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MODELLING SUGARCANE GROWTH IN RESPONSE TO AGE, INSOLATION AND TEMPERATURE

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MODELLING SUGARCANE GROWTH

IN RESPONSE TO AGE, INSOLATION AND TEMPERATURE

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 METEOROLOGY

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by

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I dedicate this dissertation to my mother and to the memory of my father.

ABSTRACT

Modelling sugarcane growth in response to age of cane, insolation and air temperature using first-order multiple regression analysis and a non-linear approach is investigated. Cane yield data in each method are restricted to one variety from irrigated fields in an effort to eliminate the impact of varietal response and rainfall.

Ten first-order models are investigated. The predictant is cane yield obtained from 600 field tests for variety H50-7209 in irrigated fields conducted between 1959 and 1978. The predictors are cumulative values of insolation, maximum temperature and minimum temperature for 3, 6, 12 and 18 months or for each crop period derived from weather observations made at stations near the test plots.

The low R-square values of the ten first-order models indicate that the selected predictor variables could not account for a substantial proportion of the variations of cane yield and the models have limited predictive values.

The non-linear model is based on known functional relationships between sugarcane growth and age, between growth and insolation, and between growth and maximum temperature. A mathematical expression that integrates the effect of age, insolation and maximum temperature is developed. The constant terms and coefficients of the equation are determined from the requirement that the model

must produce results that are reasonable when compared with observed growth data.

The non-linear model is validated and tested using monthly elongation data for variety H62-4671 measured during the period 1983 to 1985. Following the successful validation of the model, simulated growth curves in response to age, insolation and maximum temperature are generated by computer. The three-dimensional presentation of the simulation curves provides a convenient and simple means for the analysis of the individual factors and their interactions on sugarcane growth.

The proposed non-linear model may be useful in estimating potential growth and assessing growth performance. When combined with stalk population data, the model may be used to predict field cane yields.

The non-linear model shows that the growth of sugarcane is not controlled by one factor alone, nor by a set of factors present in relative minima. The model shows that each factor have some definite influence on growth rate, depending upon the intensities of the other factors. However, only one limiting factor is required to cause the growth rate to be greatly reduced. These facts lead to the conclusion that when investigating sugarcane growth, the simultaneous effect of age, insolation and maximum temperature must be taken into consideration.

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CHAPTER I

INTRODUCTION

Agricultural meteorology covers a wide range of subjects and requires extensive knowledge on the part of the agrometeorologist. While the physics of the atmosphere and soil form the foundation of agrometeorological research, this science must also use the findings of the biological sciences.

In a soil-plant-atmosphere system, soil and atmosphere are the physical media in which plants exist. Progress in agricultural production has been achieved against a background of climatic fluctuations and other environmental variabilities. Weather is involved directly or indirectly in every aspect of agricultural production. It provides the radiant energy for photosynthesis, the warm temperature for plant growth and development, and the moisture needed for good yield. Weather and climate are the primary determinants of plant growth and have overriding effects on yields.

One major area of research in agricultural meteorology is the investigation of the crop-weather relationship. Research into plant growth and plant development has concentrated in great detail on plant processes most likely to be important in yield determination. Thus, a great deal is known about photosynthetic pathways, metabolic processes, enzyme kinetics and other processes. But the interactions among these processes in relation to plant growth are less known. A major problem in plant growth research is the difficulty of discerning and describing the complex overall plant growth relationships among these processes. However, the advent of the computer has allowed the construction of elaborate crop-weather models that can provide explanations of the relationships among weather, climate, crop growth and yield.

Sugar and sugarcane production are also known to be subject to significant fluctuations as a result of spatial and temporal climatic variations. The objective of this study is to conduct an agroclimatic analysis to relate the impact of weather on sugarcane yield. If suitable mathematical models can be developed to relate crop growth and production to meteorological parameters, then climatological records could be efficiently used for the assessment of crop conditions during the growing season or for estimating yield potential for certain regions.

CHAPTER II

LITERATURE REVIEW

Sugarcane Cultivation

Sugarcane is widely grown throughout the world, mostly between the latitudes of 35 degrees north and south. Sugarcane cultivation is restricted to regions not affected by low temperatures ($<60^{o}F$) because of growth characteristics. The sugarcane plant grows rather slowly during the first few months of its life, and because of this, a long growing season is essential to high yields. It is this requirement that restricts sugarcane to the tropical areas of the world.

