR) (MJ m^{-2}) from daily total solar radiation (SOLRAD). It is assumed that 50% of solar radiation is PAR. An energy unit conversion factor is used to convert different units of solar radiation

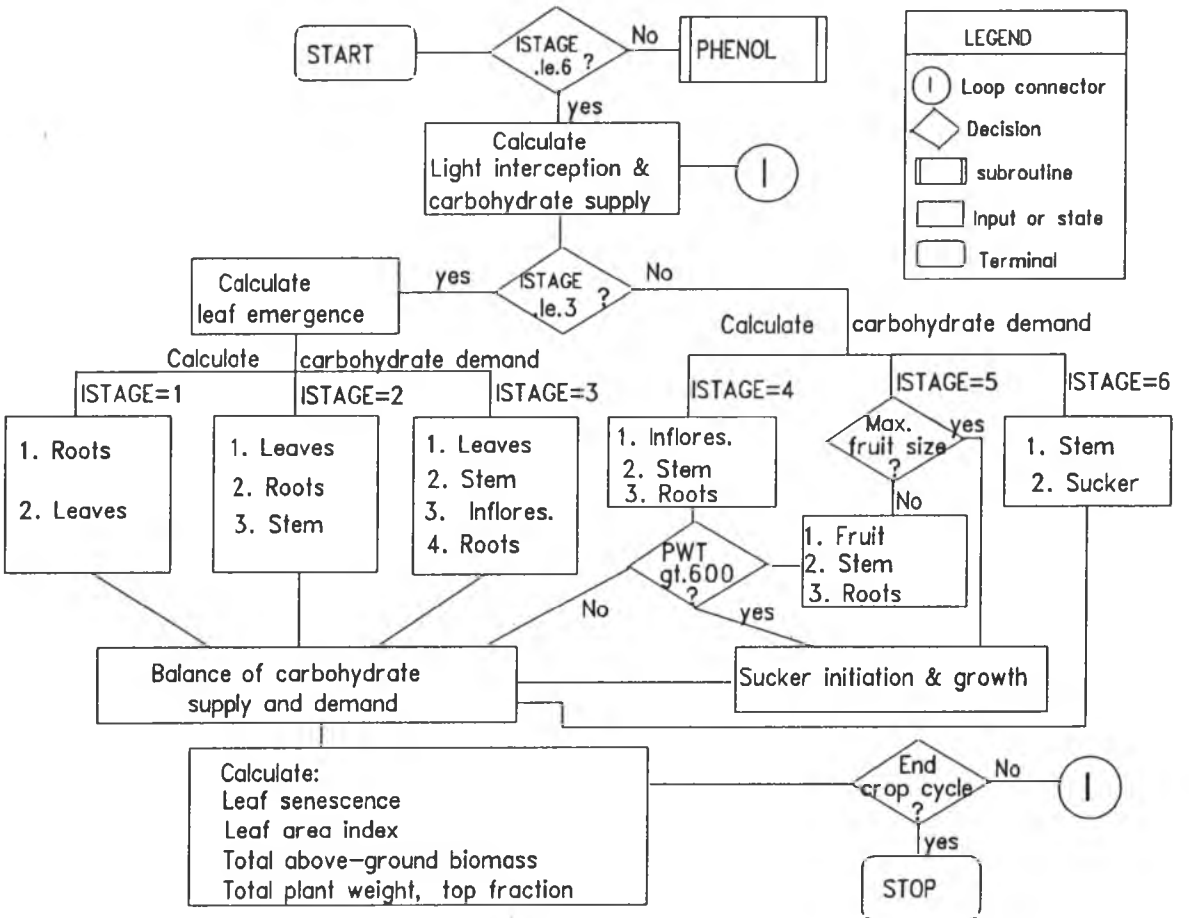


Fig. 6.4 Flow chart of Subroutine GROSUB in ALOHA-Pineapple. The acronyms are PWT, total plant weight, ISTAGE for growth stage, and Inflores., inflorescence.

into MJ m^{-2} by the equation

PAR = 0.5*SOLRAD*EnergyUnitConversionFactor.

2. Calculate the fraction of light penetrating to ground from calculated leaf area index (LAI) and an extinction coefficient (K). Homogeneous leaf distribution both horizontally and vertically is assumed. Light attenuation (I) is assumed to follow Beer's law and the coefficient of 0.52 is used here (Fleisch, 1988). Light attenuation is calculated by quation

$$I = e^{-kLAI}.$$

3. Calculate potential carbohydrate production (PCARB) at optimal conditions and actual carbohydrate (CARBO) for a day. A conversion coefficient (ConvertCoefficient) is used to convert light energy to biomass. The conversion coefficient 5.0 g MJ^{-1} was used in CERES-Maize. Since no data on the radiation use efficiency of pineapple are available, the ConvertCoefficient was estimated during model calibration. The law of minimum, which states "The growth of a plant is dependent upon the amount of 'foodstuff' presented to it in minimum quantities.", was applied to calculate actual carbohydrate production using the Fortran minimum function AMIN1. The equations used were:

PCARB = ConvertCoefficient*PAR/PLANTS*(1-I) and

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

where PLANTS is plant population density (plants m^{-2}), AMIN1 is an intrinsic

function of Fortran and PRFT, SWDF1 and NDEF1 are temperature, drought stress and nitrogen deficiency factors, respectively.

B. Leaf Initiation and Emergence

The subroutine GROSUB calculates carbohydrate demand starting with the simulation of leaf emergence. Leaf emergence is affected by air temperature and, when interplant competition begins, by plant population density (Chapter 1). The fraction of a leaf (TI) emerged each day is determined by daily thermal time (DTT) and plant population density and modified for any ontogenetic effects by an intermediate variable PC.

The beginning of interplant competition is determined emperically by a parameter (P7), which is cumulative growing degree days since the first leaf emerged after planting.

When SUMDTT, which is set to zero at the time of emergence of the first new leaf, is greater than or equal to P7, then the fraction of new leaf (TI) for that day is calculated by the equation:

TI=(0.0225-0.001*Plants)*DTT,

otherwise,

TI=0.0224*DTT.

Calculation of biomass partitioning to growing organs, growth demand, inflorescence and sucker initiation, and balance of carbohydrate supply and demand are described by stage in the following sections.

C. Growth During ISTAGE 1

1. Leaf Area Growth

Daily total green leaf area per plant (PLAG) is calculated from the total leaf area per plant (XPLA) and the total leaf area per plant for the previous day (TempPLA). Thus,

PLAG=XPLA-TempPLA.

If XPLA is less than TempPLA, XPLA is set equal to TempPLA.

Both XPLA and TempPLA are intermediate variables and are set to zero at the beginning of ISTAGE 1 in subroutine PHASEI. XPLA is calculated from the number of leaves emerged (XN) by the equation

XPLA=(17.0*XN+3.11*XN*XN)*swdf2.

PLA is the total leaf area per plant including the initial leaf area. Both TemPLA and PLA are updated after PLAG is calculated by the equations

TempPLA=TempPLA+PLAG, and

PLA=PLA+PLAG.

2. Leaf and Root Weight Growth

Since it is assumed that there is no net growth of stem during this stage, biomass partitions only to roots and leaves. The amount of biomass partitioned to roots and leaves is obtained by calculating daily root and leaf growth demand and balancing carbohydrate demand and supply.

This daily demand for carbohydrate for green leaf weight growth (GROLF) is calculated from the current total green leaf weight per plant (XLFWT) and previous

day's green leaf weight per plant (LFWT). XLFWT is calculated from green leaf area. If XLFWT is less than LFWT, XLFWT is set equal to LFWT. XLFWT and GROLD are calculated by the equations

XLFWT=(PLA/96.)1.15 and**

GROLF=XLFWT-LFWT.

Current basal leaf tissue weight (XBasalLeafWT) is calculated as a fraction of green leaf weight (XLFWT). XBasalLeafWT and daily gain in basal leaf weight (GROBSL) are calculated by the equations

XBasalLeafWT=0.42*XLFWT, and

GROBSL=Xbasalleafwt-BasalLeafWT.

Daily root weight growth (GRORT) is calculated from daily carbohydrate supply (CARBO) and daily leaf weight (GROLF) by the equation

GRORT=CARBO-GROLF-GROBSL.

If GRORT is less than 25% of CARBO, then it is set to 25% of CARBO. A growth reducing factor (GRF) is calculated by the equation

GRF=CARBO*0.75/(GROLF+GROBSL)

GROLF, GROBSL are multiplied by GRF, and PLA is recalculated by the equations

GROLF=GROLF*GRF,

GROBSL=GROBSL*GRF,

PLA=(LFWT+GROLF)0.87*96.0.**

This is to check the balance of supply and demand of carbohydrate.

LFWT and BasalLeafWT are updated, and leaf area assumed to be lost due to

senescence is calculated, and the leaf weight is reduced by the equations

LFWT=LFWT+GROLF,

BasalLeafWt=BasalLeafWT+GROBSL,

IF(GROLF.GT.0.) SLAN=PLA/1000,

LFWT=LFWT-SLAN/600.

D. Growth in ISTAGE 2

In ISTAGE 2, leaf area production, green and basal leaf tissue mass, and root mass are calculated as was done in ISTAGE 1. Stem growth begins in this stage and daily growth (GROSTM) is calculated from the current basal leaf tissue weight (XBasalLeafWT) because stem dry weight is correlated with basal leaf dry weight up to the time of forcing. XStemWT and GROSTM are calculated by the equations

XStemWT=0.52*XbasalLeafWT,

GROSTM=XStemWT-STMWT.

The balancing of carbohydrate supply and demand was done as was described for ISTAGE 1 (Section 6.24,C). If GRORT is less than 15% of CARBO, then it is set to 15% of CARBO. The following equations are the calculations of the carbohydrate supply and demand balance (detailed comments see the previous section).

GRF=CARBO*0.85/(GROLF+GROBSL+GROSTM)

GROLF=GROLF*GRF

GROBSL=GROBSL*GRF

GROSTM=GROSTM*GRF

PLA=(LFWT+GROLF)0.87*96.0**

LFWT=LFWT+GROLF

BasalLeafWT=BasalLeafWT+GROBSL

STMWT=STMWT+GROSTM

IF(GROLF.GT.0.) SLAN=PLA/1000.

LFWT=LFWT-SLAN/600.

E. GROWTH IN ISTAGE 3

At the time of forcing, leaf initiation ends although leaves are still emerging and expanding. Leaf growth ceases at the end of the stage. The LAI and leaf weight all reach their maximum values at this time. The green leaf area, and green and basal leaf tissue mass are calculated as they were for ISTAGE 2.

The inflorescence initiates at the beginning of the stage and measurable amounts of biomass begin to be partitioned to it. Daily inflorescence growth (GROFLR) is calculated from daily thermal time (unpublished data) by the equation

GROFLR=0.45*DTT/20.5*AMIN1(NDEF2,SWDF2).

After forcing, stem dry weight increases rapidly, so daily stem growth is calculated differently from the last stage by the equation

GROSTM=0.38*GROFLR1.12.**

The amount of light intercepted per plant determines the potential fruit size and the number of eyes per fruit (Sanford, personal communication). Total carbohydrate accumulated during ISTAGE 3 (SUMP) and the duration of the stage (IDURP) are calculated by the equations

SUMP=SUMP+CARBO, and

IDURP=IDURP+1.

Both will used to calculate number of eyes per fruit in subroutine PHENOL.

F. Growth in ISTAGE 4

The priority in biomass partitioning to growing organs in ISTAGE 4 depends to an unknown degree on plant size, but is in the order inflorescence, stem, root and sucker. If the total plant weight is greater than or equal to 600 g dry weight, suckers are assumed to initiate and daily gain in suckers (GROSK) and sucker weight (SKWT) are calculated by the equations

GROSK=(CARBO-GROSTM-GRORT-GROFLR)*0.5, and

SKWT=SKWT+GROSK.

G. Fruit Weight Growth in ISTAGE 5

Most biomass partitioning to fruitlets occurs during this stage and stem growth continues. If the total plant weight reaches 600 g dry weight in ISTAGE 5, suckers are assumed to initiate, otherwise, sucker growth initiated in ISTAGE 4 continues.

A zero-to-unity relative rate of biomass partitioning to fruitlets (RGFILL) is calculated from the daily mean air temperature. Then the daily fruit growth is calculated from RGFILL, total number of eyes per fruit (GPP) and maximal daily rate of biomass partitioning to each eye (G3, mg eye^{-1}), and a water stress factor (SWDF1). The equations

RGFILL=RGFILL+(1.0-0.0017*(TTMP-28.)2)/8.0 and**

GROFRT=RGFILL*GPP*G3*0.001*(0.45+0.55*swdf1)

were adopted from CERES-Maize (Jones and Kiniry, 1986).

Daily crown weight growth (GROCRWN) is assumed to be 12.5 percent of daily fruit weight growth (GROFRT) and GROFRT is calculated by the equation

GROCRWN=0.125*GROFRT.

Fruit weight and inflorescence weight are then updated by the equations

FRTWT=FRTWT+GROFRT and

FLRWT=FLRWT+GROFRT+GROCRWN.

H. Growth in ISTAGE 6

All biomass in this stage is partitioned to suckers and stem.

I. Leaf Senescence, Leaf Area Index and Total Weight

Leaf area senesced due to drought stress (SLFW), nitrogen stress (SLFN), and competition for light (SLFC) is determined by zero-to-unity factors by the equations

SLFW=0.95+0.05*SWDF1 and

SLFN=0.95+0.05*NDEF2.

If LAI is greater than 6,

SLFC=1.-0.002*(LAI-6.),

otherwise, SLFC=1.

At any time, the total amount of green leaf area is the difference between the total amount of leaf area that has been produced (PLA) and the total amount of leaf area that has senesced (SENLA). Plant leaf area senescence per day (PLAS) due to water, nitrogen, or competition stresses is calculated as follows:

PLAS=(PLA-SENLA)*(1.0-AMIN1(SLFW,SLFC,SLFN)).

SENLA is then updated by the equation

SENLA=SENLA+PLAS.

Leaf area index (LAI), above-ground biomass per unit area (BIOMAS, g m^{-2}), total plant weight, total plant dry weight per hectare (DM, Kg ha^{-1}) and plant top fraction (PTF) are calculated by the equations

LAI=(PLA-SENLA)*PLANTS*0.0001,

BIOMAS=(LFWT+STMWT+FLRWT+BasalLeafWT+SKWT)*PLANTS,

TotalPlantWT=LFWT+STMWT+BasalLeafWT+FLRWT+SKWT,

DM=BIOMAS*10.0, and

PTF=(LFWT+BasalLeafWT+STMWT+FLRWT+SKWT)/

(RTWT+LFWT+BasalLeafWT+SKWT+STMWT+FLRWT).

Other subroutines are esstially identical to those in CERES-Maize (Jones and Kiniry, 1986), so they are not described here.

CHAPTER 7

MODEL EVALUATION

7.1 METHODS OF MODEL EVALUATION

Model evaluation is an essential and important aspect of the process of crop model development, and validation. Once a crop model is developed, it is necessary to know how well the model works in a biological and physiological sense and how accurately the model predicts crop growth, development and yield. In other words, it is necessary to know how much confidence one can have in the model results. Even though it is of importance, published methods of evaluating crop models are not well developed.

Methods used to evaluate models can be classified into two types: descriptive (or qualitative) and statistical (or quantitative). Descriptive methods evaluate model performance on the basis of the similarity of the predicted and the measured results. No statistic is calculated and no hypothesis is tested using this method. So descriptive methods do not give confident answers about the model results. Examples of the descriptive method include using the difference or relative difference between simulated and observed results, expressed as a percentage of the observed (Wilkerson et al., 1983; Ingram and McCloud, 1984; Grant, 1989; Jones et al., 1980; Jones et al., 1991; Jones and Kiniry, 1986; Kiniry, 1991), using 1:1 line graphs without testing any hypothesis (Jones and Kiniry, 1986; Jones et al., 1980; Albers and Ward, 1991; White, 1991), comparing simulated and observed results graphically (Grant,

1989; Ingram and McCloud, 1984; Wilkerson et al., 1983, Jones et al., 1980; Jones et al., 1991), and using an agreement index (AI), which is defined as:

$$AI = 1 - \frac{|simulatedvalue - actualvalue|}{actualvalue}$$

(Albers and Ward, 1991; Jackson and Albers, 1991).

Statistical methods provide quantitative measures of the similarity between observed and predicted values. These methods involves statistical calculation and hypothesis testing. Several approaches have been proposed to evaluate system models statistically. The most common method is to test the hypothesis that the regression line of observed versus simulated values passes through the origin and has a slope of unity (Dent and Blackie, 1979; Carter, 1986). Dent and Blackie (1979) also tested the hypothesis that the overall distribution of results of the model was the same as the overall distribution of true values. Feldman et al. (1984) evaluated a population model in entomology by testing the hypothesis that the model was unbiased, a method that is applicable where the individual measurements are not independent.

Wallach and Goffinet (1989) proposed to use the mean squared error of prediction as a criterion for measuring the predictive accuracy of models and comparing system models whose outputs are yields. According to Wallach and Goffinet (1989), the mean squared error of prediction of a model was defined as:

$$MSEP(p) = \mathscr{E}\left[(y - f(x,p))^2 | p\right]$$

where $\mathscr{E}$ indicates an expectation (over the population of interest), y is the observed

quantity, e.g. yield, and $f(x,p)$ is the quantity predicted by the model f, and x stands for model variables, and p for model parameters. The mean squared error of prediction is simply the mean squared difference between the observed and predicted values. This method provides a statistical measure of model predictive accuracy that is useful for comparing alternative models. A major deficiency of the method is that it does not involve hypothesis testing so it can not be used for model validation.

Statistical methods are also easily misused. For example, the coefficient of determination (R^2) obtained by linear regression of simulated and observed values has been commonly but incorrectly used in model validation to indicate model prediction accuracy (Albers and Ward, 1991; Jones and Kiniry, 1986). The R^2 value is the variation accounted by the regression and its value indicates the agreement between simulated and observed values. It does not give any information about relative difference between simulated and observed values. For example, regression of simulated to actual values for the model $Y=2X$ will predict values that exceed actual values by 100 percent; the regression of simulated to actual values for the model $Y=0.5X$ will predict values that are only 50 percent of the actual values (Fig. 7.1). In both cases, the R^2 for the regression is 1.0. The third example in Fig. 7.1 shows the regression of simulated to actual values for the model $Y=X$. Even though the R^2 value is smaller (0.999) than that obtained by the above two regressions, the model will provide more accurate predictions than the other two models.

The standard deviation of the differences between simulated and observed values has also been used to evaluate models (Boote et al., 1991; Jones et al., 1991).

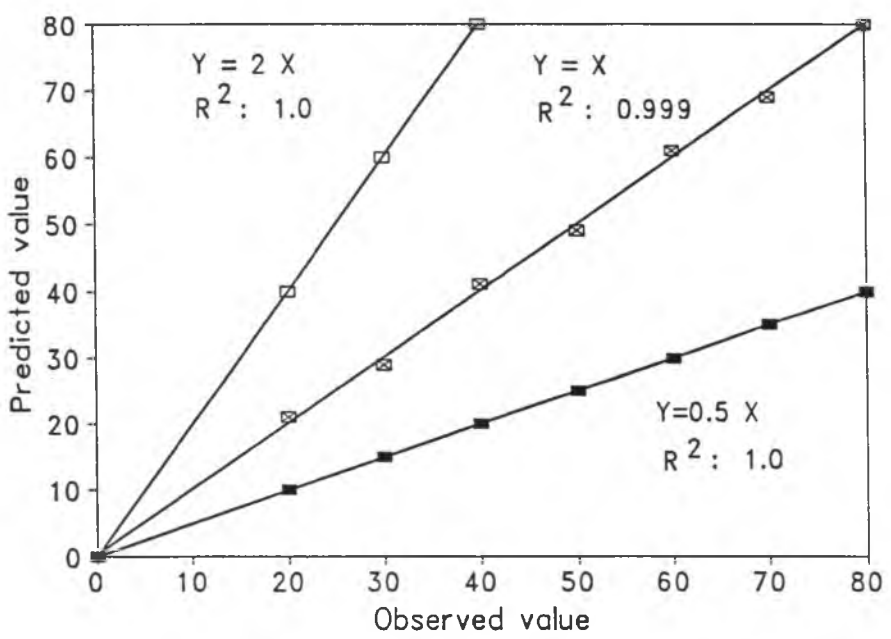


Fig. 7.1 Regressions for three hypothetical models that overestimate, accurately estimate, and underestimate observed values. In each case, essentially 100 percent of the variation in the hypothetical observed values was accounted for.

The standard deviation is a measure of dispersion of a population or a sample. Presumably, a lower standard deviation for the differences between simulated and observed values indicates the model was more accurate in prediction. A lower standard deviation indicates that the model has less variability in prediction but it may over or under predict relative to the observed data. Table 7.1 illustrates the problem of using the standard deviation. By the criteria used by Boote et al. (1991) and Jones et al. (1991), Model 1, which has a lower standard deviation than Model 2, is the more accurate model. However, Model 1 has a much higher mean difference and so is not necessarily superior to Model 2, despite its lower standard deviation.

Table 7.1 Artificial data showing the mean and standard deviation (SD) for the differences between model simulated data and experimental data.

Exp. No	Observed	Model 1	Model 2	d 1 †	d 2 ‡
1	100	200	101	100	1
2	200	300	220	100	20
3	300	400	330	100	30
4	400	500	380	100	-20
5	500	600	469	100	-31
Mean*	300	400	300	100	20.2
SD	129	129	117	0	21

† Differences between the simulated and observed values of Model 1.
‡ Differences between the simulated and observed values of Model 2.
* Mean of the absolute differences between simulated and observed values.

In this study, both mean of absolute differences between simulated and observed values and their associated standard errors were used to evaluate the model prediction for fruit yield, forcing date, fruit harvest date and date of physiological maturity. The model simulation of several plant components (leaf area index, green

leaf dry weight, and total plant dry weight) was evaluated by testing the hypothesis that the regression line of observed versus simulated values passes through the origin and has a slope of unity.

7.2 MODEL CALIBRATION

The model was calibrated to the data of the first planting of the plant population density trials described in Chapter 1, PART I. A trial and error procedure was used to calibrate the parameters of P1, P4, P5, P6 and P7 (Table 7.2) based on the goodness of fit of predicted dates of forcing, fruit harvest and physiological maturity to the observed data. The coefficient (ConvertCoefficient) for converting photosynthetically active radiation to carbohydrate was calibrated using total dry matter, and fruit yield.

Table 7.2 ALOHA-Pineapple model parameter values derived from model calibration.

P1 † (°C-day)	P4 (°C-day)	P5 (°C-day)	P6 (°C-day)	P7 (°C-day)	ConvertCoefficient (g MJ^{-1})
1230	2904	670	1845	500	2.7

† P1, number of days from emergence of first new leaf to end of zero net stem growth.
P4, cumulative growing degree days from opening of first flower to fruit harvest.
P5, cumulative growing degree days from fruit harvest to physiological maturity.
P6, number of days from root initiation to emergence of first new leaf.
P7, cumulative growing degree days from emergence of first new leaf to beginning of interplant competition.
ConvertCoefficient, a coefficient for converting intercepted photosynthetically active radiation to carbohydrate.