The growth characteristics of sugarcane contrast sharply with that of corn. For example, a field of corn at two months from planting will be five feet or taller, whereas a field of sugarcane will be about three feet. However, the growth of sugarcane will continue for 24 or more months, while the corn plant will die within three to four months. The growth rate of sugarcane is most significant through the "boom" stage between five and 12 months. It then declines gradually but, under favorable conditions, may continue to elongate for three to four years or more.

Sugarcane is usually started in winter or spring and harvested at 10 to 15 months of age. In Hawaii, sugarcane is harvested at 18 to 24 months of age at lower elevations and up to 40 months at elevations higher than 2000 feet above sea level.

Maximum sugar yield can be realized only if the sugarcane growth is optimum throughout the growing season and if the crop is well ripened before harvest. Maximum cane growth is achieved when the crop is raised with the best management and cultivation practices, and when environmental factors are optimum. The requirement for ripening is a retardation of growth rate. Low temperature, moderate moisture stress, nitrogen starvation and chemical ripeners are effective ripening agents. As the growth rate declines, less of the sugar which is manufactured by the leaves is expended in growth, and a larger proportion of the sugar goes into storage in the stalk.

Environmental and Physiological Factors Affecting Sugarcane Growth

The growth of sugarcane is affected by a multitude of plant, physiological, and environmental factors as well as by crop management and cultivation. Understanding the components of the soil-plant-atmosphere continuum and their relationships in the sugarcane ecosystem is important for the development of a sugarcane crop-weather model. The choice of the model significantly depends on available information about the various components of the continuum.

Photosynthesis is, undoubtedly, the most important factor for plant growth. For this reason agriculture is known as the exploitation of solar energy.

Photosynthesis of Sugarcane

Photosynthesis is the most important factor limiting plant growth when temperature and soil moisture are optimum and when nutrients are adequate. Photosynthesis is the process by which chlorophyll-bearing plants convert light energy to chemical energy stored in organic matter. It is frequently depicted according to the equation:

$$CO_2 + H_2O \xrightarrow{\text{light}} (CH_2O) + O_2$$

in which the elements carbon, hydrogen, oxygen in the form of carbon dioxide and water are converted to carbohydrate and molecular oxygen.

The overall photosynthesis rate of sugarcane, which is known to be one of the most efficient and productive crops, is several times greater than most other plants (Burr et al., 1957; Kortschak et al., 1965). The main factors relating to photosynthesis of sugarcane are briefly discussed below.

C_4 Pathway

The C_4 pathway by which carbon flows from the atmospheric CO_2 to sugars in sugarcane (Kortschak et al., 1965) may be responsible for the high photosynthesis efficiency. Kortschak (1968) and other researchers have associated the rapid growth rates of sugarcane, corn and other tropical grasses to the C_4 pathway, its related high light saturation levels and inherent capacity to assimilate carbon dioxide at extremely high rates. Others have attributed the superior growth of sugarcane to the extended growing season rather to any inherent link to the C_4 pathway or to temperature tolerance of C_4 species. However, there is increasing evidence that differences in such features as leaf anatomy, light response curve, CO_2 compensation point and photosynthesis rate tend to distinguish C_4 pathway plants from the Calvin-cycle plants. As a group, C_4 species assimilate CO_2 under intense illumination at rates several times faster than C_3 species.

Photorespiration

Another distinctive feature of C_4 plants is their lack of photorespiration--they do not increase respiration with respect to increasing light intensity and thus growth increases significantly with respect to light intensity. Photorespiration differences among plants may be distinguished by their CO_2 compensation points; a low compensation point corresponds to a low level and a high compensation point to a high level of photorespiration.

The CO_2 compensation point for C_4 plants is 5.0 ppm (Moss, 1962) and that of C_3 plants is 50 ppm (Zelitch, 1967). Numerous proposals have been put forward to account for the apparent lack of photorespiration in sugarcane and other C_4 plants. A generally accepted view is that there may be an active photorespiration mechanism in C_4 plants but one which is much lower than that for C_3 plants (Jackson et al., 1970).

Plant Moisture

Photosynthesis rate varies as a result of plant moisture. Hartt (1967) reported that moisture status differentially affects both CO_2 assimilation rate and the rate of sucrose movement from leaf to storage tissue. Lower moisture may cause a decrease of CO_2 assimilation while at the same time permit greater sucrose accumulation in the stalk by virtue of more efficient "unloading" from conducting phloem to storage, the latter process being of particular importance to the ripening phase of sugarcane.

Temperature

Photosynthesis is strongly influenced by temperature, although heat is not a reactant in photosynthesis. Vong and Murata (1977) found that the optimum temperature for C_4 plant photosynthesis is 86^{o} to $95^{o}F$. Studies by Glasziou et al. (1965) and Hartt (1965) on the effect of temperature on sugarcane photosynthesis reported rate increases with temperature, to an optimum temperature of $93^{o}F$. The photosynthesis rate is severely reduced above $104^{o}F$ or below $68^{o}F$. The effect of temperature is smallest in weak light and maximal in strong light and saturating CO_2.

Efficiency

The overall photosynthesis rate of sugarcane is several times greater than most other plants. Under optimum conditions, sugarcane can convert 1.5 percent of the incident solar radiation into organic matter over a period of two years and can exceed that value for short periods (Burr et al., 1957). Of this amount, a relatively small portion of the insolation is used in dry matter production, the remainder being expended in various growth and life-maintenance processes.

Energy Utilization

Komatsu et al. (1933) reported on the photosynthetic utilization of solar energy by a sugarcane plant. They showed that an increasing amount of energy is accumulated from photosynthesis during the first 6 months, with most of the energy used in growing processes. During the second 6 months less energy is obtained from photosynthesis, and still less energy is used in growth, but more energy is used for sucrose formation. At about the eleventh month, the descending growth curve intercepts the increasing sucrose curve, and from that point onward the amount of energy utilized in sucrose accumulation exceeds the energy utilized for growth.

Age Effect

Kortschak et al. (1969), reporting on the effect of age on photosynthesis rate of sugarcane, showed the decline of photosynthesis with age, in agreement with the findings of Komatsu et al. (1933). As discussed earlier, most of the energy during the more efficient photosynthesis period of the early crop age is utilized for growth development, whereas most of the energy during the lower efficiency and cane maturing period is utilized for sucrose accumulation.

In Hawaii, Clements (1964) found cane age to be important in the plant's response to different water supply conditions. He reported the first year's growth was more responsive to irrigation than the second year's. Thompson (1965), in South Africa, reported similar results for a two-year crop. Mongelard and Nickell (1972) related cane age and irrigation response partially to a sharp decrease in photosynthetic efficiency after ten months of age. Gosnell (1968) reported that increasing cane age generally reduced yield increment, growth rate, photosynthetic efficiency and sucrose yield to a significant degree.

Photosynthetic Efficiency and Light Intensity

Kortschak et al. (1969) also reported on the relationship of photosynthesis rate to shade and to season, and showed that in summer photosynthesis rate dropped to a minimum value which was 7 percent below the winter maximum. It should be noted, however, that the overall photosynthesis in summer months is much greater than that of winter due to the increase in insolation which more than offsets the corresponding decrease in efficiency. Shading, which gives rise to lower light intensity, also results in a higher photosynthesis rate.

The Soil-Plant-Atmosphere Continuum

The concept of the soil-plant-atmosphere continuum provides a theoretical basis for describing and understanding the transport of water from moist soil, into plant roots, through the plants and ultimately to the ambient atmosphere as water vapor passing through the leaf stomata. The process is primarily the result of a complex combination of soil, plant and atmospheric factors, all of which interact to control the rate of soil-water absorption by the plant and the subsequent loss of water vapor to the atmosphere. Plant-water loss in transpiration is the result of water movement through the continuum in response to gradients in soil and plant-water potentials which occur frequently during the life of most crops (Kramer, 1969).

In the last decade, research in this area has shifted away from the influence of soil-water potential and deficit on plant growth, yield and water use to a general recognition that plant growth is controlled directly by internal plant water potential and deficit (Begg and Turner, 1976). This has been supported by findings which show that temporary plant-water deficits and a mild reduction in plant growth rate can occur even in the presence of adequate soil moisture in the root zone (Hsiao, 1973; Hsiao and Acevedo, 1974). Kramer (1969) found this phenomenon to be highly associated with the diurnal increase in temperature and evapotranspiration near midday accompanied by the inability of most plant roots to meet the sharply increased demand for moisture, even from soil at optimum moisture level.