The predicted values for date of forcing, fruit harvest and physiological maturity, and fruit yield were compared to observed ones. The simulated leaf area

index (LAI), leaf dry weight and total plant dry weight were also compared to the observed values. Because the model simulates biomass on a dry weight basis, 'weight' in all cases refers to 'dry weight'. The model results were evaluated statistically using the methods described in Section 7.1.

Date of Forcing, Fruit Harvest and Physiological Maturity

The mean difference between simulated and observed dates of forcing was 1 day with a standard error of 0.49 days (Table 7.3). The largest difference for any one plant population density was only 3 days. The mean difference between simulated and observed dates of fruit harvest was 3.8 days with a standard error of 0.97 days (Table 7.4). The largest difference for any one density was 6 days. The mean difference between simulated and observed dates of fruit physiological maturity was 3 days with a standard error of 1.41 days (Table 7.5). The largest difference for any one population was 8 days. Fig. 7.2 shows that the simulated and observed values fell on or close to the one to one line.

Table 7.3 Simulated days after planting (DAP) to forcing, for five plant population densities of Smooth Cayenne pineapple planted in June, 1989.

Plant population density (plants m^{-2})	Simulated DAP to forcing	Observed DAP to forcing	Difference (days)
2.61	460	460	0
5.22	460	460	0
7.83	460	460	0
10.06	458	460	-3
12.81	461	460	2
Mean †	459.8	460	1
S_{dm} ‡			0.49

† Mean, mean of the absolute differences between simulated and observed values.
‡ S_{dm}, standard error of the mean of the differences.

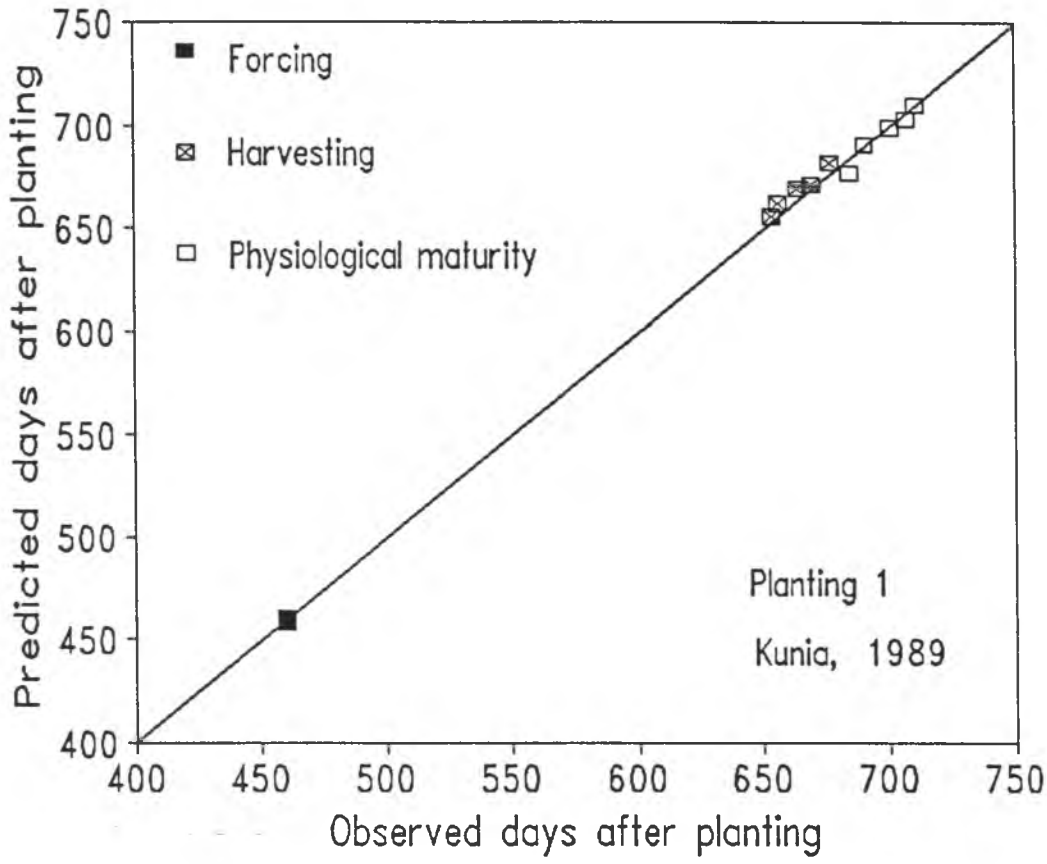


Fig. 7.2 Relationship between predicted and observed dates of forcing, fruit harvest (10% fruits ripe) and fruit physiological maturity (90% fruits ripe) for five plant population densities of Smooth Cayenne pineapple planted at Kunia, Hawaii in June, 1989 and forced in September, 1990.

Table 7.4 Simulated days after planting (DAP) to fruit harvest for five plant population densities of Smooth Cayenne pineapple planted in June, 1989.

Plant population density (p m^{-2}) ¶	Simulated DAP to fruit harvest	Observed DAP to fruit harvest	Difference (days)
2.61	656	654	2
5.22	662	656	6
7.83	669	664	5
10.06	671	670	1
12.81	682	677	5
Mean †	668	664.2	3.8
S_{dm} ‡			0.97

† Mean, mean of the absolute differences between simulated and observed values.
‡ S_{dm}, standard error of the mean of the differences.

Table 7.5 Simulated days after planting (DAP) to fruit physiological maturity for five plant population densities of Smooth Cayenne pineapple planted in June, 1989.

Plant population density (plants m^{-2})	Simulated DAP to fruit physiological maturity	Observed DAP to fruit physiological maturity	Difference (days)
2.71	677	685	-8
5.22	691	691	0
7.83	699	701	-2
10.06	703	707	-4
12.81	710	711	-1
Mean †	696	699	3
S_{dm} ‡			1.41

† Mean, mean of the absolute differences between simulated and observed values.
‡ S_{dm}, standard error of the mean of the differences.

Fruit Yield

The mean difference between the simulated and observed fruit yield (kg ha^{-1}) of five plant population densities of pineapple was 6985 kg ha^{-1}, which was only 6.9 % of the mean observed fruit yield (Table 7.6). However the standard error of the differences was higher (4573 kg ha^{-1}) because the model under simulated fruit yield by 88% at a density of 12.81 plants m^{-2}.

Table 7.6 Simulated fruit yield of five plant population densities of Smooth Cayenne pineapple planted in June, 1989.

Plant population density (plant m^{-2})	Simulated fruit yield (kg ha^{-1})	Observed fruit yield (kg ha^{-1})	Difference (kg ha^{-1})
2.61	55357	55332	25
5.22	88752	79878	8874
7.83	111214	104093	7121
10.06	122241	124215	- 1974
12.81	123238	140167	-16929
Mean †	100160.4	100737.2	6985
S_{dm} ‡			4573

† Mean, mean of the absolute differences between simulated and observed values.
‡ S_{dm}, standard error of the mean of the differences.

Leaf Area Index

The model underestimated leaf area index (LAI) at the highest population density (Fig. 7.3A) particularly during the reproductive phase from 500 to 700 days after planting. LAI was overestimated at the lowest population density during this same time period. When the simulated data for the five plant population densities were regressed against the observed data, an intercept of 0.15 and a slope of 0.95 were obtained (Fig. 7.4A). Statistical analysis showed that the intercept was not

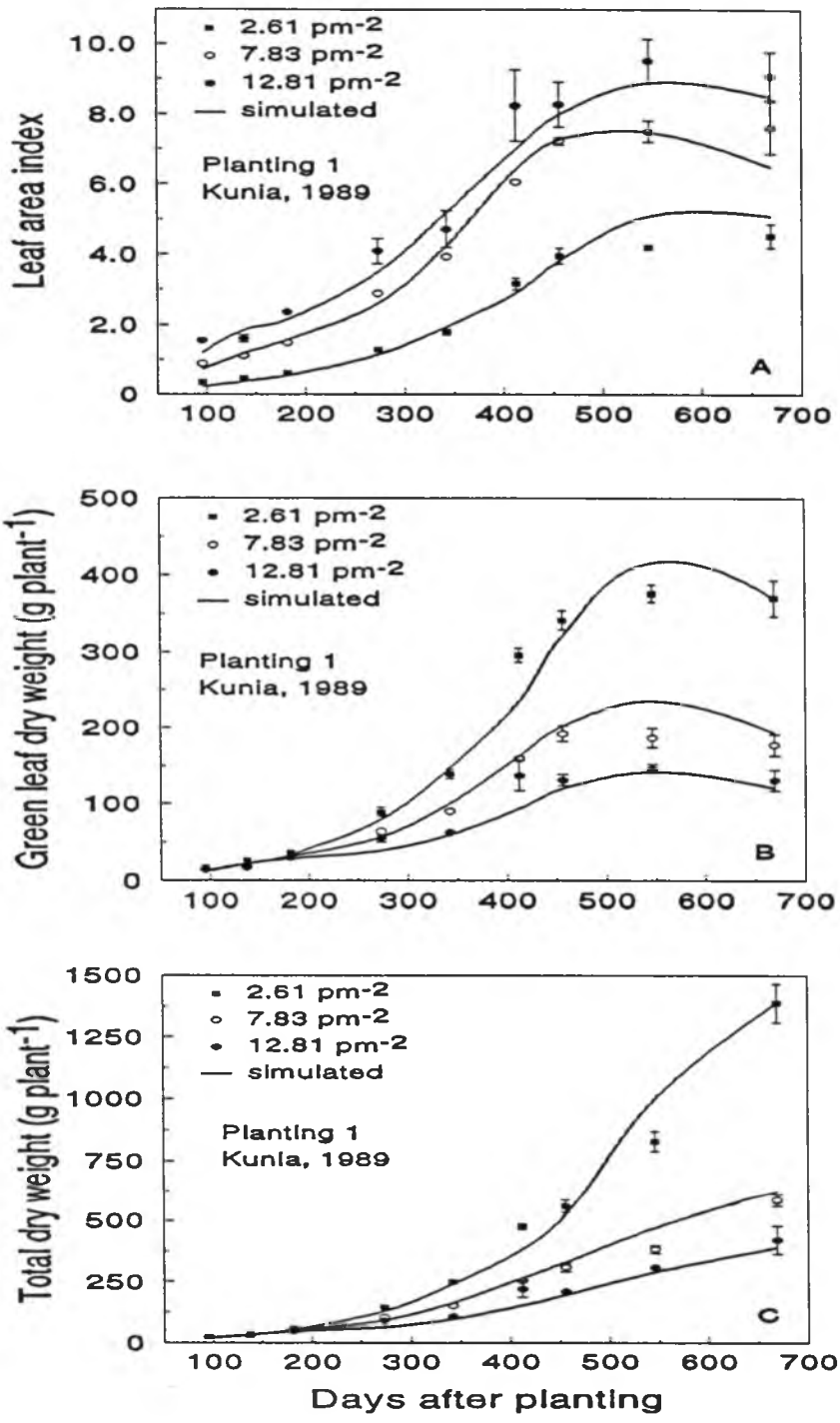


Fig. 7.3 Simulated and observed leaf area index, green leaf dry weight and total plant dry weight for plant population densities of 2.61, 7.83, and 12.81 plants m^{-2} (pm^{-2}) of Smooth Cayenne pineapple planted at Kunia, Hawaii in June, 1989 and forced in September, 1990.

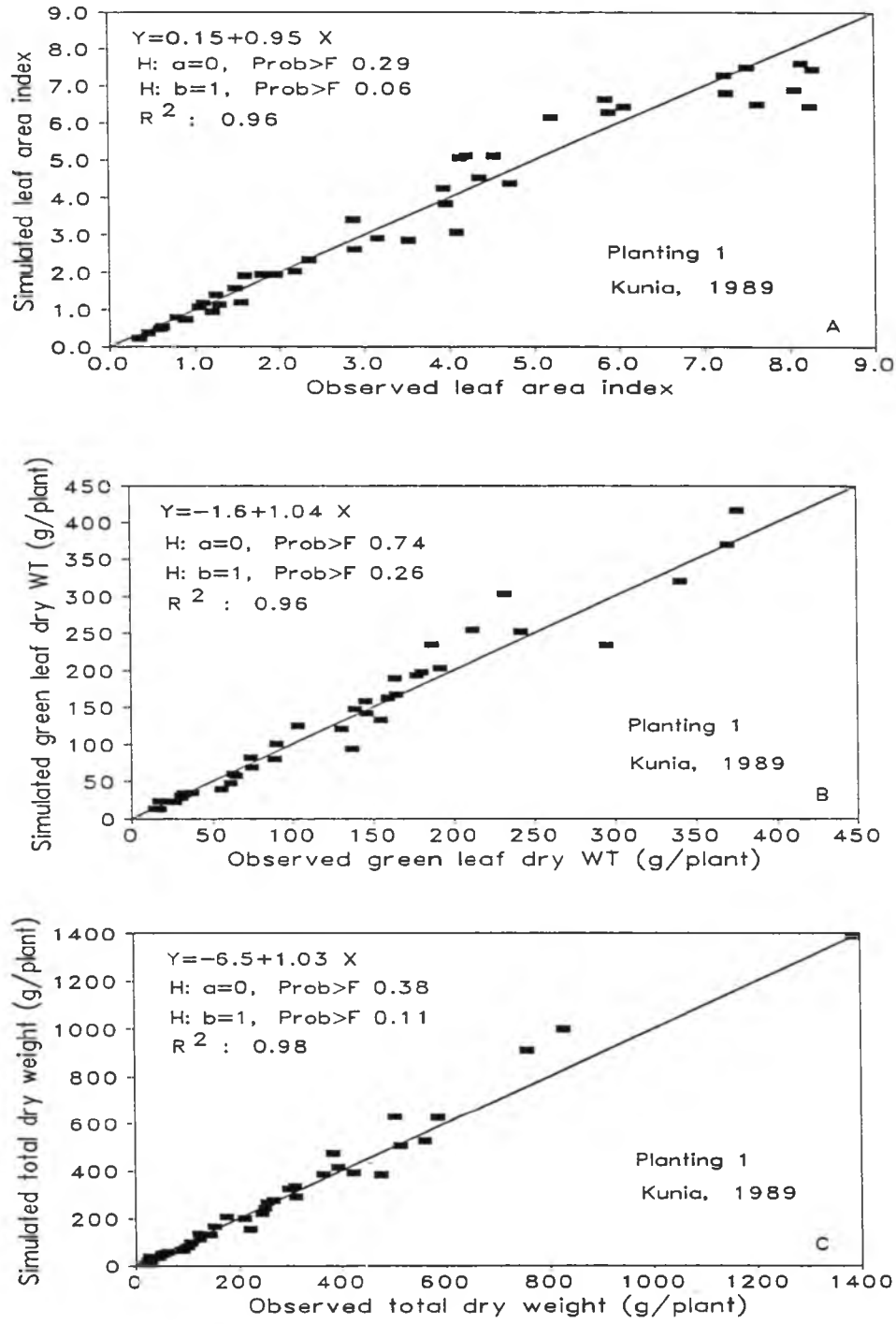


Fig. 7.4 One to one relationship between predicted and observed leaf area index, green leaf dry weight and total plant dry weight for three plant population densities of Smooth Cayenne pineapple planted at Kunia, Hawaii in June, 1989 and forced in September, 1990.

significantly different from zero and the slope was not significantly different from unity (Fig. 7.4A).

Green Leaf Weight

The model generally predicted green leaf dry weight per plant accurately, although green leaf dry weight per plant was overestimated during the reproductive phase (Fig. 7.3B). The discrepancy may be due to collection of small samples that were not representative of the population. Regressing simulated results against the observed data resulted in an intercept of -1.6 and a slope of 1.04; the values were not significantly different, respectively, from zero and unity (Fig. 7.4B).

Total Plant Weight

Simulated total dry weight per plant corresponded well with the observed data (Fig. 7.3C). The regression of simulated vs. observed total plant weight resulted in an intercept not significantly different from zero and a slope not different from unity (Fig. 7.4C).

In summary, the model was well calibrated to the field data. The simulated results for phenological development and growth agreed well with the observed data. The model simulated the mean fruit harvest date about 4 days later than the observed data. The four day error in prediction is fairly minor compared to an average interval of 200 days from forcing to fruit harvest.

7.3 MODEL VALIDATION

The model was validated using the data collected from five planting dates in

Table 7.7 Planting dates and locations of pineapple data used to validate ALOHA-Pineapple.

Location	Elevation (meters)	Planting date	Plant population (plants m^{-2})
Kunia, Oahu	200	8/15 and 10/18, 89	2.61, 5.22, 7.83, 10.06 and 12.81
Hamakuapoka, Maui	90	1/10, 5/1 and 7/24, 85	5.9
Haliimmaile, Maui	310	1/10, 5/1 and 7/24, 85	5.9
Kala, Maui	690	1/10, 5/1 and 7/24, 85	5.9

four locations (Table 7.7). The data collected at Kunia, Hawaii were described in Chapter 2, PART I. The data from the studies on Maui were described in part by Fleisch (1988). All studies were planted with crowns from the 'Smooth Cayenne' clone Champaka F153, were drip-irrigated and fertilizers were applied as foliar sprays following standard plantation practices. The simulations were done using weather data files collected for each study and actual crown weight when available, otherwise crown weight at planting was estimated.

The predicted values for date of forcing, fruit harvest and physiological maturity, and fruit yield were compared to observed ones. The simulated leaf area index (LAI), green leaf dry weight and total plant dry weight were also compared to observed values. The model results were evaluated statistically using the methods described in Section 7.1.

7.3.1 Results

Forcing Date

Fruit yield within an environment is highly correlated with total plant weight at the time of forcing (Chapter 4). Plant size is, therefore, assumed to be the primary parameter used to determine the time of forcing. In practice, scheduling of fruit

production may be an overriding factor. The data used to validate the model were from experiments not specifically designed for this purpose. All studies (Table 7.7) were forced on a calendar date to achieve a particular objective. For the Kunia studies, it was to examine the effects of PPD and PD and their interaction. For the Maui studies, the primary objective was to examine the effects of environment on reproductive development. Because pineapple was planted on one date and forced about 12 months later in the Maui studies, plant size at forcing decreased with increasing elevation. This response was assumed to be due to the decrease in average temperature with increasing elevation (Fleisch, 1988).

For the simulation, actual average plant weight at forcing for each planting was entered in the model as a decision variable. The model then predicted date of forcing when the plant "grown" by the model reached the actual plant weight at forcing. The mean difference between the simulated and observed forcing date for the two plantings grown at Kunia was 10 days with a standard error of 3.6 days (Table 7.8). The model predicted the forcing dates at the middle plant population densities (5.22 to 10.06 plants m^{-2}) more accurately than at the lower or higher ones (Table 7.8). For the Maui data, the mean difference between simulated and observed forcing date was 27.3 days with a standard error of 11.89 days (Table 7.9). This indicates that the model predicted forcing date well for some plantings but gave poor prediction for others. For example, the model accurately predicted forcing date at 90 m, but under-estimated it by about two months at 310 m, and over-estimated by about one and half months at 690 m (Table 7.9).

Table 7.8 Simulated days after planting (DAP) to forcing for five plant population densities of Smooth Cayenne pineapple planted at Kunia, Hawaii in August and October, 1989.

Planting Date	Population density (plants m^{-2})	Simulated DAP to forcing	Observed DAP to forcing	Difference (days)
August 15	2.61	415	400	15
	5.22	403	400	3
	7.83	396	400	- 4
	10.06	401	400	1
	12.81	419	400	19
October 18	2.61	346	335	11
	5.22	335	335	0
	7.83	337	335	2
	10.06	346	335	11
	12.81	369	335	34
	Mean †	376.7	367.5	10
	S_{dm} ‡			3.6

† Mean, mean of the absolute differences between simulated and observed values.
‡ S_{dm}, standard error of the mean of the differences.

Table 7.9 Simulated days after planting (DAP) to forcing for Smooth Cayenne pineapple grown on Maui, Hawaii.

Elevation (meter)	Planting date (calendar)	Simulated DAP to forcing	Observed DAP to forcing	Difference (days)
90	Jan., 1985	360	365	- 5
90	May, 1985	369	370	- 1
90	Jul., 1985	369	365	4
310	Jan., 1985	315	365	-50
310	May, 1985	312	370	-58
310	Jul., 1985	341	365	-21
690	Jan., 1985	408	365	43
690	May, 1985	411	370	41
690	Jul., 1985	382	365	23
Mean †		363	366.67	27.3
S_{dm} ‡				11.89

† Mean, mean of the absolute differences between simulated and observed values.
‡ S_{dm}, standard error of the mean of the differences.

Fruit Harvest Date

The mean simulated fruit harvest date was significantly delayed by 14.1 days compared to the observed mean for the two plantings at Kunia (Table 7.10). The delays were greatest at the highest and lowest plant population densities. For the Maui data, the mean difference between the simulated and observed fruit harvest date was 25 days with a standard error of 10.2 days (Table 7.11). The model predictions were poor at 310 and 690 m elevations.

Fruit Physiological Maturity

The mean simulated interval from planting to fruit physiological maturity was 8.8 days greater than the mean observed one for the Kunia data (Table 7.12). The over estimation of fruit physiological maturity at the lower and higher plant population densities were due to the over estimation of forcing dates. No data on fruit physiological maturity were collected from the Maui experiments.

Fruit Yield

The mean difference between the simulated and observed fruit yield (kg ha^{-1}) for the five plant population densities of pineapple was 2044 kg ha^{-1}, which was 2.6% over the observed mean (Table 7.13). The largest deviation between observed and predicted yields was about 11% and occurred at the highest plant population density for the August planting. On Maui, fruit yields were greatly under-predicted by the model (Table 7.14). On average, yields were underestimated by about 20% but the difference was as great as 37% for the July planting at 690 m. The yields at Kunia were lower than those on Maui in almost all cases.

Table 7.10 Simulated days after planting (DAP) to fruit harvest for five plant population densities of Smooth Cayenne pineapple planted at Kunia, Hawaii in August and October, 1989.

Planting Date	Population density (plants m^{-2})	Simulated DAP to fruit harvest	Observed DAP to fruit harvest)	Difference (days)
August 15	2.61	615	594	21
	5.22	607	601	6
	7.83	605	604	1
	10.06	616	613	3
	12.81	643	619	24
October 18	2.61	545	526	19
	5.22	538	537	- 1
	7.83	546	541	5
	10.06	563	547	16
	12.81	596	551	45
	Mean †	587.4	573.3	14.1
	S_{dm} ‡			4.4

† Mean, mean of the absolute differences between simulated and observed values.
‡ S_{dm}, standard error of the mean of the differences.

Table 7.11 Simulated days after planting (DAP) to fruit harvest for Smooth Cayenne pineapple grown at three elevations on Maui, Hawaii.

Elevation (meter)	Planting date (calendar)	Simulated DAP to fruit harvest	Observed DAP to fruit harvest	Difference (days)
90	Jan., 1985	578	564	14
90	May, 1985	555	552	3
90	Jul., 1985	564	552	12
310	Jan., 1985	556	571	-15
310	May, 1985	543	569	-26
310	Jul., 1985	568	569	- 1
690	Jan., 1985	671	620	51
690	May, 1985	668	600	68
690	Jul., 1985	647	612	35
Mean †		594.2	578.55	25
S_{dm} ‡				10.20

† Mean, mean of the absolute differences between simulated and observed values.
‡ S_{dm}, standard error of the mean of the differences.

Table 7.12 Simulated days after planting (DAP) to fruit physiological maturity for five plant population densities of Smooth Cayenne pineapple planted at Kunia, Hawaii in August and October, 1989.

Planting Date	Population density (plants m^{-2})	Simulated DAP to fruit physiological maturity	Observed DAP to fruit physiological maturity	Difference (days)
August 15	2.61	635	626	9
	5.22	634	634	0
	7.83	636	639	3
	10.06	647	648	- 1
	12.81	671	649	22
October 18	2.61	565	555	10
	5.22	566	568	- 2
	7.83	577	574	3
	10.06	593	583	10
	12.81	626	584	28
	Mean †	615	606	8.8
	S_{dm} ‡			4.4

† Mean, mean of the absolute differences between simulated and observed values.
‡ S_{dm}, standard error of the mean of the differences.

Table 7.13 Simulated fruit yields for five plant population densities of Smooth Cayenne pineapple planted at Kunia, Hawaii in August and October, 1989.

Planting Date	Population density (plants m^{-2})	Simulated fruit yield (kg ha^{-1})	Observed fruit yield (kg ha^{-1})	Difference (kg ha^{-1})
August	2.61	51303	52683	- 1380
	5.22	77218	77203	15
	7.83	88243	91495	- 3252
	10.06	98740	98526	214
	12.81	101101	90321	10780
October	2.61	45435	43658	1777
	5.22	66249	67324	- 1075
	7.83	81742	81615	127
	10.06	89653	88647	1006
	12.81	91109	90291	818
	Mean †	79079.3	79982.3	2044
	S_{dm} ‡			1186

† Mean, mean of the absolute differences between simulated and observed values.
‡ S_{dm}, standard error of the mean of the differences.

Table 7.14 Simulated fruit yield for the Smooth Cayenne pineapple grown at three elevations on Maui, Hawaii.

Elevation (meter)	Planting date (calendar)	Simulated fruit yield (kg ha^{-1})	Observed fruit yield (kg ha^{-1})	Difference (kg ha^{-1})
Maui, 90	Jan., 1985	82947	118474	-35527
90	May, 1985	98356	129538	-31182
90	Jul., 1985	107676	110713	- 3037
310	Jan., 1985	84248	99695	-15447
310	May, 1985	97080	108105	-11025
310	Jul., 1985	95358	97324	- 1966
690	Jan., 1985	65731	95465	-29734
690	May, 1985	77397	111082	-33685
690	Jul., 1985	66756	106085	-39329
Mean †		86172	108498	-22326
S_{dm} ‡				4841

† Mean, mean of the absolute differences between simulated and observed values.
‡ S_{dm}, standard error of the mean of the differences.

Leaf Area Index

The model generally predicted leaf area index well for the plantings at Kunia except at the highest plant population density (Fig. 7.5A and 7.6A). Regressing the simulated against the observed leaf area index resulted in intercepts and slopes that were not significantly different, respectively, from zero and unity (Fig. 7.7A and 7.8A).

The model over-predicted leaf area index for the January and May plantings at all elevations and the July planting at 310 and 690 m except for January at 690 m on Maui (Fig. 7.9A, 7.10 A and 7.11A). The model accurately predicted leaf area index for the January planting at 690 m and the July planting at 90 m on Maui (Fig. 11A). Regressing the simulated data against the observed data for the January planting at 690 m (Fig. 15 A) and July planting at 90 m (Fig. 7.12A) shows that there is good agreement between them. The intercepts of 0.17 and 0.28 were not significantly different from 0.0, and the slopes of 1.27 and 0.94 were not significantly different from unity (Fig. 7.12A, and 7.15A).

Green Leaf Weight

The model accurately predicted green leaf dry weight accumulation for the two plantings at Kunia (Fig. 7.5B and 7.6B). Regressing the simulated against the observed green leaf weight resulted in intercepts and slopes that were not significantly different, respectively, from zero and unity (Fig. 7.7B and 7.8B).

The model predicted green leaf dry weight accurately only for the January and May planting at 690 m and the July plantings at 90 and 690 m on Maui (Fig. 7.9B,

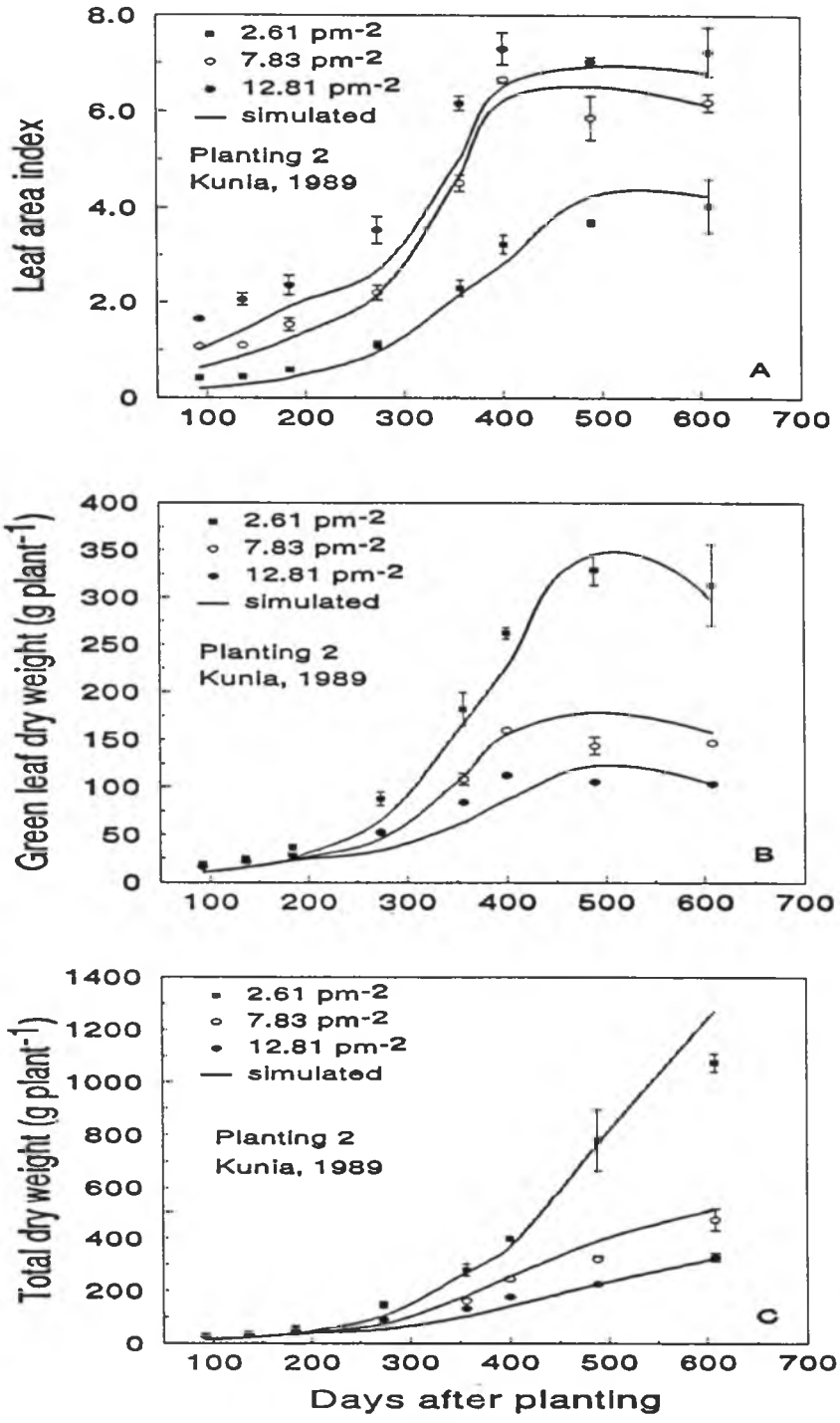


Fig. 7.5 Simulated and observed leaf area index, green leaf dry weight and total plant dry weight for plant population densities of 2.61, 7.83 and 12.81 plants m^{-2} (p m^{-2}) of smooth Cayenne pineapple planted in August, 1989 and forced in September, 1990 at Kunia, Hawaii.

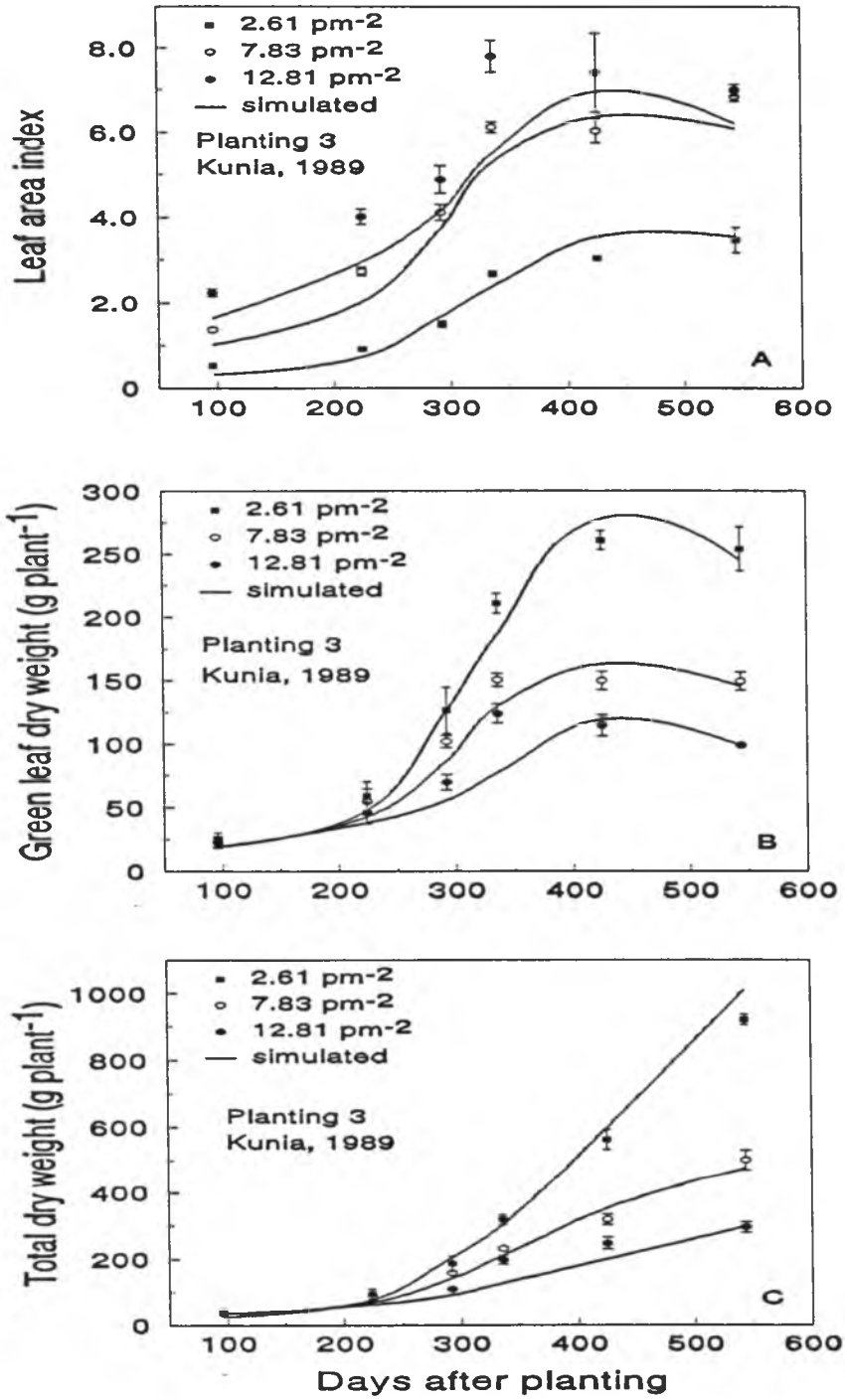


Fig. 7.6 Simulated and observed leaf area index, green leaf dry weight and total plant dry weight for plant population densities of 2.61, 7.83 and 12.81 plants m^{-2} (p m^{-2}) of smooth Cayenne pineapple planted in October, 1989 and forced in September, 1990 at Kunia, Hawaii.

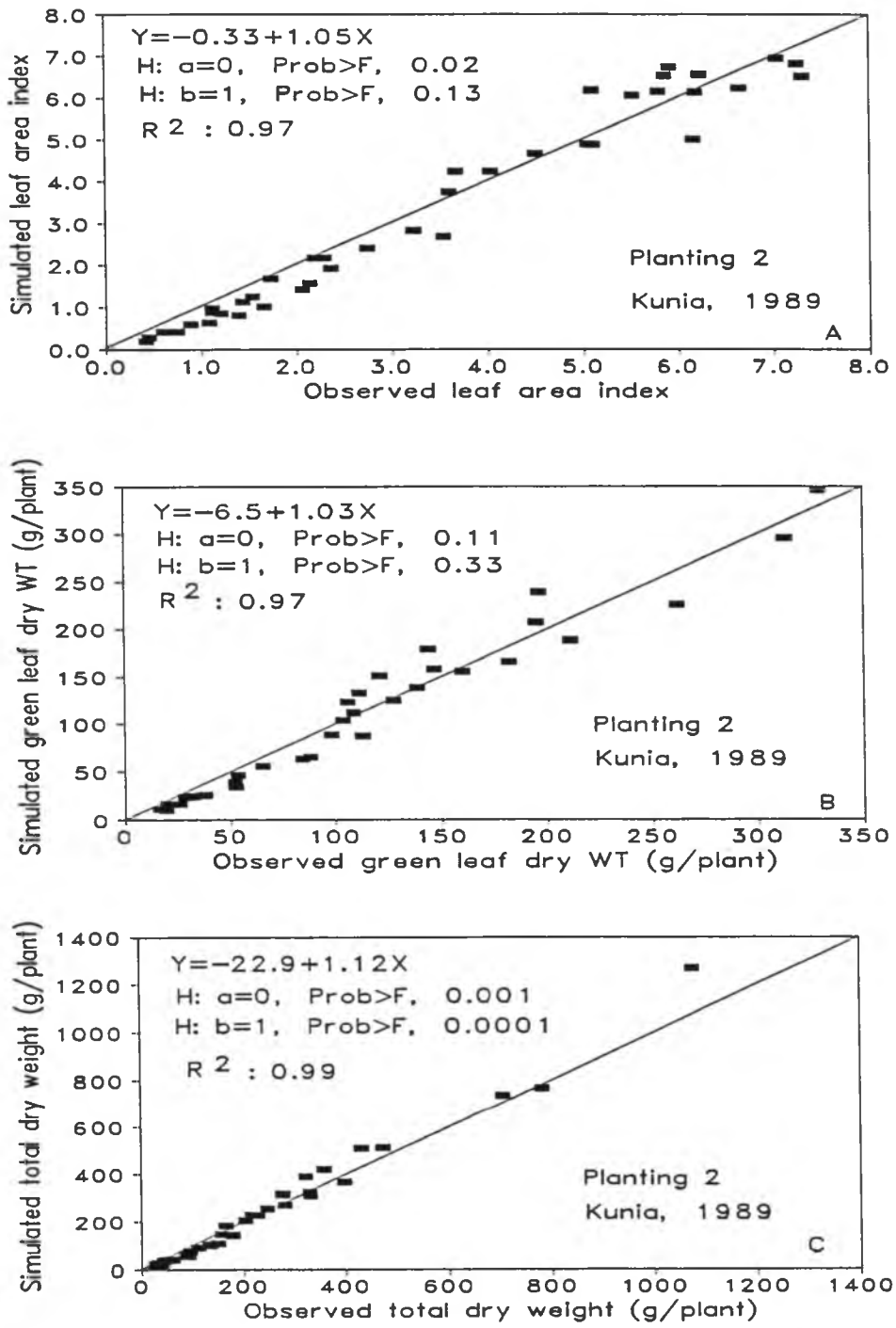


Fig. 7.7 One to one relationship between simulated and observed leaf area index, green leaf dry weight and total plant dry weight of three plant population densities of Smooth Cayenne pineapple planted at Kunia, Hawaii in August, 1989 and forced in September, 1990.

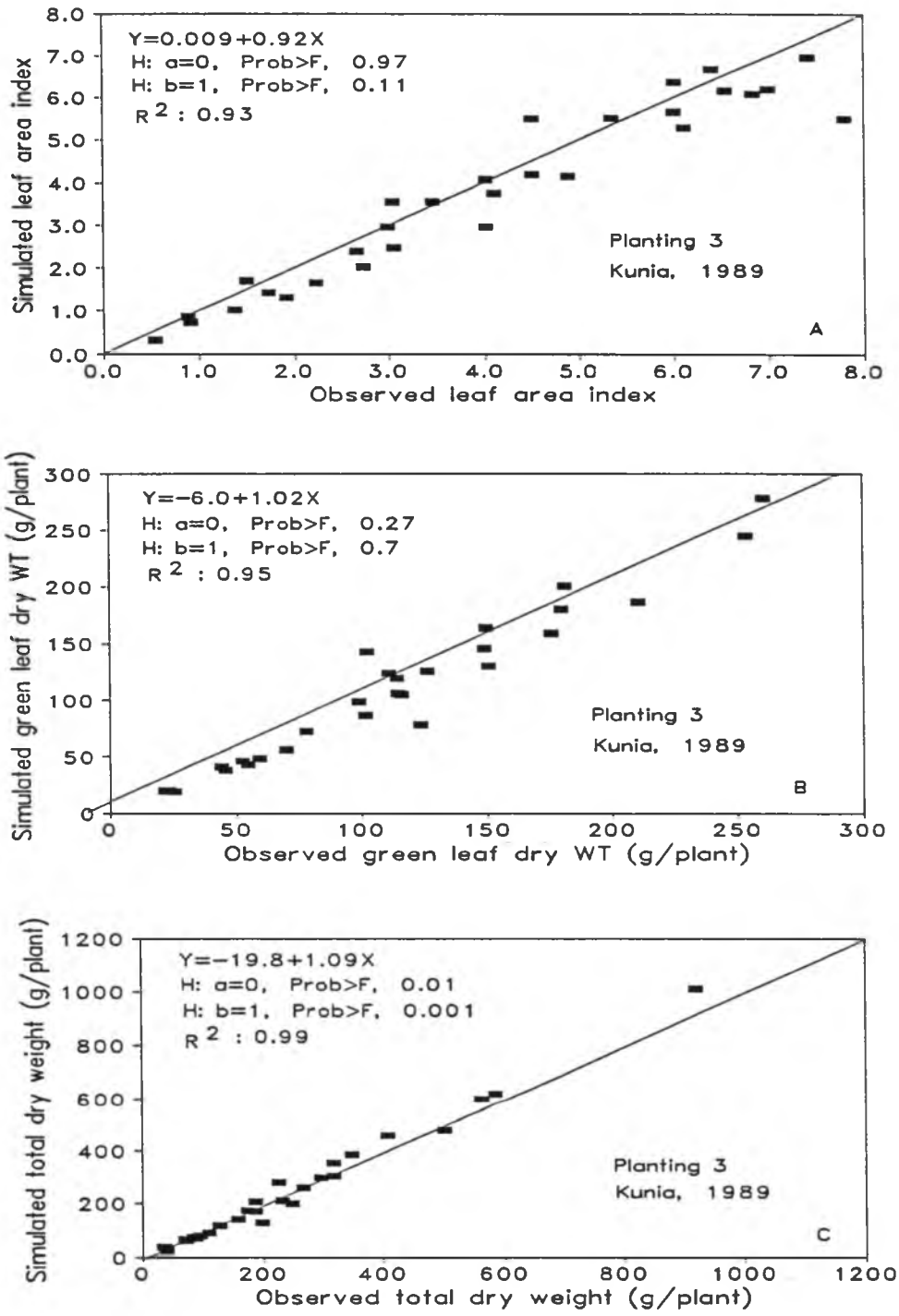


Fig. 7.8 One to one relationship between simulated and observed leaf area index, green leaf dry weight and total plant dry weight of three plant population densities of Smooth Cayenne pineapple planted at Kunia, Hawaii in October, 1989 and forced in September, 1990.

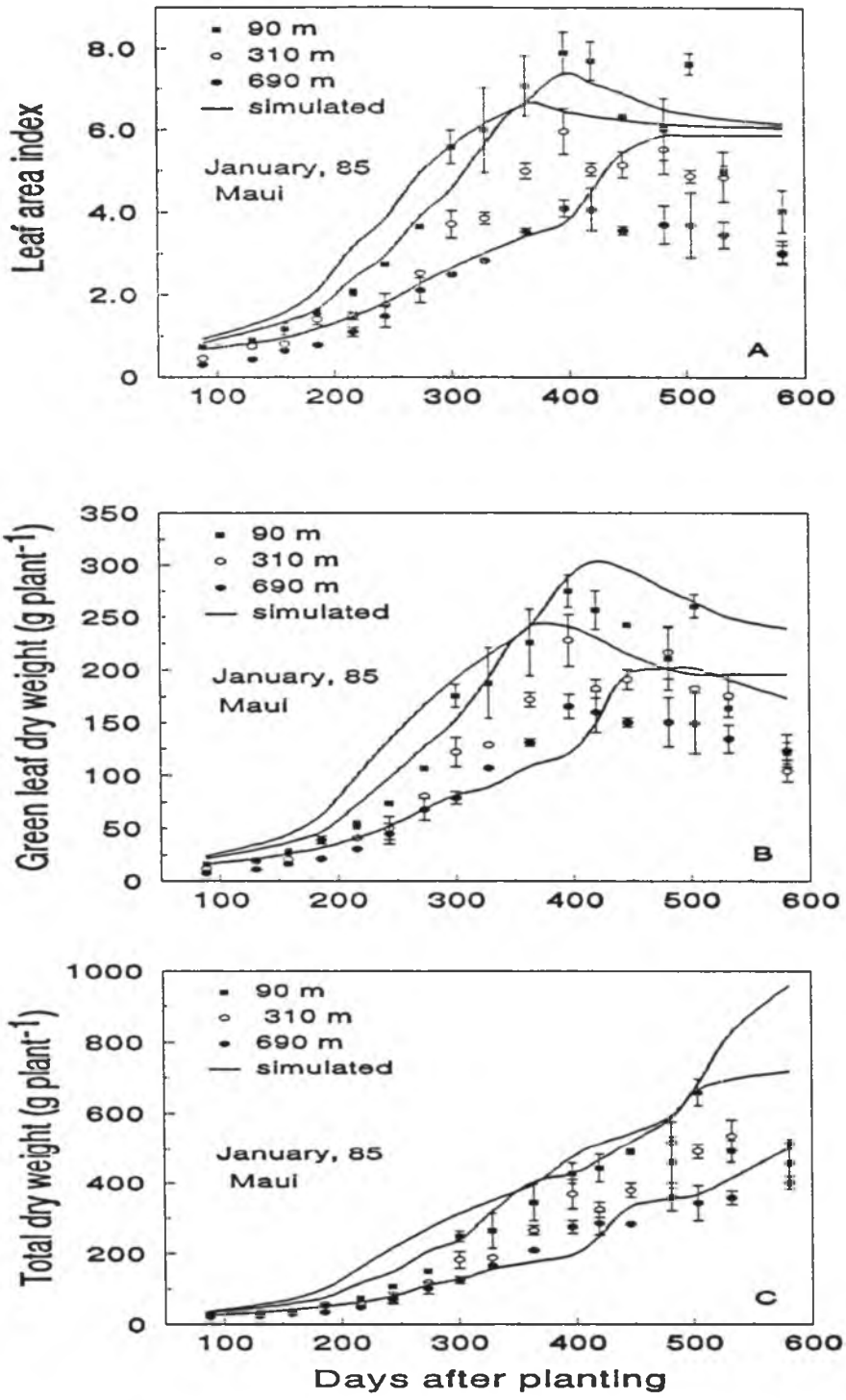


Fig. 7.9 Simulated and observed leaf area index, green leaf dry weight and total plant dry weight of Smooth Cayenne pineapple planted in January, 1985 at three elevations on Maui, Hawaii. Plants were forced in January, 1986.