Studies of plant-water relations as they affect crop growth, yield, and water use have been carried by Slatyer (1967), Sutcliff (1968), Kramer (1969), Lemon et al. (1971), Hsiao et al. (1974) and Begg and Turner (1976). These physiologically based studies emphasize the ecological relationships of the plant with the atmosphere near the ground and the soil environment.

Mongelard and Nickell (1972) published a comprehensive review of the sugarcane plant in the continuum, with focus on growth and yield. Thompson (1976, 1977) stressed the importance of better understanding water behavior in sugarcane continuum in order to achieve more efficient irrigation and higher sucrose yield. According to Slatyer (1967), water plays a major role within the plant. Water constitutes more than 80 percent of most plant cells and tissues in which active metabolism occur, and it provides a pathway for the transport of nutrients. The continuous maintenance of internal plant-water, or plant-water potential, at maximum levels in an active-growing and transpiring plant is essential in productive plants. Water movement through the continuum tends to occur along gradients of decreasing water potential, which provide the necessary driving force. In the soil-plant portion of the continuum, the soil-water potential next to the roots generally exceeds that within the plant, thereby maintaining the driving force for water transport. The lowest water potential in the soil-plant portion is found in the leaves which serve as a sink for water transport to the atmosphere during plant transpiration.

Plant transpiration is the loss of moisture from leaf stomata in the form of water vapor. Evaporation takes place from inside the leaf where the responses of stomatal openings and leaf morphological structure regulate the escape of water vapor to the atmosphere. Transpiration is a function of leaf and air temperatures, atmospheric humidity, and wind (Chang, 1968; Mongelard et al., 1972). Gates (1968) pointed out the importance of transpiration in controlling leaf temperature, a critical factor in growth and yield. During transpiration, while plant-water is released to the atmosphere, important substances such as CO_2 are taken in through the stomata and assimilated in important processes such as photosynthesis and cell elongation. Provided that the roots are fully supplied with water and other factors of production are not limiting, there is usually a sufficient driving force to permit plant transpiration at the potential rate determined by atmospheric conditions, except at the midday lag (Mongelard et al., 1972).

Temporary plant-water deficits are not known to significantly limit growth or yield. Hsiao and Avecedo (1974) reported that vegetative growth crops under long periods of cultivation can make remarkable recoveries from internal water deficits, provided they are only temporary. However, longer deficits such as those lasting several days or longer are known to significantly limit growth and yield. The latter condition is common to many irrigated fields (Mongelard et al., 1972; Rawlins and Raats, 1975).

In sugarcane cultivation, growth is almost proportional to the amount of water which flows through the crop continuum, when other factors such as age, sunlight, air and soil temperatures and fertilizers are not limiting (Campbell, 1967; Thompson, 1976, Mongelard and Nickell, 1972; Mongelard and How, 1976).

In most field crops about 95 to 98 percent of the total absorbed soil moisture is consumed in transpiration losses, while the balance is used internally for plant development, growth, and productivity (Sutcliff, 1968; Kramer, 1969). Ashton (1956) reported that photosynthesis of sugarcane did not begin to decrease until the available soil-water was nearly exhausted. This supports Veihmeyer et al. (1950) who have published considerable data indicating that growth, transpiration and yield of certain crops were not reduced until the soil moisture content fell to near wilting point. Others generally agreed that water becomes progressively less available as the water content of the soil decreases, rather than remaining available until the water content falls to permanent wilting then suddenly become unavailable.

Rain is, undoubtedly, the most dominant climatic factor affecting plant growth for unirrigated crop. Rainfall possesses certain pecularities not associated with other climatic factors. It is intermittent and irregular, and it is effective for a more or less extended period after the event. It provides a growth stimulus which begins abruptly and gradually passes as the rain disappears through evaporation, transpiration and percolation. However, total rainfall is defective as a measure of growth since large amounts of rainfall are usually lost in the form of run-off during periods of intense rainfall. The influence of rainfall on growth is due to the moisture imparted to the soil as a result of the rain. The level of soil moisture at any particular moment is the consequence of successive rains. Thus rainfall amount and rainfall distribution are of equal importance for plant growth.