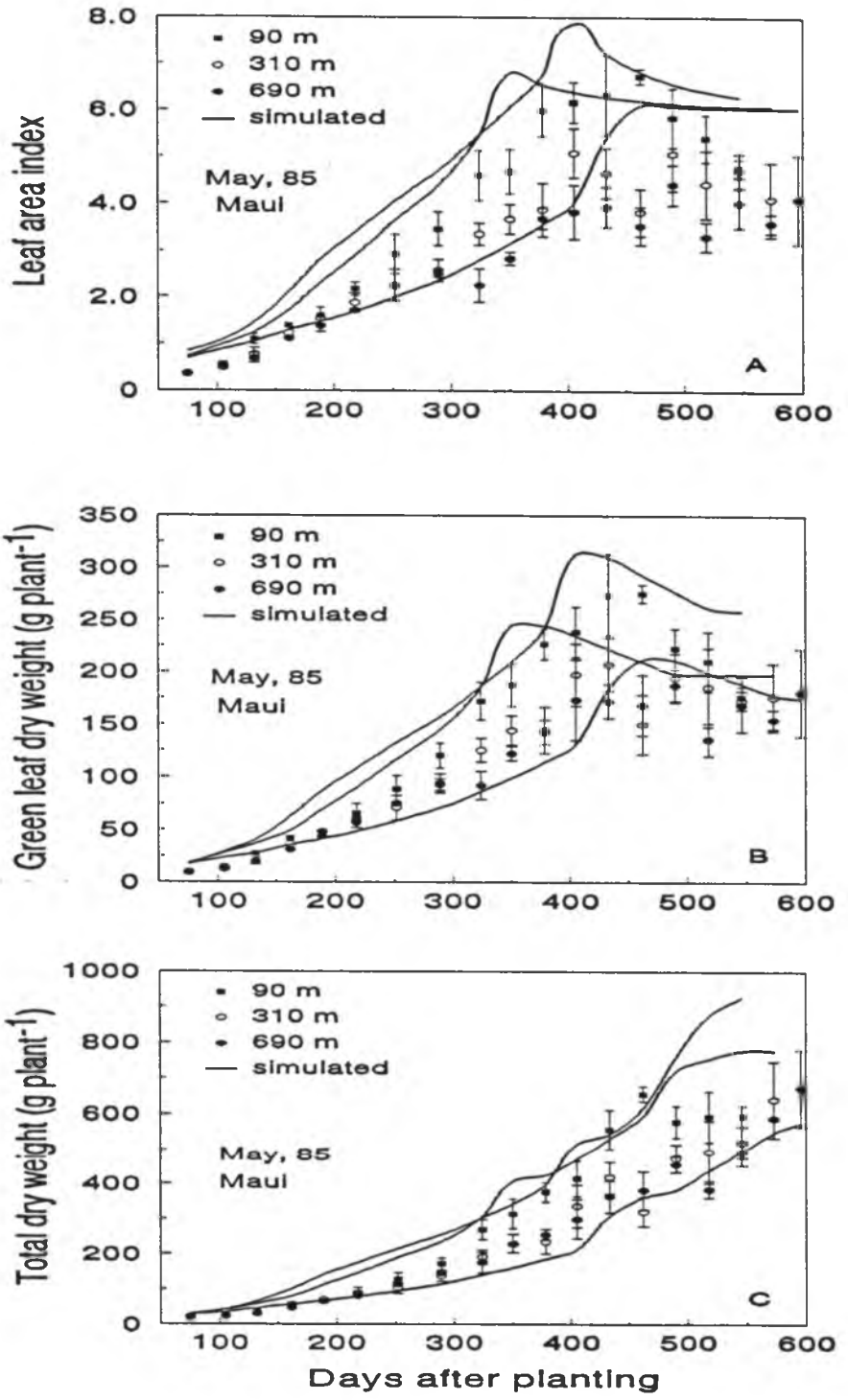


Fig. 7.10 Simulated and observed leaf area index, green leaf dry weight and total plant dry weight of Smooth Cayenne pineapple planted in May, 1985 at three elevations on Maui, Hawaii. Plants were forced in May, 1986.

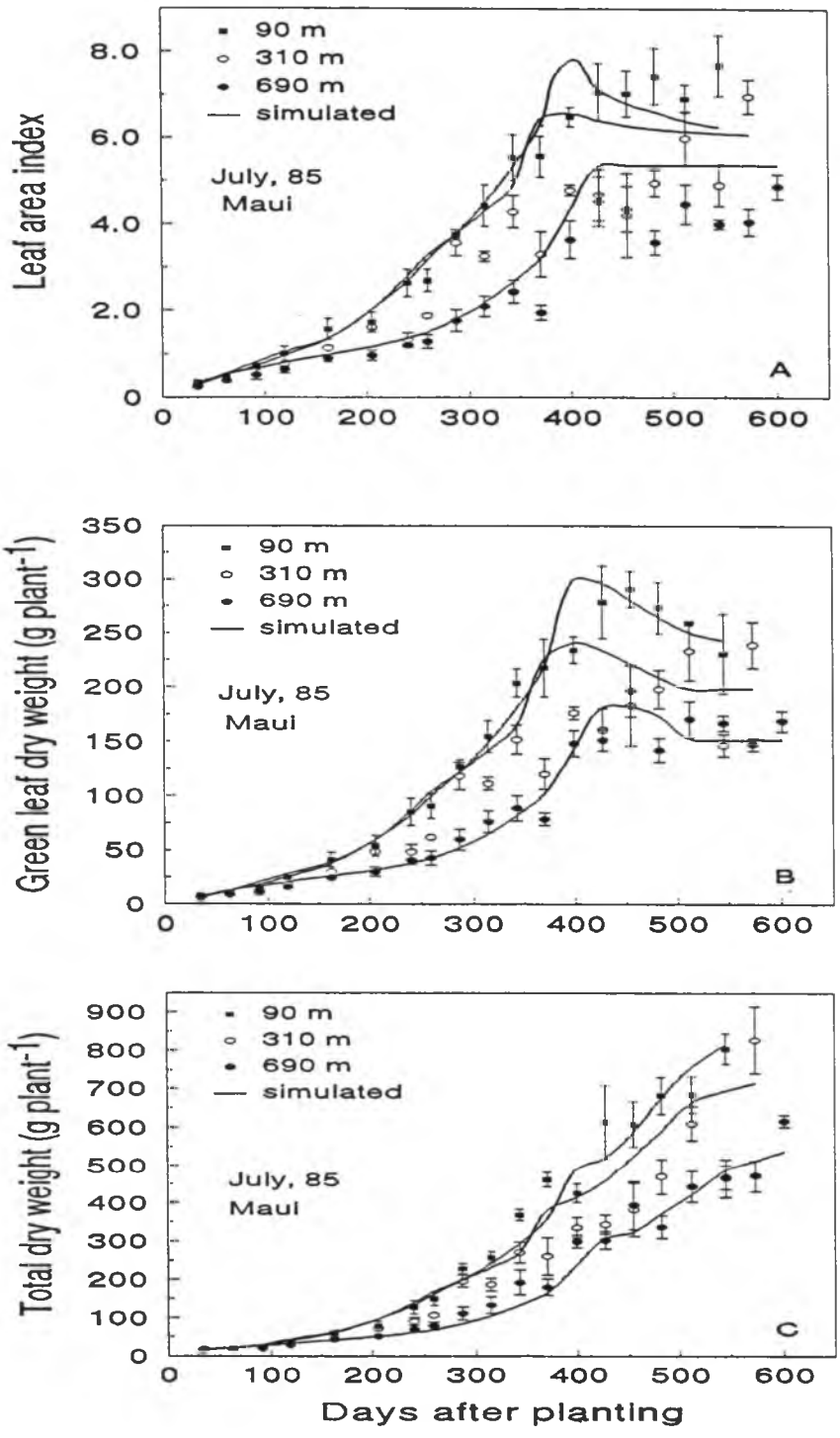


Fig. 7.11 Simulated and observed leaf area index, green leaf dry weight and total plant dry weight of Smooth Cayenne pineapple planted in July, 1985 at three elevations on Maui, Hawaii. Plants were forced in July, 1986.

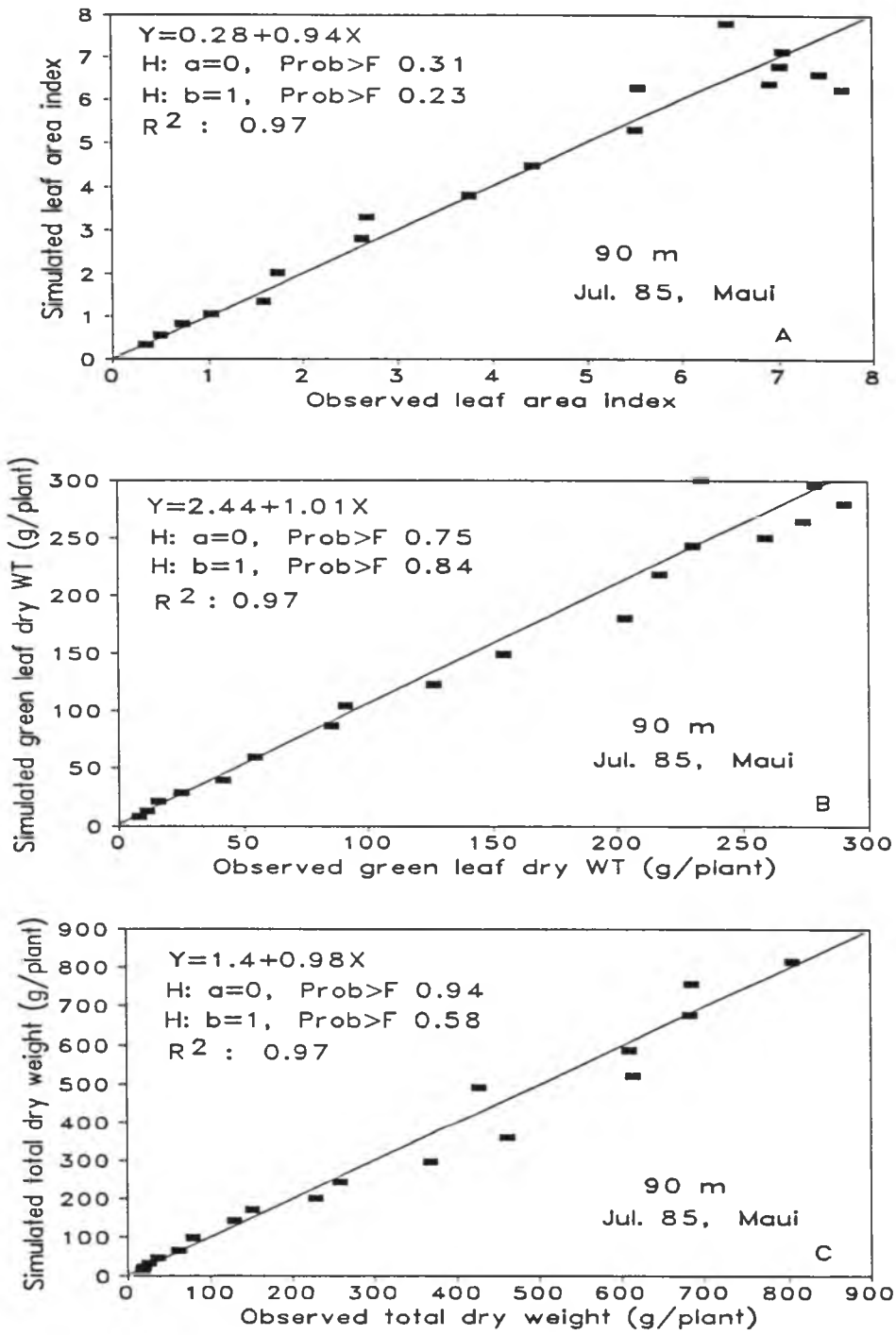


Fig. 7.12 One to one relationship between simulated and observed leaf area index, green leaf dry weight and total plant dry weight of Smooth Cayenne pineapple planted in July, 1985 at 90 meters above sea level on Maui. Plants were forced in July, 1986.

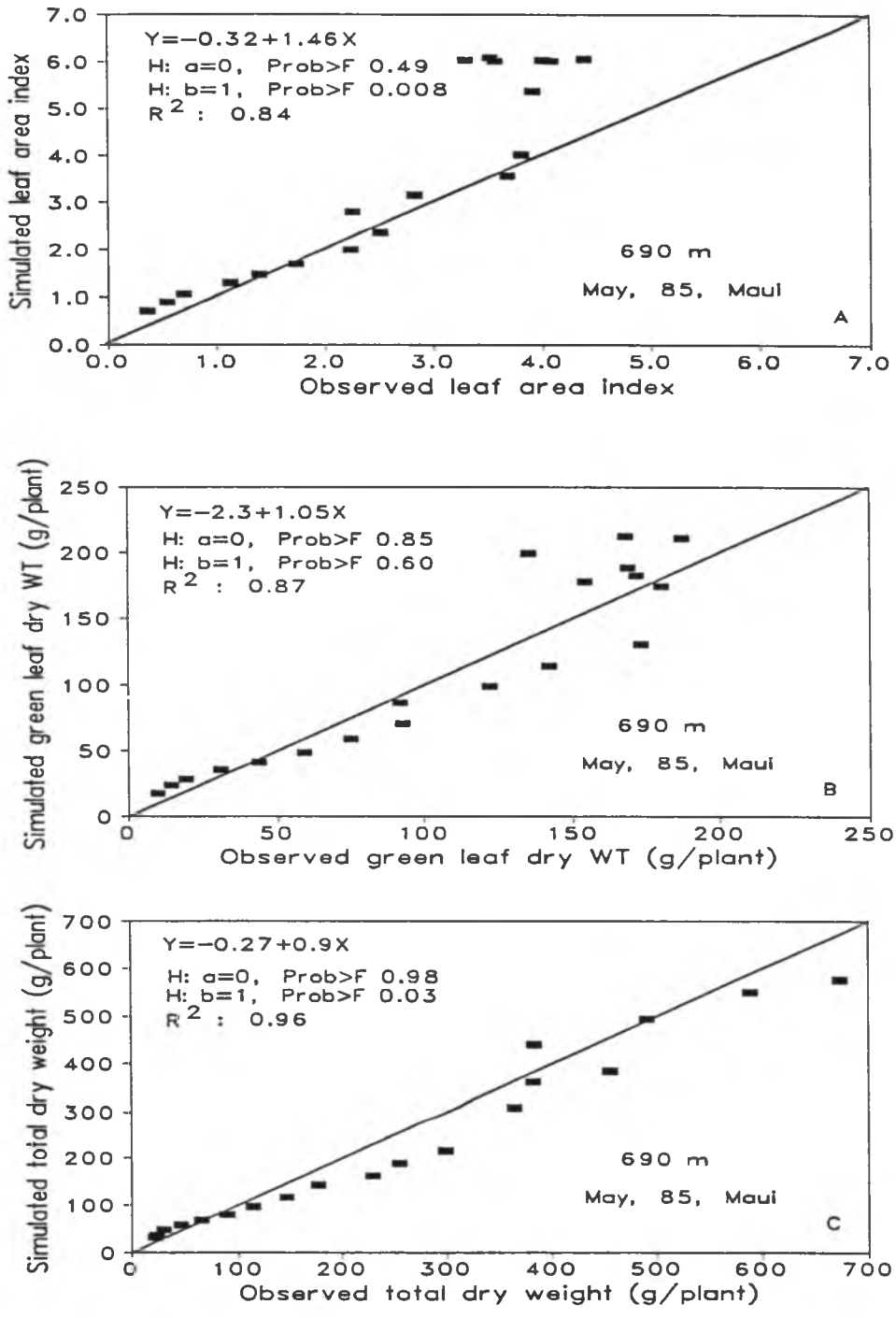


Fig. 7.13 One to one relationship between simulated and observed leaf area index, green leaf dry weight and total plant dry weight of Smooth Cayenne pineapple planted in May, 1985 at an elevation of 690 meters above sea level on Maui. Plants were forced in May, 1986.

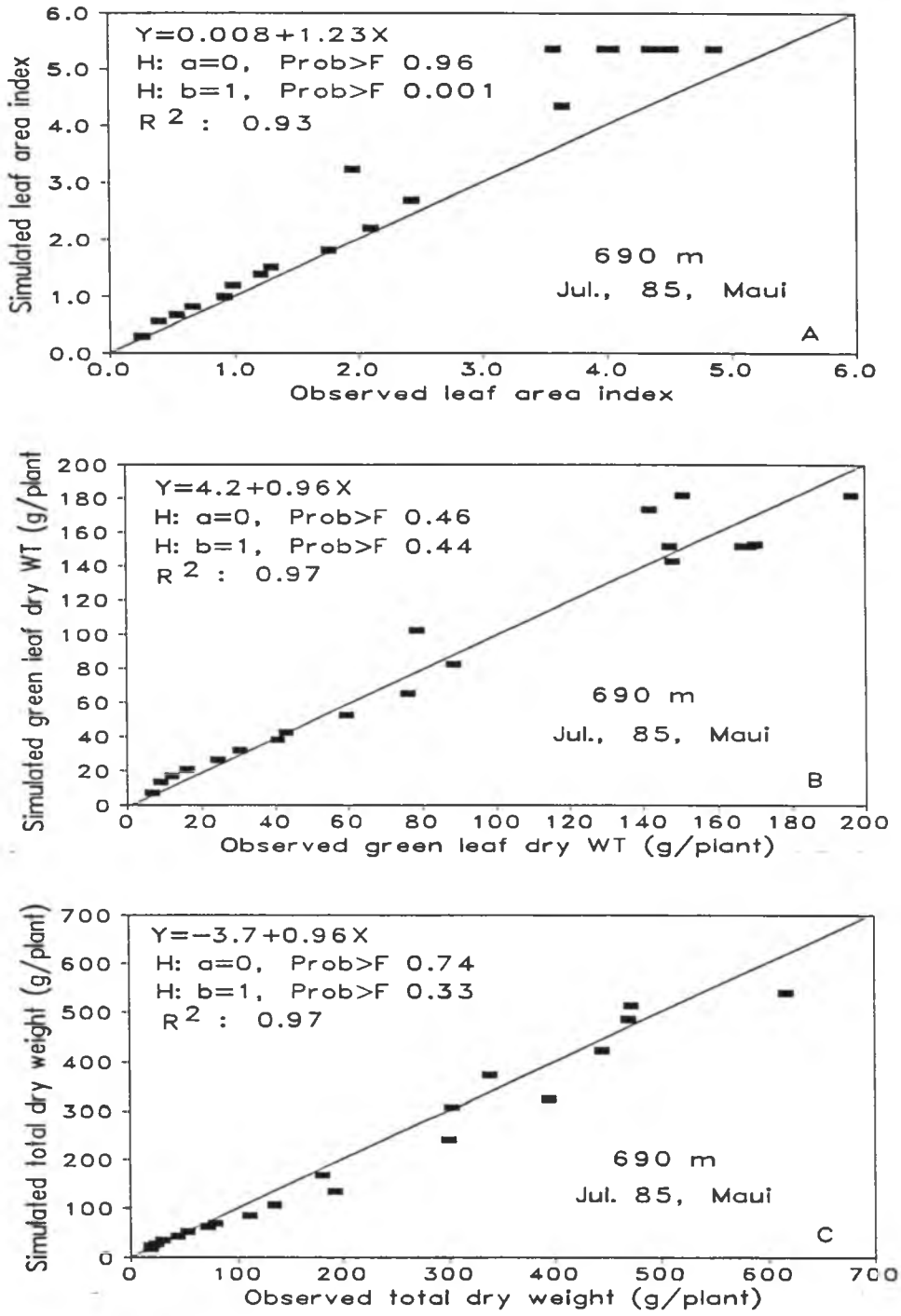


Fig. 7.14 One to one relationship between simulated and observed leaf area index, green leaf dry weight and total plant dry weight of Smooth Cayenne pineapple planted in July, 1985 at an elevation of 690 meters above sea level on Maui. Plants were forced in July, 1986.