Temperature

Temperature has been employed as a measure of the environment for plant growth and development studies since the invention of the thermometer. The relationship between plant responses and temperature have been used more than any other relationship as a measure of the physical environment. This is due to the ease in measurement and manipulation and simplicity of the instrument, and not because temperature is a better index of plant responses than other climatic factors.

Germination constitutes a critical period in the life of the plant; good germination means a good start. Clement and Nakata (1967) showed that the number of days for emergence of single-bud sugarcane pieces was strongly influenced by soil temperature. For average temperatures of 66.3^{o}F, 55.9^{o}F and 52.8^{o}F, the average number of days for emergence of five buds were 11.6, 28.2 and 56.8 days, respectively. There was little or no germination at an average temperature of 50^{o}F.

The temperature of the upper few inches of soil has a strong influence on the germination of seed pieces, whereas it is usually the temperature of the upper several feet of soil that is of importance to the fully established plant.

The effects of temperature on sugarcane growth have been studied by Stender (1924), Das (1933, 1936) and Halais (1935). When soil moisture and nutrients are adequate, stalk elongation is highly correlated with air temperature.

Clements (1980) obtained a relationship between sugarcane elongation rate and maximum temperature, which shows elongation rate increasing with temperature up to 88°F, and then falling off. The day-degree concept introduced by Walter (1910) and Das (1933) assumes that the influence of temperature on elongation is nil when the maximum temperature is 70°F, the base temperature. The day-degrees for a day with maximum temperature of 80°F is 10 day-degrees. The day-degree is more commonly known as the degree-day among meteorologists. Although there is a definite correlation between growth and day-degrees, the relationship is far from precise. Rates and duration of growth are not affected equally by temperature.

These results are to be expected since temperature is only one of the many factors influencing cane growth. The other important factors are insolation, photosynthesis rate, and age of the plant. Many of the relationships between growth and temperature may be simply the reflection of the relationship between growth and radiation, since insolation and daytime temperature tend to be highly correlated in sugarcane growing areas. It is difficult to separate the effects of solar radiation and temperature on crop growth.

Root temperature plays a major role in affecting cane growth and nutrition. Irrespective of the air temperature, root temperature of 62^{o}F or below restricts growth, water consumption, translocation and N uptake (Mongelard et al., 1971). At temperatures of 74^{o}F and above, light is the principal factor affecting growth.

<u>Solar Radiation</u>

Radiation is the controlling factor for crop growth under optimum moisture conditions in Hawaii's lowland, where temperature is not a problem (Takahashi and Nickell, 1973; Nickell, 1977). Solar radiation provides the energy for photosynthesis and the warmth for crop development. The spectrum of solar radiation can be divided into three main regions: the ultraviolet (300-400 nm), the visible (400-700 nm) and the infrared (700-3000 nm). Photosynthetically active radiation (PAR) is the part of the solar radiation in the visible (400-700 nm) region and it is approximately 50 percent of the total solar radiation. The importance of solar radiation for crop growth is related to the PAR available for crop growth. Research from several locations has suggested that PAR is a constant fraction of short wave radiation. Sziecz (1974) stated that PAR was 0.50 of solar irradiance over a wide range of atmospheric conditions. Meek and his colleagues (1984) reported that PAR can be estimated from solar radiation measurements to within 10 percent.

The energy of the incident solar radiation on the full sugarcane canopy is partitioned as follows according to studies conducted by Chang (1961): 16 percent reflected radiation, 17 percent back radiation and 67 percent net radiation. Of the net radiation, 82 percent is used in evapotranspiration (about 55 percent of the insolation) and the remaining 18 percent is used to heat the air and for photosynthesis utilization.

Potential sugarcane yield is determined to a large extent by the amount of insolation incident on the plants (Chang et al., 1963, 1965). Clements (1980) reported a linear relationship between cane yield and solar radiation. Takahashi and Nickell (1973) reported that the weights of millable cane under full sun were twice the weights of sugarcane produced in plots under 50 percent shading. Nickell (1977) also reported that the total cane yields under 50 percent shade were less than one-half the weight of cane in full sun, depending on variety and nitrogen level.