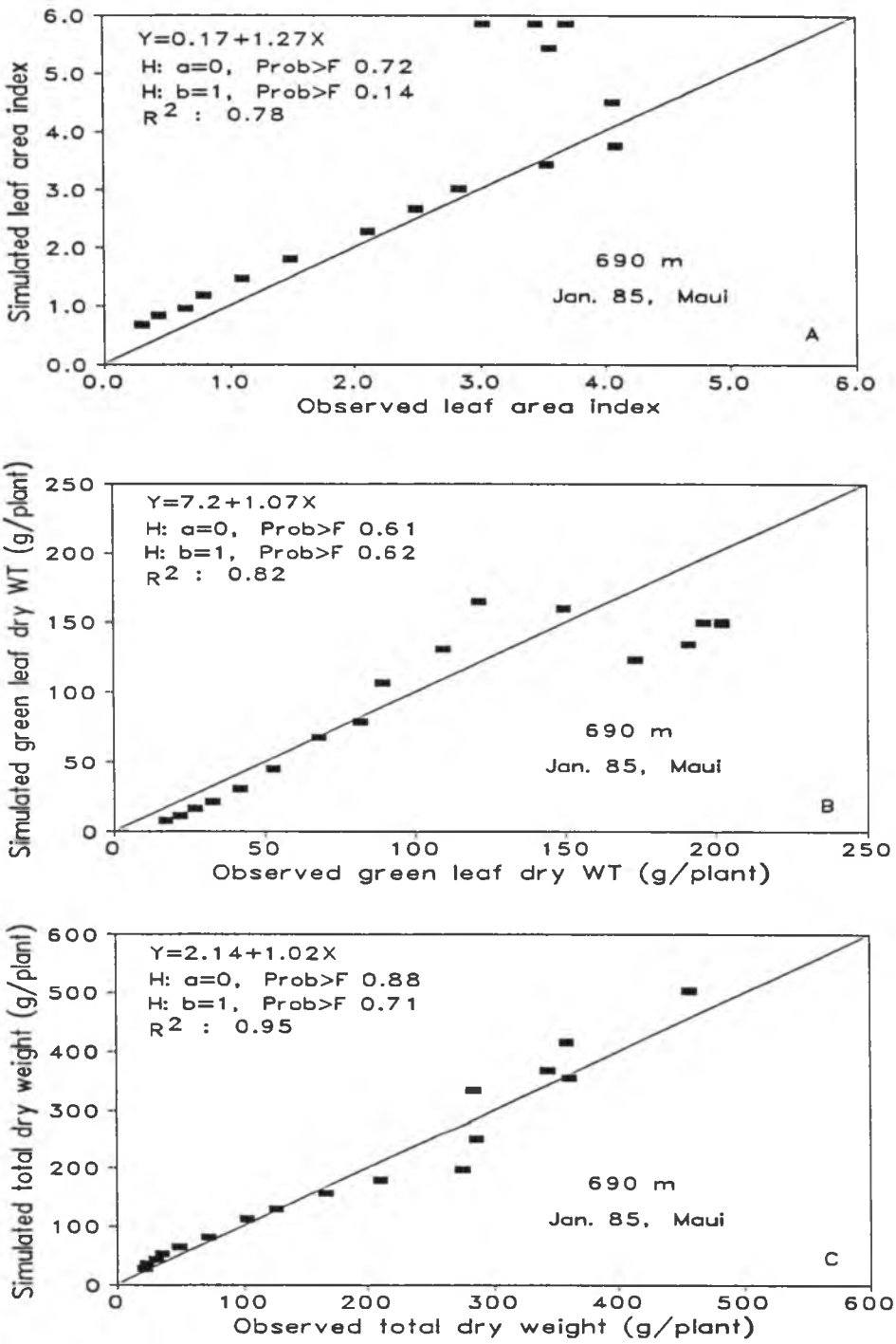


Fig. 7.15 One to one relationship between simulated and observed leaf area index, green leaf dry weight and total plant dry weight of Smooth Cayenne pineapple planted in January, 1985 at an elevation of 690 meters above sea level on Maui. Plants were forced in January, 1985.

7.10B and 7.11B). There was good agreement between the simulated and the observed data for the January and May planting at 690 m, and the July plantings at 90 and 690 m (Fig. 7.12B, 7.13B, 7.14B, and 7.15B). Regressing simulated against observed data resulted in intercepts of 2.44, 4.2, -2.3, and 7.2, which were not significantly different from zero, and slopes of 1.01, 0.96, 1.05, and 1.07, which were not significantly different from unity (Fig. 7.12B, 7.13B, 7.14B, and 7.15B). The model over-predicted green leaf dry weight for the rest of the plantings on Maui (Fig. 7.9B, 7.10B and 7.11B).

Total Plant Weight

The model generally predicted total plant weight accumulation well for the two plantings at Kunia (Fig. 7.5C and 7.6C) although weight was somewhat overestimated at 550 days after planting. The regressions of simulated vs. observed total plant weight resulted in intercepts that were significantly different from zero, and slopes that were significantly different from unity (Fig. 7.7C and 7.8C). The relatively small deviation of the slopes from unity is most likely due to the overestimation of total plant weight of the lowest plant population density at the fruit harvest stage.

For the Maui data, the model over-predicted total plant weight for all plantings grown at 310 m and for the January and May plantings grown at 90 m (Fig. 7.9C, 7.10C and 7.11C). The slopes of regressions of the simulated against observed data for those plantings were significantly greater than unity (Fig. 7.13C). The model under-predicted total plant weight for the May planting grown at 690 m. (Fig. 7.10C). The slopes of regressions of the simulated against observed data for those

plantings were significantly less than unity (results not shown). The model accurately predicted total plant weight for the January planting at 690 m and for the July plantings at 90 and 690 m (Fig. 7.9C and 7.11C). Regressing the simulated against the observed data for the January planting at 690 m and the July planting at 90 and 690 m resulted in intercepts that were not significantly different from zero and slopes that were not significantly different from the unity (Fig. 7.12C, 7.14C and 7.15C).

7.3.2 Discussion

Dates of Forcing

Accurate prediction of forcing date requires accurate weather data, an accurate estimation of total plant dry weight at the time of forcing, and correct adjustment of the parameter P6, which is the number of days from root initiation to emergence of the first new leaf. In ALOHA-Pineapple, forcing date is determined by total plant dry weight (see Chapter 6, Model Description). When total plant dry weight is greater than or equal to PlantSize, which during validation was set equal to the actual total plant dry weight at forcing for an experiment, forcing occurs. If the observed total plant dry weight is overestimated, it will take more days to reach the specific plant size. The forcing date will be delayed by the model. A smaller or larger P6 will over or under estimate total plant weight accumulation, resulting in an advance or delay in the predicted forcing date. The parameter P6 is assumed to be influenced by type of planting materials, the water status of the plant material, and the soil water content after planting. The model at this stage does not consider those factors, but P6 can be calibrated with data from field experiments.

The mean difference between the simulated and the observed forcing date of Maui plantings was lower, but the standard error of the difference was higher than that for the Kunia plantings (Table 7.7 and 7.8). The higher mean difference for the Kunia plantings was due to the overprediction of the interval between planting and forcing at the lowest and highest plant population densities. This overprediction of the interval from planting to forcing was probably due to the overestimation of the actual total plant dry weight at forcing. The over or under estimation of actual total plant weight at forcing will delay or advance the forcing date predicted by ALOHA-Pineapple because the forcing date is determined by the model when a previously specified plant weight is reached. The overprediction of forcing date possibly was also due to fact that the quantitative relationships between plant population and plant growth and phenological development used by the model do not work well at the lower and upper limits of the plant population ranges used in the study.

The high standard error of the mean of the difference for forcing date for the Maui plantings was due to the underprediction of the interval from planting to forcing at the of 310 m elevation and overprediction at the 690 m. The reasons why the model predicts date of forcing well for some tests but not for others is not known.

Fruit Harvest Date

Accurate prediction of fruit harvest date, the date when 10 percent of the fruit ripen, requires accurate prediction of forcing date, accurate air temperatures and correct adjustment of a cultivar-specific parameter P4. Overprediction of the interval from planting to fruit harvest for the Kunia plantings were mostly due to

overprediction of forcing dates (Table 7.7 and 7.9). Underpredictions of the interval from planting to fruit harvest date for the Maui test at 310 m and the overpredictions at 690 m were most likely due to the underpredictions of interval from planting to forcing at 310 m and overpredictions of the interval at 690 m, and also due to incorrect adjustment of P4 (Table 7.8 and 7.10). The value for P4 of 2904 °C-days was obtained by calibration using the Kunia data. Maximum yields at Kunia generally were less than those obtained on Maui. If growth at Kunia was subnormal, it may be that the value used in the model was larger than it should have been for the Maui data.

Fruit Physiological Maturity

Accurate prediction of date of fruit physiological maturity, the date when 95 percent of the fruits are harvested, requires accurate prediction of forcing and fruit harvest date, accurate air temperatures and correct adjustment of a cultivar-specific parameter P5. Overpredictions of the interval from planting to fruit physiological maturity for the Kunia plantings likely were due to the delay in forcing dates predicted by the model (Table 7.7 and 7.11).

Fruit Yield

Accurate prediction of fruit yield requires accurate prediction of **leaf area index,** accurate **solar radiation** data during the period from forcing to the end of fruitlet initiation, accurate **air temperatures** during reproductive development, correct adjustment of the **ConvertCoefficient,** and the cultivar-specific parameters **G2** and **G3**. The parameter G2 is potential maximum number of eyes per fruit and G3 is

maximum rate of dry matter partitioning to the eyes (Chapter 6, Model Description).

The model accurately predicted the fruit yield for the Kunia plantings (Table 7.12) but greatly underpredicted the fruit yield by 20 percent of the observed value for the Maui plantings (Table 7.13). The underpredictions of the fruit yield were possibly due to the lower ConvertCoefficient and the lower G3 used in model. The ConvertCoefficient and G3 may have been too low because they were calibrated to the data collected from Kunia, where the yield at 5.22 and 7.83 plants ha^{-1} (Table 7.6) was somewhat to much lower than the yield on Maui at a plant population density of 5.4 plants m^{-2} (Table 7.14). Maui data represents both warmer and cooler sites than Kunia. The reasons for the discrepancies need to be studied.

Leaf Area Index

Accurate prediction of leaf area index (LAI) is very important because accurate prediction of potential carbohydrate production and fruit yield depends on LAI. Accurate prediction of LAI requires accurate weather data, and correct adjustment of P6. LAI was underestimated consistently at the highest plant population for the Kunia plantings over the course of plant cycle (Fig. 7.5A and 7.6A). This may be because the quantitative relationships between plant population and the ratio of leaf area to leaf number used by the model does not work well at high plant populations when plants are small at forcing. The overpredictions of LAI during the reproductive phase for the Maui plantings at 690 m were due to the overprediction of forcing dates, which shifted the LAI peaks to the right (Fig. 7.9A, 7.10A and 7.11A). The overpredictions of LAI for the Maui plantings at 310 m were probably

because the value of P6 was smaller than it should have been. The LAI for the January and May plantings at 90 m on Maui were consistently over predicted over the course of the plant cycle, suggesting that the simulated LAI could be adjusted to match the observed data by using a larger value for P6 (Fig. 7.9A, 7.10A and 7.11A).

Green Leaf Weight

Accurate simulation of green leaf weight will lead to the accurate simulation of total plant weight, leading to the accurate prediction of dates of forcing, fruit harvest and physiological maturity, and fruit yield. Accurate prediction of green leaf weight requires accurate weather data, correct adjustment of the parameter P6 and the base temperature (Tbase). The model accurately predicted green leaf weight accumulation for Kunia plantings (Fig.7.5B and 7.6B). The probable causes for the overpredictions of green leaf weight for the Maui plantings are similar to those LAI because green leaf weight and LAI are closely related.

Total Plant Weight

Evaluating the model's ability to predict total plant weight is an overall evaluation of the model quality. Generally, the model predicted total plant weight more accurately than it did each component. The overestimation of total plant weight at the lowest plant population for the Kunia plantings suggests that the quantitative relationships between plant population and growth used in the model does not work well at very low plant populations. Consistent overpredictions of LAI, green leaf weight and total plant weight for Maui plantings suggests that not only was the value

of P6 too small but factors other than water and nitrogen need to be considered when modeling pineapple growth. Plant growth at 310 m on Maui was much less than that at 90 m even though the air temperature and solar radiation means were similar (Fig. 7.9C, 7.10C and 7.11C). The underpredictions of total plant weight at the higher elevations were due to the underestimations of stem weight (data not shown).

In summary, generally, the model accurately predicted dates of forcing, fruit harvest and physiological maturity, fruit yield, leaf area index and dry matter production for Kunia and for some Maui conditions. The model did not simulate plant growth and development well at low or high plant populations. The underpredictions or overpredictions of plant growth and development for the Maui plantings were mostly due to the lack of knowledge about the proper value for the parameter P6 in different experiments, possible other inadequacies of the model, and perhaps errors in data collection.

CHAPTER 8

SUMMARY AND CONCLUSION

A summary and conclusions for both data collection and modeling sections of the dissertation are presented here.

8.1 RESPONSE OF PINEAPPLE TO PLANT POPULATION DENSITY AND PLANTING DATE

8.1.1 Leaf Emergence

Increasing plant population density significantly reduced the rate of leaf emergence of 'Smooth Cayenne' pineapple. Leaf emergence decreased about 0.9 leaves per 1000 degree-days with each increase in population of one plant m^{-2}, beginning about 200 days after planting in this study. It was suspected that the decline in leaf emergence rate was due to the decrease in the growing point temperature caused by intense mutual shading at the higher plant population densities. Therefore, it would be better if thermal time, which is calculated from air temperature, is modified by a coefficient to correct for plant population effects in order to accurately predict pineapple leaf emergence.

8.1.2 Canopy Development and Light Interception

Leaf area (LA) per plant and leaf area index (LAI) increased with time and with increasing plant population density. Before about 200 days after planting, for a given time, leaf area per plant was constant over PPDs and leaf area index was a linear function of PPDs. Thereafter, leaf area declined and leaf area index increased

curvilinearly as plant population density increased. Maximum LAIs were obtained at the time of forcing at the higher PPDs and earlier planting dates. Light interception increased with increasing time and plant population density, but the relationship between the fraction of light intercepted and leaf area index was exponential. This relationship and the decline in LAI after a maximum was attained demonstrated that inter-plant competition began to occur by or before 200 days after planting, but become more intense after that time.

8.1.3 Vegetative Growth and Dry Matter Partitioning

Dry matter accumulation of 'Smooth Cayenne' pineapple varied substantially over plant population densities and planting dates. This was due to the decline in net assimilation rate during vegetative growth as PPD increased and to the differences in the initial size of the planting material and growth duration. Dry matter was partitioned more to leaves during vegetative growth and then more to inflorescence and stem during reproductive development. The proportion of dry matter partitioned to leaves during vegetative growth was not significantly affected by PPDs. The proportion of dry matter partitioned to stem during reproductive growth decreased linearly and dry matter partitioning to fruit increased curvilinearly as PPD increased and as planting date was delayed. The ratio leaf area per plant:number of leaves per plant was highly correlated with leaf number up to forcing, and the relationship was not significantly influenced by PPDs or planting dates.

8.1.4 Reproductive Development and Yield

Fruit development rate declined curvilinearly as plant population density

increased but was not significantly affected by plant size (planting date) within a plant population density. Fruit harvest date was delayed about seven days for each increase in population of 2.5 plants m^{-2} over the population range of the study. Average fruit weight decreased significantly with increasing plant population density and decreasing plant size within a population. The larger the plants at forcing, the higher the average fruit weight. Plants in lower plant populations and earlier plantings produced more larger (2.5T) fruits and fewer smaller sized fruits (1T and S1T). Fruit yield (all fruits) per unit area increased curvilinearly with increasing plant population, showing an asymptotic relationship, but the yield response curve for each fruit size and plant population density relationship was parabolic. It is concluded that fruit development rate was influenced not only by air temperature and time but also by plant population density.

8.2 SIMULATION OF PINEAPPLE GROWTH AND DEVELOPMENT

A simulation model of pineapple growth and development (ALOHA-Pineapple) was developed, based on the CERES-Maize model structure, a heat unit model for pineapple inflorescence development, and data collected from the population trial described above. ALOHA-Pineapple is process-oriented and incremented daily. It has the potential to simulate the effects of cultivars, though data for cultivars other than Smooth Cayenne are likely unavailable, planting date, plant population density, plant size at planting and at forcing, and weather on pineapple crop growth, development and fruit yield. The soil water and nitrogen subroutines of CERES-

Maize remain in the model but have not been adapted for pineapple. The model uses the IBSNAT minimum data set and runs alone or under the DSSAT shell (IBSNAT, 1989).

ALOHA-Pineapple accurately predicted dates of forcing, fruit harvest and physiological maturity, leaf area index, dry matter production and fruit yield for the Kunia experiments and some Maui experiments. The model underpredicted dry weight accumulation, causing a delay in predicted forcing date of three to four weeks for the lower and upper limits of plant population at Kunia. The model under or over predicted growth and development for some Maui experiments. These were assumed to be mostly due to the variability in the parameter P6 and improper base temperature for cool areas, and possible errors in estimating growth.

In conclusion, ALOHA-Pineapple is able to simulate pineapple growth and development with reasonable accuracy. Prediction errors in time have been reduced to less than two weeks for Kunia conditions and some Maui conditions. ALOHA-Pineapple is semi-emperical, especially in handling plant population density effect. The variability in prediction can be reduced and prediction accuracy can be improved by refining the model using data from wide range of environments or by handling plant population effect mechanistically. In addition, ALOHA-Pineapple provides a frame-work for further pineapple research and a decision aid for pineapple farmers. Other models describing interactions between insect pests, nematodes, and diseases and pineapple crop growth can be linked to ALOHA-Pineapple.

8.3 PROBLEMS IDENTIFIED AND WORK NEEDED

Model development and validation is an iterative process. Every simulation of an experiment will contribute something to ALOHA-Pineapple by adding factors or correcting coefficients or identifying problems in the model. Following are the lists of the problems identified during model development and validation and the suggested work needed for future development.

1. Determination of first leaf emergence. Identify the factors determining the time to root initiation and to emergence of the first new leaf and quantify their effects.
2. Differences among Smooth Cayenne clones, and among cultivars, need to be characterized to account for differences in productivity and ratooning ability known to exist in different regions. If the model is to be extended to other groups (Spanish, Perola, etc.), additional growth data for the important clones will need to be collected.
3. Modeling plant population density effect more mechanistically by using a geometrical light interception model.
4. Development of a submodel describing the interaction between nematodes and crop growth.
5. Formulation of experimental procedures for model validation.
6. Establishment of a collaboration network.

APPENDIX A

RESULTS OF STATISTICAL ANALYSIS

The following are the tables of results of analyses of variance for the dependent variables used in the study. The experiment consists of five plant population densities. The plant population density treatments were replicated three times and arranged in a randomized complete block design. The experiment was planted on three different dates June 15, August 15 and October 18, 1989. All plants were forced on September 18, 1990. Nine, eight, and six biomass harvests were done for Planting 1, 2, and 3, respectively. Depending on the purposes, only subsets of the data were analyzed. Because planting was not replicated and randomized, the results of analysis for the effect of planting date may be bias. The acronyms are P1VOTH, the effect of Planting 1 vs. other plantings, P2V3, Planting 2 vs. Planting 3, TRT, the treatment effect, REP, the replication effect, LACKOFIT, the effect due to lack of fit by the model, and PPD, plant population density.

Table A.1 Analysis of variance for green leaf area per plant (cm^2 $plant^{-1}$) at forcing.

Source	DF	SS	MS	F	F-test†	Estimate
Intercept						15482
Planting	2	41.56	20.78	45.41	**	
P1VOTH	1	37.25	37.25	81.39	**	1340
P2V3	1	4.32	4.32	9.43	**	-1289
REP(Planting)	6	2.75	0.46			
TRT	4	243.15	60.79	79.26	**	
PPD	1	233.01	233.01	303.81	**	-1237
PPD*PPD	1	8.32	8.32	10.81	**	39
LACKOFIT	2	1.82	0.91	1.19	NS	
TRT*Planting	8	18.42	2.30	3.00	*	
P1VOTH*PPD	1	9.37	9.37	12.22	**	- 90
P2V3*PPD	1	5.33	5.33	6.95	**	118
LACKOFIT	6	9.05	1.51	1.97	NS	
ERROR	24	18.41	0.77			
Corrected total	44	324.29				

† * and ** denote significance at the 0.05 and 0.01 level of probability, respectively, and NS indicates the effect was not significant at the 0.05 level of probability.

Table A.2 Analysis of variance for D-leaf dry weight (g leaf^{-1}) at forcing.

Source	DF	SS	MS	F	F-test†	Estimate
Intercept						26.76
Planting	2	188.21	94.10	128.32	**	
P1VOTH	1	126.50	126.51	172.50	**	3.75
P2V3	1	61.71	61.69	84.14	**	-3.76
REP(Planting)	6	4.40	0.70			
TRT	4	785.41	196.40	122.40	**	
PPD	1	744.81	744.81	464.29	**	-2.46
PPD*PPD	1	40.40	40.40	25.18	**	0.086
LACKOFIT	2	0.20	0.10	0.06	NS	
TRT*Planting	8	97.51	12.20	7.60	**	
P1VOTH*PPD	1	47.51	47.50	29.61	**	- 0.2
P2V3*PPD	1	34.90	34.90	21.76	**	0.3
LACKOFIT	6	15.10	2.51	1.57	NS	
ERROR	24	38.51	1.60			
Corrected total	44	1114.0				

† * and ** denote significance at the 0.05 and 0.01 level of probability, respectively, and NS indicates the effect was not significant at the 0.05 level of probability.

Table A.3 Analysis of variance for D-leaf leaf area (cm^2 $leaf^{-1}$) at forcing.

Source	DF	SS	MS	F	F-test†	Estimate
Intercept						1084
Planting	2	29.42	14.71	137.22	**	108
P1VOTH	1	19.72	19.72	183.99	**	- 147
P2V3	1	9.70	9.70	90.46	**	
REP(Planting)	6	0.64	0.10			
TRT	4	122.14	30.53	123.02	**	- 96
PPD	1	115.97	115.97	467.23	**	3.3
PPD*PPD	1	6.15	6.15	24.78	**	
LACKOFIT	2	0.01	0.01	0.03	NS	
TRT*Planting	8	14.88	1.86	7.49	**	- 8
P1VOTH*PPD	1	7.26	7.26	29.26	**	12
P2V3*PPD	1	5.26	5.26	21.20	**	
LACKOFIT	6	2.35	0.39	1.58	NS	
ERROR	24	5.96	0.25			
Corrected total	44	173.03				

† * and ** denote significance at the 0.05 and 0.01 level of probability, respectively, and NS indicates the effect was not significant at the 0.05 level of probability.

Table A.4 Analysis of variance for green leaf dry weight (g plant^{-1}) at forcing.

Source	DF	SS	MS	F	F-test†	Estimate
Intercept						348
Planting	2	26.93	13.47	110.99	**	
P1VOTH	1	24.16	24.16	199.10	**	35.9
P2V3	1	2.78	2.78	22.88	**	-32.34
REP(Planting)	6	0.73	0.12			
TRT	4	131.50	32.88	131.13	**	
PPD	1	124.13	124.13	495.13	**	-32.39
PPD*PPD	1	7.24	7.24	28.89	**	1.15
LACKOFIT	2	0.12	0.06	0.25	NS	
TRT*Planting	8	12.72	1.59	6.34	**	
P1VOTH*PPD	1	7.39	7.39	29.46	**	- 2.54
P2V3*PPD	1	3.33	3.33	13.27	**	2.95
LACKOFIT	6	2.00	0.33	1.33	NS	
ERROR	24	6.02	0.25			
Corrected total	44	177.89				

† * and ** denote significance at the 0.05 and 0.01 level of probability, respectively, and NS indicates the effect was not significant at the 0.05 level of probability.

Table A.5 Analysis of variance for stem dry weight per plant (g plant^{-1}) at forcing.

Source	DF	SS	MS	F	F-test†	Estimate
Intercept						72.71
Planting	2	33.48	16.74	31.68	**	
P1VOTH	1	31.83	31.83	60.25	**	15.21
P2V3	1	1.65	1.65	3.12	**	- 7.74
REP(Planting)	6	3.17	0.53			
TRT	4	63.53	15.88	25.01	**	
PPD	1	57.75	57.75	90.94	**	- 7.68
PPD*PPD	1	4.70	4.70	7.40	**	0.29
LACKOFIT	2	1.08	0.54	0.85	NS	
TRT*Planting	8	23.15	2.89	4.56	*	
P1VOTH*PPD	1	16.59	16.59	26.13	**	- 1.2
P2V3*PPD	1	1.87	1.87	2.94	*	0.7
LACKOFIT	6	4.69	0.78	1.23	NS	
ERROR	24	15.24	0.63			
Corrected total	44	138.58				

† * and ** denote significance at the 0.05 and 0.01 level of probability, respectively, and NS indicates the effect was not significant at the 0.05 level of probability.

Table A.6 Analysis of variance for total plant dry weight (g plant^{-1}) at forcing.

Source	DF	SS	MS	F	F-test†	Estimate
Intercept						544.08
Planting	2	91.02	45.51	126.83	**	
P1VOTH	1	83.78	83.78	233.49	**	69.35
P2V3	1	7.24	7.24	20.17	**	-53.77
REP(Planting)	6	2.15	0.36			
TRT	4	314.19	78.55	115.48	**	
PPD	1	296.43	296.43	435.80	**	-50.37
PPD*PPD	1	17.69	17.69	26.01	**	1.8
LACKOFIT	2	0.07	0.03	0.05	NS	
TRT*Planting	8	45.25	5.66	8.32	**	
P1VOTH*PPD	1	29.16	29.16	42.87	**	- 5.04
P2V3*PPD	1	9.42	9.42	13.85	**	4.96
LACKOFIT	6	6.67	1.11	1.63	NS	
ERROR	24	16.33	0.68			
Corrected total	44	468.94				

† * and ** denote significance at the 0.05 and 0.01 level of probability, respectively, and NS indicates the effect was not significant at the 0.05 level of probability.

Table A.7 Analysis of variance for relative growth rate (RGR, g g-1 day-1) during vegetative growth for Planting 1 and 2.

Source	DF	SS	MS	F	F-test†	Estimate
Intercept						0.0089
Planting	1	0.00	0.00	0.00	NS	
REP(Planting)	4	0.12	0.03			
TRT	4	17.04	4.26	56.67	**	
PPD	1	16.66	16.66	226.67	**	0.00021
LACKOFIT	3	0.38	0.13	1.73	NS	
TRT*Planting	4	0.19	0.048	0.63	NS	
ERROR	16	1.20	0.075			
Corrected total	29	18.55				

† * and ** denote significance at the 0.05 and 0.01 level of probability, respectively, and NS indicates the effect was not significant at the 0.05 level of probability.

Table A.8 Analysis of variance for net assimilation rate (NAR, g m^{-2} day^{-1}) during vegetative growth for Planting 1 and 2.

Source	DF	SS	MS	F	F-test†	Estimate
Intercept						0.00031
Planting	1	0.84	0.84	14.11	**	5.3E-06
REP(Planting)	4	0.24	0.06			
TRT	4	28.00	7.00	35.00	**	
PPD	1	26.90	26.90	134.50	**	-1.6E-05
PPD*PPD	1	0.87	0.87	4.36	*	4.88E-07
LACKOFIT	2	1.10	0.55	2.75	NS	
TRT*Planting	4	0.13	0.03	0.16	NS	
ERROR	16	3.20	0.20			
Corrected total	29	32.40				

† * and ** denote significance at the 0.05 and 0.01 level of probability, respectively, and NS indicates the effect was not significant at the 0.05 level of probability.

Table A.9 Analysis of variance for leaf area partition coefficient (LAPC) during vegetative growth for Planting 1 and 2.

Source	DF	SS	MS	F	F-test†	Estimate
Intercept						25.99
Planting	1	5.72	5.72	1.57	NS	
REP(Planting)	4	14.56	3.64			
TRT	4	37.01	9.25	2.24	NS	0.16
TRT*Planting	4	12.06	3.02	0.73	NS	
ERROR	16	66.19	4.14			
Corrected total	29	135.55				

† * and ** denote significance at the 0.05 and 0.01 level of probability, respectively, and NS indicates the effect was not significant at the 0.05 level of probability.

Table A.10 Analysis of variance for specific leaf area extension (SLAE) during vegetative growth for Planting 1 and 2.

Source	DF	SS	MS	F	F-test†	Estimate
Intercept						41.31
Planting	1	0.43	0.43	0.06	NS	
REP(Planting)	4	31.22	7.81			
TRT	4	72.90	18.23	3.53	*	
PPD	1	31.25	31.25	6.06	*	0.29
LACKOFIT	3	41.65	13.88	2.69	NS	
TRT*Planting	4	24.17	6.04	1.17	NS	
ERROR	16	82.49	5.16			
Corrected total	29	211.20				

† * and ** denote significance at the 0.05 and 0.01 level of probability, respectively, and NS indicates the effect was not significant at the 0.05 level of probability.

Table A.11 Analysis of variance for green leaf weight partition coefficient (LWPC) during vegetative growth for Planting 1 and 2.

Source	DF	SS	MS	F	F-test†	Estimate
Intercept						0.63
Planting	1	0.43	0.43	26.06	**	-0.012
REP(Planting)	4	0.07	0.02			
TRT	4	0.07	0.02	0.56	NS	0.0...37
TRT*Planting	4	0.12	0.03	0.92	NS	
ERROR	16	0.52	0.03			
Corrected total	29	1.20				

† * and ** denote significance at the 0.05 and 0.01 level of probability, respectively, and NS indicates the effect was not significant at the 0.05 level of probability.

Table A.12 Analysis of variance for leaf basal tissue weight partition coefficient (BLWPC) during vegetative growth for Planting 1 and 2.

Source	DF	SS	MS	F	F-test†	Estimate
Intercept						50.3
Planting	1	0.03	0.03	1.79	NS	
REP(Planting)	4	0.06	0.01			
TRT	4	0.23	0.06	4.09	*	
PPD	1	0.18	0.18	12.80	**	0.51
LACKOFIT	3	0.05	0.02	1.19	NS	
TRT*Planting	4	0.03	0.01	0.49	NS	
ERROR	16	0.22	0.01			
Corrected total	29	0.55				

† * and ** denote significance at the 0.05 and 0.01 level of probability, respectively, and NS indicates the effect was not significant at the 0.05 level of probability.

Table A.13 Analysis of variance for stem weight partition coefficient (SWPC) during vegetative growth for Planting 1 and 2.

Source	DF	SS	MS	F	F-test†	Estimate
Intercept						0.136
Planting	1	0.71	0.71	25.82	**	0.016
REP(Planting)	4	0.11	0.03			
TRT	4	0.27	0.07	3.09	*	
PPD	1	0.15	0.15	6.63	*	0.0019
LACKOFIT	3	0.13	0.04	1.90	NS	
TRT*Planting	4	0.11	0.03	1.26	NS	
ERROR	16	0.35	0.02			
Corrected total	29	1.56				

† * and ** denote significance at the 0.05 and 0.01 level of probability, respectively, and NS indicates the effect was not significant at the 0.05 level of probability.

Table A.14 Analysis of variance for leaf area-plant dry weight ratio (LAR) during vegetative growth for Planting 1 and 2.

Source	DF	SS	MS	F	F-test†	Estimate
Intercept						31.1
Planting	1	17.70	17.70	18.34	**	-0.769
REP(Planting)	4	3.90	1.00			
TRT	4	48.10	12.00	6.02	**	
PPD	1	39.90	39.90	19.96	**	0.323
LACKOFIT	3	8.20	2.7	1.37	NS	
TRT*Planting	4	4.10	1.00	0.51	NS	
ERROR	16	32.00	2.00			
Corrected total	29	105.80				

† * and ** denote significance at the 0.05 and 0.01 level of probability, respectively, and NS indicates the effect was not significant at the 0.05 level of probability.

Table A.15 Analysis of variance for specific leaf area ratio (SLAR) during vegetative growth for Planting 1 and 2.

Source	DF	SS	MS	F	F-test†	Estimate
Intercept						50.3
Planting	1	6.7	6.7	2.11	NS	
REP(Planting)	4	12.7	3.2			
TRT	4	114.9	28.7	11.07	*	
PPD	1	99.8	99.8	38.48	*	0.51
LACKOFIT	3	15.1	5.0	1.94	NS	
TRT*Planting	4	5.7	1.4	0.55	NS	
ERROR	16	41.5	2.6			
Corrected total	29	181.6				

† * and ** denote significance at the 0.05 and 0.01 level of probability, respectively, and NS indicates the effect was not significant at the 0.05 level of probability.

Table A.16 Analysis of variance for green leaf weight ratio (LWR) during vegetative growth for Planting 1 and 2.

Source	DF	SS	MS	F	F-test†	Estimate
Intercept						
Planting	1	0.23	0.23	46.00	**	
REP(Planting)	4	0.02	0.01			
TRT	4	0.01	0.00	0.25	NS	
TRT*Planting	4	0.03	0.01	0.83	NS	
ERROR	16	0.16	0.01			
Corrected total	29	0.46				

† * and ** denote significance at the 0.05 and 0.01 level of probability, respectively, and NS indicates the effect was not significant at the 0.05 level of probability.

Table A.17 Analysis of variance for basal leaf weight ratio (BLWR) during vegetative growth for Planting 1 and 2.

Source	DF	SS	MS	F	F-test†	Estimate
Intercept						
Planting	1	0.03	0.03	2.27	*	
REP(Planting)	4	0.04	0.01			
TRT	4	0.01	0.00	0.59	NS	
TRT*Planting	4	0.00	0.00	0.13	NS	
ERROR	16	0.09	0.01			
Corrected total	29	0.17				

† * and ** denote significance at the 0.05 and 0.01 level of probability, respectively, and NS indicates the effect was not significant at the 0.05 level of probability.

Table A.18 Analysis of variance for stem weight ratio (SWR) during vegetative growth for Planting 1 and 2.

Source	DF	SS	MS	F	F-test†	Estimate
Intercept						
Planting	1	0.42	0.42	40.98	**	
REP(Planting)	4	0.04	0.01			
TRT	4	0.06	0.02	3.00	NS	
TRT*Planting	4	0.04	0.01	1.75	NS	
ERROR	16	0.08	0.01			
Corrected total	29	0.64				

† * and ** denote significance at the 0.05 and 0.01 level of probability, respectively, and NS indicates the effect was not significant at the 0.05 level of probability.

Table A.19 Analysis of variance for stem-plant dry weight ratio at fruit harvest (HSWR) (g/g).

Source	DF	SS	MS	F	F-test†	Estimate
Intercept						0.213
Planting	2	0.48	0.24	4.65	*	
P1VOTH	1	0.43	0.43	8.32	*	0.025
P2V3	1	0.05	0.05	0.97	NS	
REP(Planting)	6	0.31	0.05			
TRT	4	2.02	0.51	8.36	*	
PPD	1	1.83	1.83	30.29	**	-0.0056
LACKOFIT	3	0.19	0.06	1.57	NS	
TRT*Planting	8	1.23	0.15	2.54	*	
P1VOTH*PPD	1	0.61	0.61	10.10	**	-0.0023
LACKOFIT	7	0.62	0.09	1.71	NS	
ERROR	24	1.45	0.06			
Corrected total	44	5.49				

† * and ** denote significance at the 0.05 and 0.01 level of probability, respectively, and NS indicates the effect was not significant at the 0.05 level of probability.

Table A.20 Analysis of variance for fresh fruit-plant dry weight ratio at fruit harvest (HFWR) (g/g).

Source	DF	SS	MS	F	F-test†	Estimate
Intercept						0.22
Planting	2	0.39	0.20	4.50	NS	
P1VOTH	1	0.38	0.38	8.77	*	-0.016
P2V3	1	0.01	0.01	0.23	NS	
REP(Planting)	6	0.26	0.04			
TRT	4	3.45	0.86	46.00	**	
PPD	1	2.93	2.93	156.27	**	0.022
PPD*PPD	1	0.50	0.50	26.67	**	-0.001
LACKOFIT	2	0.02	0.01	0.53	NS	
TRT*Planting	8	0.40	0.05	2.67	*	
P1VOTH*PPD	1	0.16	0.16	8.53	*	0.001
LACKOFIT	7	0.24	0.03	1.83	NS	
ERROR	24	5.53	0.23			
Corrected total	44	10.20				

† * and ** denote significance at the 0.05 and 0.01 level of probability, respectively, and NS indicates the effect was not significant at the 0.05 level of probability.

Table A.21 Analysis of variance for fruit development rate (day^{-1}) between forcing and harvest for three plantings of pineapple.

Source	DF	SS	MS	F	F-test†	Estimate
Intercept						0.0053
Planting	2	0.094	0.047	4.2	NS	
REP(Planting)	6	0.067	0.011			
TRT	4	1.65	0.41	80.5	**	
PPD	1	1.60	1.60	311.9	**	0.000058
LACKOFIT	3	0.05	0.017	3.3	NS	
TRT*Planting	8	0.24	0.007	1.4	NS	
ERROR	24	0.58	0.005			
Corrected total	44	2.63				

† * and ** denote significance at the 0.05 and 0.01 level of probability, respectively, and NS indicates the effect was not significant at the 0.05 level of probability.

Table A.22 Analysis of variance for fruit development rate (day^{-1}) between forcing and fruit physiological maturity for three plantings of pineapple.

Source	DF	SS	MS	F	F-test†	Estimate
Intercept						0.0047
Planting	2	0.049	0.024	0.71	NS	
REP(Planting)	6	0.21	0.034			
TRT	4	13.1	3.28	63.90	**	
PPD	1	12.6	12.6	245.85	**	0.000092
PPD*PPD	1	0.46	0.46	9.05	**	0.00000291
LACKOFIT	2	0.036	0.018	0.35	NS	
TRT*Planting	8	0.28	0.07	1.37	NS	
ERROR	24	1.23	0.051			
Corrected total	44	14.9				

† * and ** denote significance at the 0.05 and 0.01 level of probability, respectively, and NS indicates the effect was not significant at the 0.05 level of probability.

Table A.23 Analysis of variance for the reciprocal of average fruit weight (Kg^{-1})

Source	DF	SS	MS	F	F-test†	Estimate
Planting	2	0.508	1.96	93.33	**	
REP(Planting)	6	0.128	0.021			
TRT	4	2.629	0.66	140.42	**	
TRT*Planting	8	0.278	0.035	7.45	**	
ERROR	24	0.113	0.0047			
Corrected total	44	3.655				

† * and ** denote significance at the 0.05 and 0.01 level of probability, respectively, and NS indicates the effect was not significant at the 0.05 level of probability.

Table A.24 Analysis of variance for the reciprocal of average fresh fruit weight (Kg^{-1}).

Source	DF	SS	MS	F	F-test†	Estimate
Planting	2	0.312	0.156	13.22	**	
REP(Planting)	6	0.071	0.0118			
TRT	4	1.875	0.469	146.56	**	
TRT*Planting	8	0.177	0.0221	6.9	**	
ERROR	24	0.0768	0.0032			
Corrected total	44	2.511				

† * and ** denote significance at the 0.05 and 0.01 level of probability, respectively, and NS indicates the effect was not significant at the 0.05 level of probability.

APPENDIX B

SOURCE CODE OF SUBROUTINE PHENOL, PHASEI AND GROSUB

********** SUBROUTINE TO CALCULATE PHENOLOGICAL STAGE **********

The phenological stages are not defined as clearly as maize. They are defined to facilitate calculation of leaf production, biomass partitioning, and fruit development. Assumptions are therefore made for each stage accordingly.

```
      SUBROUTINE PHENOL(iret)
$Include: 'pine1.blk'
$Include: 'pine2.Blk'
$Include: 'pine3.Blk'
$Include: 'pine4.Blk'
$Include: 'Ntrc1.Blk'
$Include: 'Ntrc2.Blk'
$Include: 'Predob.Blk'
$Include: 'Comibs.Blk'
$NOTRUNCATE
      Character*29 String(5)
      DATA STRING/
     1 'EMERG-END O STEM GROWTH',
     2 'END ZSG to FORCING',
     3 'FORCING to SCY',
     4 'SCY to EARLY FLOWERING',
     5 'FRUIT ENLARGEMENT '/
      xanc=tanc*100.0
      aptnup=stovn*10*plants
      iret=0
      DTT=TEMPM-TBASE
```

Growing degree day is computed in the next section for different temperature regimes during vegetative stages. TTMP is interpolation of air temperature using 3-hour temperature correction factor (TMFAC(I).

```
      IF (ISTAGE.GE.3.AND.ISTAGE.LT.7) GO TO 150
      IF (TEMPMN.GT.TBASE.AND.TEMPMX.LT.33.) GO TO 200
      IF (TEMPMX.LT.TBASE) DTT=0.0
      IF (DTT.EQ.0.0) GO TO 200
      DTT=0.0
      DO 100 I=1,8
```

```
          TTMP=TEMPMN+TMFAC(I)*(TEMPMX-TEMPMN)
          IF (TTMP.GT.TBASE.AND.TTMP.LE.33.) DTT=DTT+(TTMP-TBASE)/8.0
          IF (TTMP.GT.33.AND.TTMP.LT.44.) DTT=DTT+(34.-TBASE)
     1    *(1.-(TTMP-33.)/10.)/8.
  100 CONTINUE
      GO TO 200
```

DTT is computed for different temperature regimes during the reproductive stages (Fleisch, 1988). DTT is modeified by a multiplier within each temperature range.

```
  150 IF (TEMPM.LT.TBASE) DTT=0.0
      IF (DTT.EQ.0.0) GO TO 200
      IF (TEMPM.LE.13.) THEN
          DTT=DTT*2.03
         ELSEIF (TEMPM.LE.15.) THEN
            DTT=DTT*1.21
             ELSEIF (TEMPM.LE.17.) THEN
                DTT=DTT*1.09
                 ELSEIF (TEMPM.LE.19.) THEN
                    DTT=DTT*1.03
                     ELSEIF (TEMPM.LE.21.) THEN
                        DTT=DTT*1.0
                         ELSEIF (TEMPM.LE.23.) THEN
                            DTT=DTT*0.99
                              ELSEIF (TEMPM.LE.25.) THEN
                                 DTT=DTT*1.0
                                  ELSEIF (TEMPM.LE.27.) THEN
                                     DTT=DTT*1.01
                                      ELSEIF (TEMPM.LE.29.) THEN
                                         DTT=DTT*1.03
                                          ELSEIF (TEMPM.LE.31.) THEN
                                            DTT=DTT*1.08
                                            ELSE
                                            DTT=DTT*1.11
        ENDIF
  200 Continue
      SUMDTT=SUMDTT+DTT
      GO TO (1350,1400,1600,1800,2000,2400,300,800,1200), ISTAGE
C********** DETERMINE PLANTING DATE **********************************
  300 CALL CALDAT  ! convert day of the year to calendar date
  400 FORMAT(1X,I2,1x,a3,F7.0,' PLANTING',15X,F6.0,1X,F5.2,1X,F5.1,2X
     1,F4.2,3(1X,F5.0))
  500 FORMAT(/,'  DATE   CDTT  PHENOLOGICAL STAGE      BIOM    LAI'
     1,' NUPTK   N%   CET  RAIN  PESW')
  550 FORMAT(/,'         c-day                          G/M^2       '
     1,' kg/ha        ---mm----   cm ')
      IF(IPHOUT)WRITE (*,500)
      IF(IPHOUT)WRITE (*,550)
```

```
      IF(IPHOUT)Write (Nout1,500)
      IF(IPHOUT)WRITE (NOUT1,550)
      IF(IPHOUT)WRITE (*,400) nd,month,cumdtt,Biomas,Lai,Aptnup,
     1  Xanc,Cet,CRAIN,PESW
      IF(IPHOUT)Write(Nout1,400)nd,month,cumdtt,Biomas,Lai,Aptnup,
     1  Xanc,Cet,CRAIN,PESW
      NDAP=0.
      CALL PHASEI
      IF (ISWSWB.EQ.0) RETURN  ! No change around here
      CUMDEP=0.
      DO 600 L=1,NLAYR
           CUMDEP=CUMDEP+DLAYR(L)
           IF (SDEPTH.LT.CUMDEP) GO TO 700
  600 CONTINUE
  700 LO=L
      RETURN

C********** DETERMINE ROOT INITIATION DATE **************
C  This stage is defined solely to follow the CERES-MAIZE structure.  It
C does nothing when water balance is off. NDAP is number of days after
C planting
  800 IF (ISWSWB.EQ.0) GO TO 1000
      IF (SW(LO).GT.LL(LO)) GO TO 1000
      SWSD=(SW(LO)-LL(LO))*0.65+(SW(LO+1)-LL(LO+1))*0.35
      NDAP=NDAP+1
      IF (NDAP.LT.40) GO TO 900
      ISTAGE=6
      PLANTS=0.0
      GPP=1.
      FRTWT=0.
      IF(IPHOUT)WRITE(*,3500)
      IF(IPHOUT)Write(Nout1,3500)
      RETURN
  900 IF (SWSD.LT.0.02) RETURN
 1000 CALL CALDAT
      IF (IPHOUT) WRITE (*,1100)nd,month,Cumdtt,Biomas,Lai,Aptnup,
     1  Xanc,Cet,Crain,Pesw
      IF (IPHOUT) WRITE (Nout1,1100)nd,month,Cumdtt,Biomas,Lai,Aptnup,
     1  Xanc,Cet,Crain,Pesw
 1100 Format(1x,i2,1x,a3,f7.0,' ROOT INITIATION',8x,F6.0,1X,F5.2,1X
     1,F5.1,2X,F4.2,3(1X,F5.0))
      CALL PHASEI
      RETURN
C********** DETERMINE FIRST NEW LEAF EMERGENCE DATE ***************
 1200 RTDEP=RTDEP+0.15*DTT ! depth of root is a function of DTT.
      NDAP=NDAP+1
      IF (SUMDTT.LT.P6) RETURN
      CALL CALDAT             ! Call CALDAT to record date of the event
      IF(IPHOUT)WRITE (*,1300)nd,month,Cumdtt,Biomas,Lai,Aptnup,
     1  Xanc,Cet,Crain,Pesw
      IF(IPHOUT)WRITE(nout1,1300)nd,month,Cumdtt,Biomas,Lai,Aptnup,
```

The first new leaf is the first leaf emerged after planting. The date of emergence of the first new leaf is influenced by type of planting material, water status of the planting material and soil water content after planting. No data are available to simulate this process. A parameter P6, which is the cumulative growing degree days after planting, was used to determine the emergence of the first new leaf. The value of P6 was estimated from model calibration.

```
     1  Xanc,Cet,Crain,Pesw
 1300 Format(1x,i2,1x,a3,f7.0,' LEAF EMERGENCE',9x,F6.0,1X,F5.2,1X
     1,F5.1,2X,F4.2,3(1X,F5.0))
      CALL PHASEI
      RETURN
C********** DETERMINE END OF ZERO NET STEM GROWTH *********
```