Evapotranspiration

Evapotranspiration (ET) is the sum of evaporation and transpiration from a plant crop. When soil-moisture is at optimum level, potential evapotanspiration (PET) will take place. PET and actual ET vary according to the prevailing climate. Numerous studies (Campbell et al. 1959), Ekern (1970, 1977) have been conducted on the measurement of PET by sugarcane crop using lysimeters. Since lysimeter measurements could not be routinely taken, PET was related to pan evaporation. Daily pan evaporation readings are then used as estimates of PET or crop consumptive use.

Campbell et al. (1959) evaluated the PET or water consumption under no moisture-stress condition of the cane plant at various growth stages, and determined the ratio of PET to evaporation from a Class A evaporation pan installed 5 feet above ground level. The ratio increased from 0.4 for one month old cane to 1.01 for 5-month old cane when the canopy was fully developed. The ratio increased slightly to 1.20 from 5 to 11 months of age and then decreased to nearly 1.00 at 17 months of age. Advected heat affected PET more than pan evaporation, according to Ekern (1970, 1977) who obtained a ratio of PET to Class A pan evaporation of 0.85 for drip-irrigated cane after five months of age.

Evapotranspiration has been shown to be proportional to sugarcane growth (Thompson, 1976). Nickell (1968) showed a linear relationship between the amount of water utilized by sugarcane and dry matter yields. Thompson (1976) obtained a linear relationship between cane yield and crop water use with a correlation coefficient of 0.95. Sugar yield and water use, on the other hand, showed linear and curvilear relationships with correlation coefficient of 0.75 and 0.78.

Crop-weather Modelling Methods

The importance of the effect of weather and climate on crop production has brought about numerous research projects and publications dealing with crop-weather relationship. Various statistical and mathematical techniques have been used. McQuigg (1976) described two basic approaches to model the impact of meteorological variability on crop yields: (i) The physiological/physical processes which take place within a time interval in the plant-soil system and in the immediate atmospheric-soil environment of the plant; and (ii) the statistical or correlative approach which is based on the application of some sort of statistical technique--typically a regression technique--to yield and climatic data.

Jensen (1975) in his review of work on the effects of temperature and precipitation on yields, refers to three types of models: (i) statistical models as described by Thompson (1969, 1975); (ii) statistical models based on crop-weather-soil moisture as reported by Leeper et al. (1974); and (iii) physiological models as reported by Benci et al. (1975). The main difference between the two statistical models are: Thompson's model was developed from long-term normals for climate and yield data, whereas the Leeper et al. model was built on experimental data from the growing of corn under appropriate field conditions over a period of years. Haun (1974) proposed a wheat yield-weather prediction model based on the cause and effect relationship. It is not considered an empirical model although the weighting coefficients for pre-selected temperature and moisture variables are by necessity obtained in an empirical manner.

Baier (1979) classified crop-weather models into three categories: (i) crop growth simulation models, defined as simplified mathematical representations of the complex physical, chemical and physiological mechanisms underlying plant growth responses; (ii) crop-weather analysis models, which provide a running account of the accumulated crop responses to selected agrometeorological variables as a function of time or crop development; and (iii) empirical-statistical models, in which one or several variables representing weather or climate, soil characteristics or a time trend are statistically related to seasonal yield or other crop data.

CHAPTER III

MATERIALS AND METHODS

First-Order Regression Models

Meteorological Data

The meteorological data for the field tests conducted during the period 1959 to 1978 were obtained from the climatic data center of the Hawaiian sugar industry at the HSPA Experiment Station. Hawaii's sugar plantations have maintained a dense network of weather stations since the beginning of the century. There are about 400 rainfall, 150 temperature, 100 solar radiation and 70 evaporation stations on 220,000 acres of sugarcane land. The network is operated and maintained by plantations with quality assurance provided by HSPA staff. All weather data recorded by plantations are also reported to HSPA on a regular monthly basis.

All stations and instruments are set up to conform with the standards for a National Weather Service station. The solar radiation measuring instrument is, however, an exception since it is not an Eppley pyranometer, the standard instrument used.