This stage is defined so stem growth can be calculated. Measurements of pineapple growth indicate that for some unknown period after planting, there is no gain in stem dry weight. A parameter P1, which is the cumulative growing degree days since emergence of the first new leaf, is used to determine the end of zero net stem growth.

```
 1350 XSTAGE=SUMDTT/P1
      NDAP=NDAP+1
      IF (SUMDTT.LT.(P1+P6)) RETURN
      CALL CALDAT
      IF(IPHOUT)WRITE(*,1360)nd,month,Cumdtt,Biomas,Lai,Aptnup,
     1  Xanc,Cet,CRAIN,PESW
      IF(IPHOUT)WRITE(Nout1,1360)nd,month,Cumdtt,Biomas,Lai,Aptnup,
     1  Xanc,Cet,CRAIN,PESW
1360  FORMAT(1x,i2,1x,a3,f7.0,' ZERO STEM GROWTH',7X,f6.0,1x,f5.2,1x
     1  ,f5.1,2x,f4.2,3(1x,f5.0))
      CALL PHASEI
      RETURN
C********** DETERMINE PLANT FORCING DATE ************************
```

The model simulates only the forced flowering pineapple because it is assumed this represents the most common practice. Data in the literature indicate that fruit yield is related to total plant weight at the time of forcing. A parameter PlantSize, which is determined by the user, is used to predict the time when plants are ready to force.

```
1400  IF (TotalPlantWT.LT.PlantSize) RETURN
```

```
      CALL CALDAT
      ISDATE=DOY   ! Record forcing date.  CERES-Maize variable used
      IF(IPHOUT)WRITE (*,1500)nd,month,Cumdtt,Biomas,Lai,Aptnup,
     1 Xanc,Cet,CRAIN,PESW
      IF(IPHOUT)WRITE (Nout1,1500)nd,month,Cumdtt,Biomas,Lai,Aptnup,
     1   Xanc,Cet,CRAIN,PESW
 1500 Format(1x,i2,1x,a3,f7.0,' FORCING',16X,f6.0,1x,f5.2,1x,f5.1,
     1 2x,f4.2,3(1x,f5.0))
      GO TO 2600
C**** DETERMINE DATE OF SEPALS CLOSED ON YOUNGEST FLOWERS **********
```

The duration of this stage is strongly influenced by air temperature and the difference between day and night temperature (Fleisch and Bartholomew, 1987). A cultivar-related coefficient P2, which is the modified growing degree days from forcing to the end of ISTAGE 3, is used to determine the end of the stage. Plant size or more specifically the amount of light interceped per plant during this stage, is assumed to be important in determining fruitlet number and potential fruit size of pineapple. Total fruitlets per fruit is calculated in this stage.

```
 1600 IF (SUMDTT.LT.P2) RETURN  ! P2: GDD needed to complete this stage
      CALL CALDAT
      MAXLAI=LAI                  ! MaxLAI = LAI at the end of the stage
      ABIOMS=BIOMAS                 ! Above biomass per square meter
      PHOTOSYNEYE=SUMP*1000./IDURP*3.5/5.0
      GPP=G2*PHOTOSYNEYE/7200+50.    ! Total fruitlets per fruit
      IF (GPP.GT.G2) GPP=G2     ! G2 is genetic coefficient for potential
                                  ! fruitlet number
      IF (GPP.LT.0.0) GPP=0.0
      FRUITS=PLANTS*(1.-0.10*PLANTS/14.0)
C      number of fruits=plants/m2*FRUITING%
      IF(IPHOUT)WRITE (*,1700) nd,month,Cumdtt,Biomas,Lai,Aptnup,
     1 Xanc,Cet,CRAIN,PESW
      IF(IPHOUT)WRITE (nout1,1700)nd,month,Cumdtt,Biomas,Lai,Aptnup,
     1 Xanc, Cet,CRAIN,PESW
 1700 Format(1x,i2,1x,a3,f7.0,' SCY',20X,f6.0,1x,f5.2,1x,
     1 f5.1,2x,f4.2,3(1x,f5.0))
      GO TO 2600
C********** DETERMINE DATE OF OPENING OF FIRST FLOWER ***************
```

The end of this stage occurs at anthesis of the first flower at the base of the fruit. A cultivar-related parameter P3, which is the cumulative growing degree days since sepals closed on youngest flowers, is used to determine to end of the stage.

```
 1800 XSTAGE=1.5+3.0*SUMDTT/P3
      IF (SUMDTT.LT.P3) RETURN
```

```
      CALL CALDAT
      IEFDATE=DOY
      IF(IPHOUT)WRITE (*,1900)nd,month,Cumdtt,Biomas,Lai,Aptnup,
     1  Xanc,Cet,CRAIN,PESW
      IF(IPHOUT)WRITE (nout1,1900) nd,month,Cumdtt,Biomas,Lai,
     1 Aptnup,Xanc, Cet,CRAIN,PESW
 1900 Format(1x,i2,1x,a3,f7.0,' EARLY FLOWERING',8X,F6.0,1X,F5.2,1X,
     1 F5.1,2X,F4.2,3(1X,F5.0))
      GO TO 2600

C********** DETERMINE FRUIT HARVEST DATE ********************
```

Fruit harvest date is defined as the time when ten percent of fruits have exceeded shell color 1 (Py, 1987). A cultivar-related parameter P4, which is the modified cumulative growing degree days since opening of the first flower, is used to determine the end of the stage.

```
 2000 XSTAGE=4.5+5.5*SUMDTT/(P4*.95) ! used by CERES-MAIZE
      IF (SUMDTT.LT.(P4+(PLANTS-8.0)*2.4*20.95)) RETURN
C        P4 is the GDD needed to complete this stage
      CALL CALDAT
      MDATE=DOY   ! Maturity  date
      YIELD=FRTWT*10.*FRUITS   !  fruit dry weight yield (kg/ha)
      If(Plants.eq.0.) goto 2600
      IF (GPP.GT.0.) EYEWT=FRTWT/GPP
      PEYEWT=EYEWT*1000.       ! Eye weight (mg/eye)
      GPSM=GPP*FRUITS          ! Number of eyes per square meter
      STOVER=BIOMAS*10.-YIELD  ! Total plant weight except fruit
      YIELD=YIELD/0.12         ! Fresh fruit yield (kg/ha)
      YIELDB=YIELD/0.8914      ! Fresh fruit yield (lb/acre)
      IF(IPHOUT)WRITE (*,2200)  nd,month,Cumdtt,Biomas,Lai,Aptnup,
     1 Xanc,Cet,CRAIN,PESW
      IF(IPHOUT)WRITE (nout1,2200)nd,month,Cumdtt,Biomas,Lai,Aptnup,
     1 Xanc,Cet,CRAIN,PESW
 2200 Format(1x,i2,1x,a3,f7.0,' FRUIT HARVEST ',9X,F6.0,1X,
     1 F5.2,1X,F5.1,2X,F4.2,3(1X,F5.0))
       GO TO 2600

C*************** DETERMINE FRUIT PHYSIOLOGICAL MATURITY ************
```

Fruit physiological maturity is defined as 90% of fruits have been harvested. It is determined by P5, which is the modified cumulative growing degree days from fruit harvest to physiological maturity.

```
 2400 XSTAGE=4.5+5.5*SUMDTT/P5
      IF(SUMDTT.LT.(P5+P4+(3.15*(PLANTS-8.0)-0.254*(PLANTS-8)**2)
```

```
     1    *20.95)) RETURN !
          CALL CALDAT
          PMDATE=DOY                ! physiological maturity date
          IF(IPHOUT)WRITE (*,2500)  nd,month,Cumdtt,Biomas,Lai,Aptnup,
     1 Xanc,Cet,CRAIN,PESW
          IF(IPHOUT)WRITE (nout1,2500)nd,month,Cumdtt,Biomas,Lai,Aptnup,
     1 Xanc,Cet,CRAIN,PESW
 2500 Format(1x,i2,1x,a3,f7.0,' PH. MATURITY ',10X,F6.0,1X,
     1 F5.2,1X,F5.1,2X,F4.2,3(1X,F5.0))
          IF(iswnit.ne.0)then
               IF(frtWT.GT.0.0)THEN
                    XGNP=(GRAINN/frtWT)*100.0
                    XPTN=XGNP*6.25
                    GNUP=GRAINN*FRUITS*10.
               ENDIF
               TOTNUP=GNUP+APTNUP
          Endif
          IF (ISLKJD.EQ.0) PLSEMS=0.0
          IF (ISLKJD.NE.0) PLSEMS=ISLKJD-ISOW
          IF (PLSEMS.LT.0) PLSEMS=365.-ISOW+ISDATE
          PLSEPR=ISDATE-ISOW
          IF (PLSEPR.LT.0) PLSEPR=365.-ISOW+ISLKJD
          IF (MATJD.EQ.0.OR.ISLKJD.EQ.0) SEMTMS=0.0
          IF (MATJD.NE.0.AND.ISLKJD.NE.0) SEMTMS=MATJD-ISLKJD
          IF (SEMTMS.LT.0) SEMTMS=365.-ISDATE+MDATE
          SEMTPR=MDATE-ISDATE
          IF (SEMTPR.LT.0) SEMTPR=365.-ISLKJD+MATJD
 2600 If(iswswb.eq.0) then
               SI1(ISTAGE)=0.0
               SI2(ISTAGE)=0.0
          Else
               SI1(ISTAGE)=CSD1/ICSDUR
               SI2(ISTAGE)=CSD2/ICSDUR
          Endif
          If(iswnit.eq.0)Then
               Si3(istage)=0.0
               Si4(istage)=0.0
          Else
               SI3(ISTAGE)=CNSD1/ICSDUR
               SI4(ISTAGE)=CNSD2/ICSDUR
          Endif
          IF (ISTAGE.Eq.6) GO TO 2700
          CALL PHASEI
          RETURN
 2700 IF(IPHOUT)Write(*,3700)yield,yieldb,GPSM,PEYEWT
          IF(IPHOUT)Write(nout1,3700)yield,yieldb,GPSM,PEYEWT
          IF(IPHOUT)WRITE (*,3800)
          IF(IPHOUT)Write(nout1,3800)
          DO 2800 I=1,5
               IF(IPHOUT)WRITE (*,3900) I,SI1(I),SI2(I),SI3(I),SI4(I)
     1  ,STRING(I)
```

```
          IF(IPHOUT)WRITE (nout1,3900) I,SI1(I),SI2(I),SI3(I),SI4(I)
     1  ,STRING(I)
2800 CONTINUE
     IF(IPHOUT)Write(*,4000)
     IF(IPHOUT)Write(nout1,4000)
     IF(.NOT.RUNALL.and.IPHOUT) THEN
          Write(*,*) ' Press "ENTER" to continue.'
          Read(5,'(A1)') a
     ENDIF
     IF(IPHOUT)Call Clear
     if(iirr.eq.2.or.iirr.eq.3)then
          IF(IPHOUT)write(*,2900)nirr,effirr
2900      format(/,i6,' IRRIGATION APPLICATIONS AT ',F5.2,' EFFICIENCY'
    1,/)
          LINES=NIRR/14
          IF(LINES*14.LT.NIRR)LINES=LINES+1
          DO 3000 I=1,LINES
               I1=14*(I-1)+1
               I2=I1+13
               IF(I2.GT.NIRR)I2=Nirr
               IF(IPHOUT)WRITE(NOUT1,3100)(Iday(MPX),MPX=I1,I2)
               IF(IPHOUT)WRITE(NOUT1,3200)(AIRR(MPX),MPX=I1,I2)
               IF(IPHOUT)WRITE(*,3100)(Iday(MPX),MPX=I1,I2)
               IF(IPHOUT)WRITE(*,3200)(AIRR(MPX),MPX=I1,I2)
3000      CONTINUE
3100      FORMAT(1X,'DAY OF YR ',14(I3,2X))
3200      FORMAT(1X,'AMOUNT mm ',14(F4.0,1X))
          totir=0.0
          do 3300 i=1,nirr
3300      totir=totir+airr(i)
          IF(IPHOUT)WRITE(NOUT1,3400)TOTIR
          IF(IPHOUT)WRITE(*,3400)TOTIR
3400      FORMAT(/1X,'IRRIGATION THIS SEASON : ',F5.0,' mm')
     endif
     IF(.not.IMULTI) then
          CALL OPHARV
     ELSE
          CALL FOUT5
     ENDIF
     CALL PHASEI
     iret=1
     RETURN
3500 FORMAT(1X,'CROP FAILURE BECAUSE OF LACK OF ROOT INITIATION',
    1' WITHIN 100 DAYS OF PLANTING')
3700 Format(/,1x,'YIELD (KG/HA)=',F8.0,1X,'(LB/A)=',F9.1,1X,
    1 'EYEPSM=',F6.0,1X,'EYE WT.(mg)=',f8.1)
3800 FORMAT (/,1X,'ISTAGE',6X,'CSD1',5X,'CSD2',5X,'CNSD1',5X,
    1  'CNSD2',2X,' S T A G E  OF  G R O W T H ')
3900 FORMAT (1X,I6,4F10.2,3X,A35)
4000 Format(' * NOTE: In the above table, 0.0 represents minimum'
    1,/,'    stress and 1.0 represents maximum stress for water (CSD)'
```

```
     2,/,'    and nitrogen (CNSD), respectively.')
      END
C
C********** PHASE INITIALIZATION SUBROUTINE ************************
```

This subroutine updates growing stages when a stage is completed and initializes or resets some important variables at the beginning of a stage.

```
      SUBROUTINE PHASEI
$Include: 'pine1.blk'
$Include: 'pine2.Blk'
$Include: 'pine3.Blk'
$Include: 'pine4.Blk'
$Include: 'Ntrc1.Blk'
$NOTRUNCATE
      CNSD1=0.0
      CNSD2=0.0
      CSD1=0.
      CSD2=0.
      ICSDUR=0
  100 GO TO (200,300,400,500,550,600,700,800,900),ISTAGE
c********ISTAGE 2: NET ZERO STEM GROWTH TO FORCING *************
  200 ISTAGE=2              ! When Istage 1 is ended, set it to 2
      TEMPSTMWT=0.0         ! TempSTMWT is an intermediate variable.
      XSTMWT=0.0
      GROSTM=0.0
      RETURN
C********ISTAGE 3:  FORCING TO SEPALS CLOSED ON YOUNGEST FLOWERS ****
  300 ISTAGE=3        ! When Istage 2 is ended, set it to 3
      TBASE=6.25      ! Base temperature of 6.25 is used during forcing to
c                       sepals closed on youngest flowers
      SUMDTT=0.0      ! Cumulative growing degree days
      SUMP=0.         ! SUMP is the total carbohydrate accumulated during
c                       Istage 4.
      IDURP=0         ! Duration of Istage 3
      PLAMX=PLA
      GROFLR=0.
      GROCRWN=0.
      GROFRT=0.
      FLRWT=0.0
      FRTWT=0.0
      CRWNWT=0.0
      RETURN
C****************ISTAGE 4:  SCY TO EARLY FLOWERING ********************
  400 ISTAGE=4              ! When Istage 3 is ended, set it to 4
      TBASE=12.50           ! TBASE of 12.50 is used in this stage
      SUMDTT=0.0            ! Cumulative growing degree days
      FLRWT=0.1*STMWT
```

```
      SKWT=0.0
      GROSK=0.0
      SWMIN=STMWT*.65      ! SWMIN is minimal stem weight
      PTF=1.0              ! PTF is plant top fraction
      EYEWT=0.0            ! EYEWT is fruitlet weight
      VANC=TANC
      VMNC=TMNC
      RETURN
c***********ISTAGE 5: FRUIT GORWTH *********************
  500 ISTAGE=5             ! When Istage 4 is ended, set it to 5
      FRTWT=FLRWT*0.5      ! FRTWT (g/plant) is fruit weight.  It is
c   assumed to be 50% of inflorescence at begining of the stage
      CRWNWT=FLRWT*0.2     ! CRWNWT (g/plant) is crown weight which is
c     assumed to be 20% of inflorescence at the begining of the stage
      TBASE=4.0            ! Tbase of 4.0 is used in the stage
      SUMDTT=0.0           ! Cumulative growing degree days
      RETURN
C*************ISTAGE 6:  PHYSIOLOGICAL MATURITY**********************
  550 ISTAGE=6             ! When Istage 5 is ended, set it to 6
      TBASE=4.0
      SWMAX=STMWT          ! SWMAX is maximal stem weight
      RETURN
c************ISTAGE 7:  PREPLANTING *************************
  600 ISTAGE=7             ! When Istage 6 is ended, set it to 7
      CRAIN=0.             ! Variables used in water balance
      CES=0.
      CEP=0.
      CET=0.
      PLA=CROWNWTINITIAL*0.6*63.0
      LAI=PLA*PLANTS*0.0001
      BIOMAS=CROWNWTINITIAL*PLANTS
      RETURN
c**************ISTAGE 8:  PLANTING TO ROOT INITIATION **************
  700 ISTAGE=8             ! When Istage 7 is ended, set it to 8
      RTDEP=SDEPTH
      SUMDTT = 0.
      PLA=CROWNWTINITIAL*0.6*63.0
      LAI=PLA*PLANTS*0.0001
      BIOMAS=CROWNWTINITIAL*PLANTS
      RETURN
c***ISTAGE 9:  ROOT INITIATION TO EMERGENCE OF FIRST NEW LEAF *******
  800 ISTAGE=9     ! When Istage 8 is ended, set it to 9
      CET=0.       ! Cumulative evapotranspiration after root intiation
      CES=0.       ! Cumulative evaporation after root initiation (mm)
      CEP=0.       ! Cumulative transpiration after root initiation (mm)
      NDEF1=1.0
      NDEF2=1.0
      NDEF3=1.0
      CRAIN=0.
      SUMDTT=0.
      TBASE=12.0           ! Tbase of 12.0 is used
```

```
      yl=0.                ! fraction of light penetrating to the ground
      PLA=CROWNWTINITIAL*0.6*63.0
      LAI=PLA*PLANTS*0.0001
      BIOMAS=CROWNWTINITIAL*PLANTS
      RTWT=0.
      RETURN
c****ISTAGE 1:  EMERGENCE OF FIRST NEW LEAF TO NET ZERO ROOT GROWTH****
  900 ISTAGE=1          ! When Istage 9 is ended, set it to 1
      Tbase=Tbase1      ! Tbase1 used for calibration
      SUMDTT=0.0        ! Cumulative growing degree days set to 0.0
      CUMDTT=0.0        ! CUMDTT is also cumulative growing degree days
c                         but it is set to 0.0  olny at root initiation
      PLA=CROWNWTINITIAL*0.6*63.0
c                     CrownWTInitial is average crown weight
      PLAY=PLA
      TempPLA=0.0         ! TempPLA is an intermediate variable
      XPLA=0.
      PLAG=0.0            ! PLAG is daily green leaf area growth
      LAI=PLANTS*PLA*0.0001 ! leaf area index
      LFWT=CROWNWTINITIAL*0.53
      RTWT=0.20                    ! RTWT is root weight
      STMWT=CROWNWTINITIAL*0.115 ! STMWT is 25% of initial crown weight
      BasalLeafWT=LFWT*0.66      ! Basal white leaf weight is 35% of
c                                  initial crown weight
      FLRWT=0.                     ! Inflorescence weight
      STOVWT=CROWNWTINITIAL        ! STOVWT is stover weight
      BIOMAS=0.
      XLFWT=0.
      XBASALLEAFWT=0.
      XSTMWT=0.
      TEMPSTMWT=0.
      FLRWT=0.
      DO 1100 I=1,35
           SLA(I)=0.0
           GBLA(I)=0.0
 1100 CONTINUE
      GROSTM=0.                    ! GROSTM is daily stem growth
      SENLA=0.                     ! SENLA is area of leaf senesces
c                                    due to stress on a given day
      PLAS=0.0
      SLAN=0.                      ! SLAN is total normal leaf
c                                  ! senescence since emergence
      GRORT=0.                     ! GRORT is daily root growth
      GROBSL=0.0                   ! GROBSL is daily basal leaf growth
      GROLF=0.0                    ! GROLF is daily green leaf growth
      IDUR=0                       ! IDUR is duration of the stage
      CUMPH=0.514                  ! CUMPH is number of leaves emerged
      LN=1                         ! LN is leaf number
      IF (ISWSWB.EQ.0) RETURN  ! Next section is used for water balance
      DO 1200 L=1,NLAYR
           CUMDEP=CUMDEP+DLAYR(L)
```

```
          RLV(L)=0.20*PLANTS/DLAYR(L)
          IF (CUMDEP.GT.RTDEP) GO TO 1300
 1200 CONTINUE
 1300 RLV(L)=RLV(L)*(1.-(CUMDEP-RTDEP)/DLAYR(L))
      L1=L+1
      DO 1400 L=L1,Nlayr
          RLV(L)=0.
 1400 CONTINUE
      DO 1500 L=1,Nlayr
          RWU(L)=0.
 1500 CONTINUE
      IF (ISWNIT.EQ.0) GO TO 1600 ! Next section for nitrogen balance
      RANC=0.022
      TANC=0.044
      ROOTN=RANC*RTWT
      STOVN=STOVWT*TANC
 1600 RETURN
      END
C
C************** GROWTH SUBROUTINE ***************
```

This subroutine calculates leaf area development, light interception, photosynthesis, and partitioning of biomass to various plant parts. Calculation of plant growth is balanced by the carbohydrate supply and demand for new growth.

```
      SUBROUTINE GROSUB
      REAL NSINK,NPOOL1,NPOOL2,NPOOL,NSDR
$Include: 'pine1.blk'
$Include: 'pine2.Blk'
$Include: 'pine3.Blk'
$Include: 'pine4.blk'
$Include: 'Ntrc1.Blk'
$Include: 'Comibs.Blk'
$NOTRUNCATE


c******* CALCULATION OF BIOMASS PRODUCTION FOR A DAY *********
      IF (ISWNIT.NE.0.and.Istage.lt.7) CALL NFACTO
      PAR=0.5*SOLRAD*EnergyUnitConversionFactor
      y1=exp(-0.52*lai)
      PCARB=ConvertCoefficient*PAR/plants*(1.-y1)
C*** A temperature factor is calculated for biomass production ********
      PRFT=1.-0.0025*((0.25*TEMPMN+0.75*TEMPMX)-28.)**2
      IF (PRFT.LT.0.) PRFT=0.
      CARBO=PCARB*AMIN1(PRFT,SWDF1,NDEF1)  ! The law of minimum
      IF(DTT.LT.0.) DTT=0.
      IF (ISTAGE.GT.3) GO TO 100
```

1). Calculate photosynthetically active radiation (PAR, MJ m^{-2}) from daily solar radiation. It is assumed that 50% of solar radiation are PAR. An energy unit conversion factor is used here to convert different unit of solar radiation into MJ/m2.

2). Calculate fraction of light penetrating to ground. Homogeneous leaf distribution both horizontally and vertically is assumed. Light attenuation follows Beer's law. The extinction coefficient of 0.52 is used here.