Solar radiation were measured by photochemical method up to 1966. The basic principle of the photochemical measurement of sunlight depends upon chemical decomposition when exposed to light. The solution used is made of oxalic acid which has been sensitized with uranium sulphate. The decomposition is proportional to the amount of sunlight and converted to radiation units by relating the results to the corresponding readings obtained by Eppley pyranometers (Brodie, 1964).

Wig-Wag integrators were introduced in 1965, and used as replacement after testing and calibration with Eppley pyranometers. Since both the photochemical method and the Wig-Wag monitors were calibrated against Eppley pyranometers, the data obtained by the two methods are compatible.

The Wig-Wag instrument, described in detail by Brodie (1965), was developed by the HSPA Experiment Station and manufactured by Beckman Inc. It operates on the basis of expansion of the gaseous phase of methyl alcohol as a result of conversion of radiant energy to sensible heat. The Wig-Wag consists of three basic components: (1) a pulse-glass and its mounting, (2) a mechanical counter, and (3) a cast aluminium housing with a hemispherical glass dome. The pulse glass is made of two spherical glass bulbs of 1.5-inch outside diameter. The bulbs are painted flat black and are connected by an 8-inch glass tube bent 90 degrees at each end. The pulse-glass is partially filled with anhydrous methyl alcohol and sealed after air is evacuated. It is mounted at its mid-point on a shaft inclined 20 degrees from the vertical; in this position, the bulb exposed to the sun is lower than the shaded one. Radiant energy falling on the exposed bulb causes an increase in the saturated vapor pressure of the alcohol and forces the liquid to move against gravity to the upper bulb, which swings to the lower position when it becomes heavier. This action is perpetual as long as there is sufficient incident energy. The Wig-Wag monitor is serviced and calibrated regularly against an Eppley pyranometer by HSPA staff. Hanshuncheong (1974) discussed the method used to convert the Wig-Wag counts to radiational units in calories/cm^2/day, also known as langleys/day (ly/day), and reported a mean deviation of $\pm$ 4 percent when monthly Wig-Wag results were compared to results obtained by Eppley pyranometers.

Maximum temperature is measured by a mercury-in-glass thermometer with a constriction just above the bulb. Minimum temperature is measured by an alcohol-in-glass thermometer with a floating index. The thermometers are read to a tenth of a degree (F) and exposed inside a louvered shelter, which is mounted 32 inches above the ground level. Weather stations on sugarcane plantations in Hawaii are usually located a short distance from sugarcane fields.

Solar radiation, maximum temperature and minimum temperature are used for the multiple regression analysis.

The monthly data for each test was extracted from computer files. Cumulative values for 3, 6, 12, 18 months and for each crop cycle were derived from these data and used as input for the crop yield/weather modelling.

Agronomic Data: Field Test Harvest Data

The agronomic data used for the multiple regression analysis consist of the harvested sugarcane results of FT7 field tests conducted by the HSPA Experiment Station from 1959 to 1978. These yield data represent the end measurement of sugarcane growth in tons of cane per acre (TCA) for 20 to 26 month old crops.

Field tests are conducted by the Genetics and Pathology Department of the Experiment Station as part of their breeding, selection and propagation program in Hawaii. The yield data from this program are among the more accurate and reliable data available.

The FT7 test, which is the final stage of yield testing, consists of 50 feet by 50 feet test plots of ten lines planted on plantation fields in a combination of replicated and unreplicated plots in a randomized block arrangement with 3-4 blocks. Planning of the yield tests starts with careful selection of representative and uniform sites, and proper blocking of plot layout to minimize plot-to-plot variation within each block. Fertilizer levels and timing of application are consistent with plantation practices. Normally, plant stand adequacy in yield test plots is evaluated during the second month after planting and gaps of four feet or wider are replanted. The FT7 yield test results not only provide one of the more reliable and accurate sources of yield data, they are the only source of data that are available for the study of the yield-weather relationship for a specific cane variety over a reasonably long period of time.

Plantation data on any one variety are usually limited to a period of about 10 years, or less, and the amount of yield data depends on the age of harvest, which ranges from 18 to 40 months. The relatively short production period of any one variety is due to the tendency of a cane variety to decline in yield after a few years of continuous cultivation.