3). Calculate Potential biomass production at optimal conditions and actual biomass production for a day. A convert coefficient is used here to convert light energy to biomass. The law of minimum is applied here to calculate actual biomass production.

```
c********** CALCULATE LEAF EMERGENCE **************
c If SUMDTT>P7, plant population density begins to affect leaf
c emergence, P7 is cummulative growing degree days since first leaf
c emergence.
      IF (TempM .gt. Tbase) then
       IF (SUMDTT.GT.P7) then
           TI=(0.0225-0.00108*Plants)*DTT  ! J. Zhang (1991) (Chapter 1)
       ELSE
           TI=0.0224*DTT
        ENDIF
      else
         TI = 0.0      ! If mean air temperature is less than Tbase,
      endif            ! no leaf emerges
      CUMPH=CUMPH+TI   ! CUMPH is number of expanded leaves.
      XN=CUMPH+1.      ! XN is leaf number of the oldest expanding leaf
      LN=XN            ! LN is leaf number
  100 GO TO (200,300,400,600,1300,3000 ),ISTAGE
C*** ISTAGE 1: EMERGENCE OF FIRST NEW LEAF TO END 0 NET STEM GROWTH ***
  200 XPLA=(17.0*XN+3.11*XN*XN)*swdf2  ! J. Zhang (1991) (Chapter 3)
      IF (XPLA.LT.TempPLA) XPLA=TempPLA
         PLAG=XPLA-TempPLA
         TempPLA=TempPLA+PLAG
      PLA=PLA+PLAG                ! Update total leaf area
c******* GREEN LEAF WEIGHT IS CALCULATED FROM LEAF AREA  **********
      XLFWT=(PLA/96.)**1.15
      IF (XLFWT.LT.LFWT) XLFWT=LFWT
      GROLF=XLFWT-LFWT
      XBasalLeafWT=0.42*XLFWT
      IF(BasalLeafWt.GE.LFWT) BasalLeafWt=LFWT*0.66
      IF(XBasalLeafWT.LT.BasalLeafWT) XBasalLeafWT=BasalLeafWT
      GROBSL=XBasalLeafWT-BasalLeafWT
c** DAILY ROOT GROWTH IS CALCULATED FROM CARBO AND DAILY LEAF WEIGHT**
C If GRORT is less than 25% of CARBO then set to 25% of CARBO. A growth
```

```
C reducing factor (GRF) is calculated and GROLF, GROBSL are reduced by
C GRF. PLA is recalculated.
      GRORT=CARBO-GROLF-GROBSL
      IF (GRORT.GE.0.25*CARBO) GO TO 280
      IF (GROLF.GT.0.0.OR.GROBSL.GT.0.0) THEN
          GRF=CARBO*0.75/(GROLF+GROBSL)
          GRORT=CARBO*0.25
      ELSE
          GRF=1.0
      ENDIF
       GROLF=GROLF*GRF
       GROBSL=GROBSL*GRF
      PLA=(LFWT+GROLF)**0.87*96.0
  280 LFWT=LFWT+GROLF                    ! Update green leaf weight
      BasalLeafWt=BasalLeafWT+GROBSL     ! Update basal leaf weight
      IF(GROLF.GT.0.) SLAN=PLA/1000.
      LFWT=LFWT-SLAN/600.                ! recalculate green leaf weight
      GO TO 2200

C**** ISTAGE 2: END OF 0 NET STEM GROWTH TO FORCING ****
  300 XPLA=(17.0*XN+3.11*XN*XN)*AMIN1(NDEF2,swdf2)  ! J. Zhang (1991)
      IF (XPLA.LT.TempPLA) XPLA=TempPLA
         PLAG=XPLA-TempPLA
         TempPLA=TempPLA+PLAG
      PLA=PLA+PLAG
      XLFWT=(PLA/96.)**1.15
      IF (XLFWT.LT.LFWT) XLFWT=LFWT
      GROLF=XLFWT-LFWT
      XBasalLeafWT=0.42*XLFWT
      IF (XBasalLeafWT.LT.BasalLeafWT) XBasalLeafWT=BasalLeafWT
      GROBSL=XBasalLeafWT-BasalLeafWT
C
c******CALCULATION OF DAILY STEM GROWTH*****************
C Because stem dry weight is correlated with basal leaf dry weight up to
C the time of forcing, XSTEMWT is calculated from XbasalLeafWT.  XSTEMWT
C and TEMPSTMWT are set to 0. at the end of zero net stem growth.
c
       XStemWT=0.52*XbasalLeafWT
       IF (XSTEMWT.LT.STMWT) XSTEMWT=STMWT
         GROSTM=XSTEMWT-STMWT
       IF(GROSTM.GT.GROBSL) GROWSTM=GROBSL
      GRORT=CARBO-GROLF-GROBSL-GROSTM
      IF (GRORT.GE.0.15*CARBO) GO TO 380
      IF (GROLF.GT.0.0.OR.GROBSL.GT.0.0.OR.GROSTM.GT.0.0) THEN
          GRF=CARBO*0.85/(GROLF+GROBSL+GROSTM)
          GRORT=CARBO*0.15
      ELSE
          GRF=1.0
      ENDIF
       GROLF=GROLF*GRF
       GROBSL=GROBSL*GRF
```

```
      GROSTM=GROSTM*GRF
     PLA=(LFWT+GROLF)**0.87*96.0
 380 LFWT=LFWT+GROLF
     BasalLeafWt=BasalLeafWT+GROBSL
     STMWT=STMWT+GROSTM
     IF(GROLF.GT.0.) SLAN=PLA/1000.
     LFWT=LFWT-SLAN/600.
     GO TO 2200
C***** ISTAGE 3: FORCING TO SEPALS CLOSED ON YOUNGEST FLOWERS *********
```

After forcing, stem dry weight increases rapidly. Number of eyes are determined in this stage. Inflorescence growth is assumed to be the funtion of growing degree days. Total biomass accumulated during the stage and duration of the stage are calculated. Both will used to calculate fruitlet number per fruit.

```
 400 XPLA=(17.0*XN+3.11*XN*XN)*AMIN1(NDEF2,swdf2)  ! J. Zhang (1991)
     IF (XPLA.LT.TempPLA) XPLA=TempPLA
        PLAG=XPLA-TempPLA
        TempPLA=TempPLA+PLAG
     PLA=PLA+PLAG
     XLFWT=(PLA/96.)**1.15
     GROLF=XLFWT-LFWT
     XBasalLeafWT=0.425*XLFWT
     IF (XBasalLeafWT.LT.BasalLeafWT) XBasalLeafWT=BasalLeafWT
     GROBSL=XBasalLeafWT-BasalLeafWT
     GROFLR=0.45*DTT/20.5*AMIN1(NDEF2,SWDF2).
     GROSTM=GROFLR**1.02.
      IF (GROSTM.LT.0.0) GROSTM=0.0
      XSTEMWT=XSTEMWT+GROSTM
       IF (GROFLR.LT.0.0) GROFLR=0.0
     GRORT=CARBO-GROLF-GROBSL-GROSTM-GROFLR
     IF (GRORT.GE.0.10*CARBO) GO TO 500
     IF (GROLF.GT.0.0.OR.GROBSL.GT.0.0.OR.GROSTM.GT.
    10.0.OR.GROFLR.GT.0.0) THEN
         GRF=CARBO*0.90/(GROLF+GROBSL+GROSTM+GROFLR)
         GRORT=CARBO*0.10
     ELSE
         GRF=1.0
     ENDIF
     GROLF=GROLF*GRF
     GROBSL=GROBSL*GRF
     GROSTM=GROSTM*GRF
     GROFLR=GROFLR*GRF
     PLA=(LFWT+GROLF)**0.87*96.
 500 LFWT=LFWT+GROLF
     BasalLeafWt=BasalLeafWT+GROBSL
     TempSTMWT=TempSTMWT+GROSTM  !Temperory stem weight
     STMWT=STMWT+GROSTM
```

```
      FLRWT=FLRWT+GROFLR
      IF(GROLF.GT.0.) SLAN=PLA/1000.
      LFWT=LFWT-SLAN/600.
      SUMP=SUMP+CARBO      ! Total biomass cumulated during the stage
      IDURP=IDURP+1        ! Duration of the stage
      GO TO 2200
C************** ISTAGE 4: SCY TO OPENING OF FIRST FLOWER ************
C Biomass begins to be partitioned to the inflorescence.  Stem grows
C continuously.
  600 GROFLR=0.45*DTT/20.5*AMIN1(NDEF2,SWDF2).
      GROSTM=GROFLR**1.02.
       IF (GROSTM.LT.0.0) GROSTM=0.0
       XSTEMWT=XSTEMWT+GROSTM
        IF (GROFLR.LT.0.0) GROFLR=0.0
      IF (TotalPlantWT.GT.600.) goto 700
           GRORT=CARBO-GROSTM-GROFLR
      IF (GRORT.GE.0.05*CARBO) GO TO 800
      IF (GROSTM.GT.0.0.OR.GROFLR.GT.0.0) THEN
          GRF=CARBO*0.95/(GROSTM+GROFLR)
          GRORT=CARBO*0.05
      ELSE
          GRF=1.0
      ENDIF
      GOTO 750
700   GRORT=CARBO*0.05
      GROSK=(CARBO-GROSTM-GRORT-GROFLR)*0.5
      IF (GROSK.GE.0.) GO TO 800
      GROSK=0.
      IF (GROSTM.GT.0.0.OR.GROFLR.GT.0.0) THEN
         GRF=CARBO*0.95/(GROSTM+GROFLR)
      ELSE
          GRF=1.0
      ENDIF
750   GROSTM=GROSTM*GRF
      GROFLR=GROFLR*GRF
  800 STMWT=STMWT+GROSTM
      FLRWT=FLRWT+GROFLR
      SKWT=SKWT+GROSK
      GO TO 2200
C******ISTAGE 5: FRUIT ENLARGEMENT AND MATURITY****************
```

Most biomass partitioning to fruitlets occurs during this stage and stem growth contiues. If the total plant weight reaches 600 g in ISTAGE 5, suckers are assumed to initiate, otherwise, sucker growth initiated in ISTAGE 4 continues.

```
C 1300 IF (PLANTS.EQ.0.01) RETURN
C      IF(Carbo.eq.0.) Goto 1450
1300  SLAN=PLA/1000.
      LFWT=LFWT*0.998
```

```
      BasalLeafWT=BasalLeafWT*1.001
      RGFILL=0.0
      DO 1400 I=1,8
         TTMP=TEMPMN+TMFAC(I)*(TEMPMX-TEMPMN)
      IF(TTMP.GT.4.0) RGFILL=RGFILL+(1.0-0.0017*(TTMP-28.)**2)/8.
 1400 CONTINUE
      GROFRT=RGFILL*GPP*G3*0.001*(0.45+0.55*swdf1)
      GROCRWN=0.125*GROFRT
      CRWNWT=CRWNWT+GROCRWN
      GROSTM=0.135*GROFRT
       IF (GROSTM.LT.0.0) GROSTM=0.0
      IF (TotalPlantWT.GT.600.) then
         GROSK=CARBO-GROSTM-GROFRT-GROCRWN
         IF (GROSK.LT.0.0) GROSK=0.0
         SKWT=SKWT+GROSK
         STMWT=STMWT+GROSTM
      ELSE
       IF (GROSTM.LT.0.) GO TO 1700
       STMWT=STMWT+GROSTM
       GRORT=GROSTM*0.10
      ENDIF
       GO TO 1900
 1700 STMWT=STMWT+CARBO-GROFRT
      IF (STMWT.GT.SWMIN*1.07) GO TO 1900
      STMWT=STMWT+LFWT*0.0050+BasalLeafWT*0.0050
 1800 IF (STMWT.GE.SWMIN) GO TO 1900
      STMWT=SWMIN
      GROFRT=CARBO
 1900 IF (ISWNIT.EQ.0) GO TO 2100
C********** GRAIN N ALLOWED TO VARY BETWEEN .01 AND .018.
C********** HIGH TEMP., LOW SOIL WATER, AND HIGH N INCREASE GRAIN N
      SFAC=1.125-.125*swdf2
      TFAC=0.69+0.0125*TEMPM
      GNP=(0.004+0.013*NFAC)*AMAX1(SFAC,TFAC)
      NSINK=GROGRN*GNP
      IF (NSINK.EQ.0.0) GO TO 2000
      RMNC=0.75*RCNP
      IF(RANC.LT.RMNC)RANC=RMNC
      VANC=STOVN/STOVWT
      IF(VANC.LT.VMNC)VANC=VMNC
      NPOOL1=STOVWT*(VANC-VMNC)
      NPOOL2=RTWT*(RANC-RMNC)
      xnf=0.15+0.25*nfac
      tnlab=xnf*npool1
      rnlab=xnf*npool2
      npool=tnlab+rnlab
      IF(ICSDUR .EQ. 1) GPP=AMIN1(GPP*NDEF3,(NPOOL/(.062*.0095)))
      NSDR=NPOOL/NSINK
      if(nsdr.lt.1.0)nsink=nsink*nsdr
      If(nsink.gt.tnlab)then
           STOVN=STOVN-tnlab
```

```
            rnout=nsink-tnlab
            rootn=rootn-rnout
            RANC=ROOTN/RTWT
      else
            STOVN=STOVN-NSINK
            VANC=STOVN/STOVWT
      endif
 2000 GRAINN=GRAINN+NSINK
c
c************ UPDATE FRUIT WEIGHT **************
c
 2100 FRTWT=FRTWT+GROFRT
      FLRWT=FLRWT+GROFRT+GROCRWN
c      IF (STMWT.GT.SWMAX) STMWT=SWMAX
C
 2200 IF (CARBO.EQ.0.0) CARBO=0.001
      PDWI=PCARB*(1.0-GRORT/CARBO)
      PGRORT=PCARB*GRORT/CARBO
      GO TO 2400
 2300 NFAC=1.0
c
c **** Calculation of zero-to-unity factors for leaf senescence due to
drought
c stress (SLFW), competition for light (SLFC), and low temperature
(SLFT).
c
 2400 SLFW=0.95+0.05*SWDF1
      SLFN=0.95+0.05*NDEF2
      SLFC=1.0
      IF (LAI.GT.6.) SLFC=1.-0.002*(LAI-6.)
      SLFT=1.
      IF (TEMPM.GT.4.0) GO TO 2500
      SLFT=1.-(4.0-TEMPM)/4.0
 2500 IF (TEMPMN.GT.0.0) THEN
            ICOLD=0
      ELSE
            SLFT=0.0
            ICOLD=ICOLD+1
      ENDIF
c*** Leaf area senescence on a day (PLAS) and LAI is calculated for
ISTAGE 1 to 5.
c
      IF (SLFT.LT.0.) SLFT=0.
      PLAS=(PLA-SENLA)*(1.0-AMIN1(SLFW,SLFC,SLFT))
      SENLA=SENLA+PLAS
      IF (SENLA.LT.SLAN) SENLA=SLAN
      IF (SENLA.GE.PLA) SENLA=PLA
      LAI=(PLA-SENLA)*PLANTS*0.0001
      IF(LN.GT.3.AND.LAI.LE.0..AND.ISTAGE.LE.3) THEN
            WRITE(*,2800)
            WRITE(NOUT1,2800)
```

```
            ISTAGE=4
        ELSE
            IF(ICOLD.GE.7) THEN
                WRITE(*,2800)
                WRITE(NOUT1,2800)
                ISTAGE=5
            ENDIF
        ENDIF
        RTWT=RTWT+0.5*GRORT-0.01*RTWT
c Half GRORT is used for respiration and 50% of root is lost due to
c senescence. Finally, total biomass per unit area (BIOMAS, g m-2),
total
c plant weight, total plant dry weight per hactare (DM, kg ha-1) and
c plant top fraction (PTF) are calculated.
c
        BIOMAS=(LFWT+STMWT+FLRWT+BasalLeafWT+SKWT)*PLANTS
        TotalPlantWT=LFWT+STMWT+BasalLeafWT+FLRWT+SKWT
        DM=BIOMAS*10.0
        PTF=(LFWT+BasalLeafWT+STMWT+FLRWT+SKWT)/(RTWT+LFWT+
       1 BasalLeafWT+SKWT+STMWT+FLRWT)
        IF (ISWNIT.NE.0) CALL NUPTAK
        RETURN
 2800 FORMAT(2X,'CROP FAILURE GROWTH PROGRAM TERMINATED ')
 3000 RETURN
        END
```

GLOSSARY

The following is a glossary of some important variables used in the Subroutines PHENOL, PHASEI and GROSUB of ALOHA-Pineapple. Variables used in other subroutines and the intermediate variables are not included.

ABIOMS	Above-ground biomass per square meter (g m^{-2}), data type: real.
BASALLEAF-WT	Basal leaf weight of the previous day, data type: real.
BIOMAS	Total biomass per square meter (g m^{-2}), data type: real.
CARBO	Daily biomass production (g $plant^{-1}$), data type: real.
CONVERTC-OEFFICIENT	coefficient to converte from per MJ of PAR to gram dry matter, data type: real.
CROWNWT-INITIAL	Initial crown weight (g $plant^{-1}$), data type: real.
CRWNWT	Current day's crown weight, data type: real.
CUMDTT	Cumulative daily thermal time after root initiation, data type: real.
DTT	Daily accumulation of growing degree days, data type: real.
EYEWT	The weight of the fruitlet (eye) (g eye^{-1}), data type: real.
FLRWT	Current day's inflorescence dry weight, data type: real.
FRTWT	Current day's fruit weight (g $plant^{-1}$), data type: real.
FRUITS	Number of fruits per $m^{2,}$ data type: real.
G2	Potential fruitlet (eye) number (eyes $fruit^{-1}$), data type: integer.
G3	the maximum daily rate of fruitlet growth (mg eye^{-1} day^{-1}), data type: real.

GPP	Total number of fruitlets (eyes) per fruit, data type: real.
GPSM	Number of fruitlets per square meter, data type: real.
GRNWT	Grain weight (g $plant^{-1}$), only used for CERES-Maize, data type: real.
GROBSL	Daily basal leaf growth, data type: real.
GROCRWN	Daily growth of crown, data type: real.
GROFLR	Daily growth of inflorescence (including peduncle), data type:real.
GROFRT	Daily growth of fruit (g $plant^{-1}$ day^{-1}), data type: real.
GROLF	Daily green leaf growth (g $plant^{-1}$ day^{-1}), data type: real.
GRORT	Daily root growth (g $plant^{-1}$ day^{-1}), data type: real.
GROSK	Daily sucker growth (g $plant^{-1}$ day^{-1}), data type: real.
GROSTM	Daily stem growth (g $plant^{-1}$ day^{-1}), data type: real.
IDURP	Duration of stage 3 (days), data type: integer.
IEFDATE	Date of anthesis of first flower, data type: integer.
IRET	Simulation cycle counter, data type: integer.
ISDATE	Forcing date, data type: integer.
ISTAGE	Phenological stage, data type: integer.
ISWSWB	Switch that determines whether the model calculates the soil water components of the model, data type: logical.
JDATE	Day of the year, data type: integer.
LAI	Leaf area index (m^2 leaf m^{-2} ground), data type: real.
MAXLAI	LAI at the end of the stage 4, data type: real
MDATE	Maturity date, data type: real.

NDAP	Number of days after planting, data type: integer.
P1	Cumulative growing degree days from first leaf emergence to the end of zero net stem growth, data type: real.
P2	Cumulative growing degree days from forcing to end of floret initiation, data type: real.
P3	Cumulative growing degree days from end of floret initiation to opening of first flower, data type: real.
P4	Cumulative growing degree days from opening of first flower to fruit harvest, data type: real.
CP4	P4 corrected for the effect of plant population density.
P5	Cumulative growing degree days from fruit harvest to physiological maturity, data type: real.
CP5	P5 corrected for the effect of plant population density.
P6	Cumulative growing degree days since root initiation to first leaf emergence under no water stress condition, data type: real.
P7	Cumlulative growing degree days from emergence of first new leaf to the beginning of interplant competition (restricts vegetative growth) data type: real.
PAR	Photosynthetically active radiation (MJ m^{-2} d^{-1}), data type: real.
PCARB	Daily potential dry matter production with optimum water, nitrogen, and temperature conditions (g $plant^{-1}$ day^{-1}), data type: real.
PEYEWT	Fruitlet weight in mg $plant^{-1}$, data type: real.
PHOTOSYN-EYE	Average rate of photosysthesis during stage 3 (g $plant^{-1}$ day^{-1}), data type: real.
PLAG	Daily green leaf area growth (cm^2 $plant^{-1}$ day^{-1}), data type: real.
PLANTSIZE	Total above-ground plant dry weight at the time of forcing. It is a decision variable decided by users, data type: real.

PRFT	Photosynthetic reduction factor for low and high temperatures (0-1), data type: real.
PTF	PTF is plant top fraction (g $plant^{-1}$), data type: real.
RAIN	Precipitation (mm d^{-1}), data type: real.
RGFILL	Relative rate of dry matter partitioning to fruit eyes (0-1), data type: real.
SENLA	Area of leaf senescenced (cm^2 $plant^{-1}$) from a plant on a given day, data type: real.
SLAN	Total normal leaf senescence since emergence(cm^2 $plant^{-1}$), data type: real.
SLET	Leaf senescence factor due to low temperature (0-1), data type: real.
SLFT	Leaf senescence factor due to competition for light (0-1), data type: real.
SLFW	Leaf senescence factor due to water stress (0-1), data type: real.
SOLRAD	Solar radiation, data type: real.
STOVER	Total plant weight except fruit (g $plant^{-1}$), data type: real.
SKWT	Sucker weight (g $plant^{-1}$), data type: real.
SUMDTT	The sum of growing degree days for a phenological stage, data type: real.
SUMP	The total weight of biomass accumulated in stage 3 (g $plant^{-1}$), data type: real.
SWAF1	Soil water deficit factor used to calculate the reduction in plant cell expansion (0-1), data type: real.
SWDF1	Soil water deficit factor used to calculate the reduction in photosynthesis (1-0), data type: real.
SWMAX	Maximal stem weight (g $plant^{-1}$), data type: real.

SWMIN	Minimal stem weight (g plant^{-1}), data type: real. It is 65% of STMWT
TBASE	Base temperature during daylight hours (°C), data type: real.
TEMPM	Mean air temperature (°C), data type: real.
TEMPMN	Minimum temperature (°C), data type: real.
TEMPMX	Maximum air temperature (°C), data type: real.
TEMPPLA	An intermediate variable used calculating daily green leaf area growth, data type: real.
TEMPSTM-WT	An intermediate variable for stem weight (g plant^{-1}). It is set to 0.0 at the beginning of Istage 2, data type: real.
TOTAL-PLANTWT	Total above-ground plant dry weight per plant (g plant^{-1}), data type: real.
TTMP	3-hour mean temperature (°C), data type: real.
XBASAL-LEAFWT	New basal leaf weight for the day, data type: real.
XFRTWT	Measured fruit dry weight (g fruit^{-1}), data type: real.
XSTEMWT	New stem weight for the day, data type: real.
YIELD	Fresh fruit yield (kg ha^{-1}), data type: real.
YIELDB	Fresh fruit yield (lb acre^{-1}), data type: real.

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