FT7 yield results for a variety, on the other hand, may be available for a considerably longer time. FT7 yield data for a variety start with the planted crop on most plantations, followed by one or two ratoon crops. Usually many FT7 are repeated for areas where that variety shows great potential. In general, a variety may be in the experimental stage for ten years or more before being adopted as a commercial variety. However, the availability of FT7 yield data for that variety does not stop with the commercial implementation of that variety. This variety continues to be planted in FT7 tests, but this time as the check variety against which all new varieties will be compared. Thus, it is possible to obtain consistent and accurate yield data for one variety for a period of about 20 years or so.

There is yet another advantage of working with FT7 yield data. By selecting one variety the factor of varietal impact on yield in response to weather can be eliminated. FT7 yield tests of variety H50-7209, the leading variety from 1962 through 1972, were chosen for this study. Some 600 sets of test results for the period 1959 to 1978 were obtained and used.

Only yield tests on irrigated fields were used in order to minimize the dominant effect of rainfall variability. It should be noted, however, that fields are not always irrigated to the optimum, and may also suffer from moisture stress depending on the availability of irrigation water. Irrigation water is usually brought in from watershed areas by many miles of ditches. Widespread drought is usually caused by low rainfall in the watershed areas and at the sugarcane fields for extended periods. During drought periods, the limited irrigation water is distributed among fields using a procedure that minimize the impact on the plantation as a whole. Usually fields in advanced stages of growth are given higher priority to the extent of keeping the plants alive in order to preserve whatever sucrose or cane already produced. Younger crops, which usually need less water, are also high on the priority list in order to prevent major failure of the next season's crop.

Model Formulation

FT7 yield data and the climatic data for the 600 tests are used as input to the classical method of statistical analysis--multiple regression analysis--to determine the relationships between yield and climatic variables, and to determine the variability of sugarcane crop that is attributable to climatic variability. Multiple regression analysis is the most frequently used statistical technique for estimating the relationships between crop yields and climatic variables. Reduction of the number of variables is achieved by grouping monthly insolation, and maximum and minimum temperatures into cumulative values for 3, 6, 12 and 18 months and for each crop cycle.

It is necessary to group monthly values into longer periods in order to overcome an experimental design problem characterized by too few observations and too many predictor variables. There are a total of 72 monthly values for insolation, and maximum and minimum temperatures for a field harvested after 24 months, while the number of FT7 harvest yield results varies between 38 and 136 per plantation. Only the first-order regression analysis model is used because of this constraint.

Many researchers, Thompson (1969, 1975), Sakamoto (1981) among others, have shown that weather is not the only source of variability in crop yields. Significant yield increases have been attributed to technology, which includes increased rate of fertilizer application and the introduction of higher yielding varieties. Trend lines are included in some statistical models to account for the trend in crop yields. However, in this study there is no such requirement since no such trend is observed from the FT7 yield data.

Linear multiple regression analysis is performed using the sugarcane yield reported in tons of cane per acre as the dependent variable, and solar radiation, maximum temperature and minimum temperature totals for various periods as the independent variables.

The independent variables were standardized in order to remove non-essential ill-conditioning, as discussed by Snee (1973), and to make comparisons between the models more meaningful. The ill-conditioning is not due to any real defect in the data, but only to the arbitrary origins of the scales on which the predictor variables are expressed. The standardization of data was done in two steps, namely by centering and scaling. Centering is the process by which the mean is subtracted from each variable and scaling is the process by which the centered variable is divided by its standard deviation. In a linear model, centering removes the correlation between the constant term and all linear terms. In a quadratic model, centering reduces and may completely remove the correlation between the linear and quadratic terms. Scaling expresses the equation in a form that lends itself to more straight forward interpretation and use. The advantages of standardization of the predictor variables are (1) coefficients are estimated within the range of the data, and, therefore, are estimated with maximum precision, (2) ranking of coefficients is meaningful and (3) interpretation of coefficients is straight forward.

Non-Linear Model

Meteorological Data

The meteorological data used as input to the non-linear functional model were obtained from weather stations near the fields from which elongation data are used (Fig. 1). The details regarding weather station location and instrumentation are identical to the description of meteorological data in Part A. The input are monthly mean insolation and maximum temperature.

Monthly rainfall and evaporation data for these stations are also available. Evaporation data were reported to be significantly correlated with potential evapotranspiration (PET) of sugarcane according to studies in Hawaii (Campbell et al, 1959; Chang, 1961; Ekern, 1977).

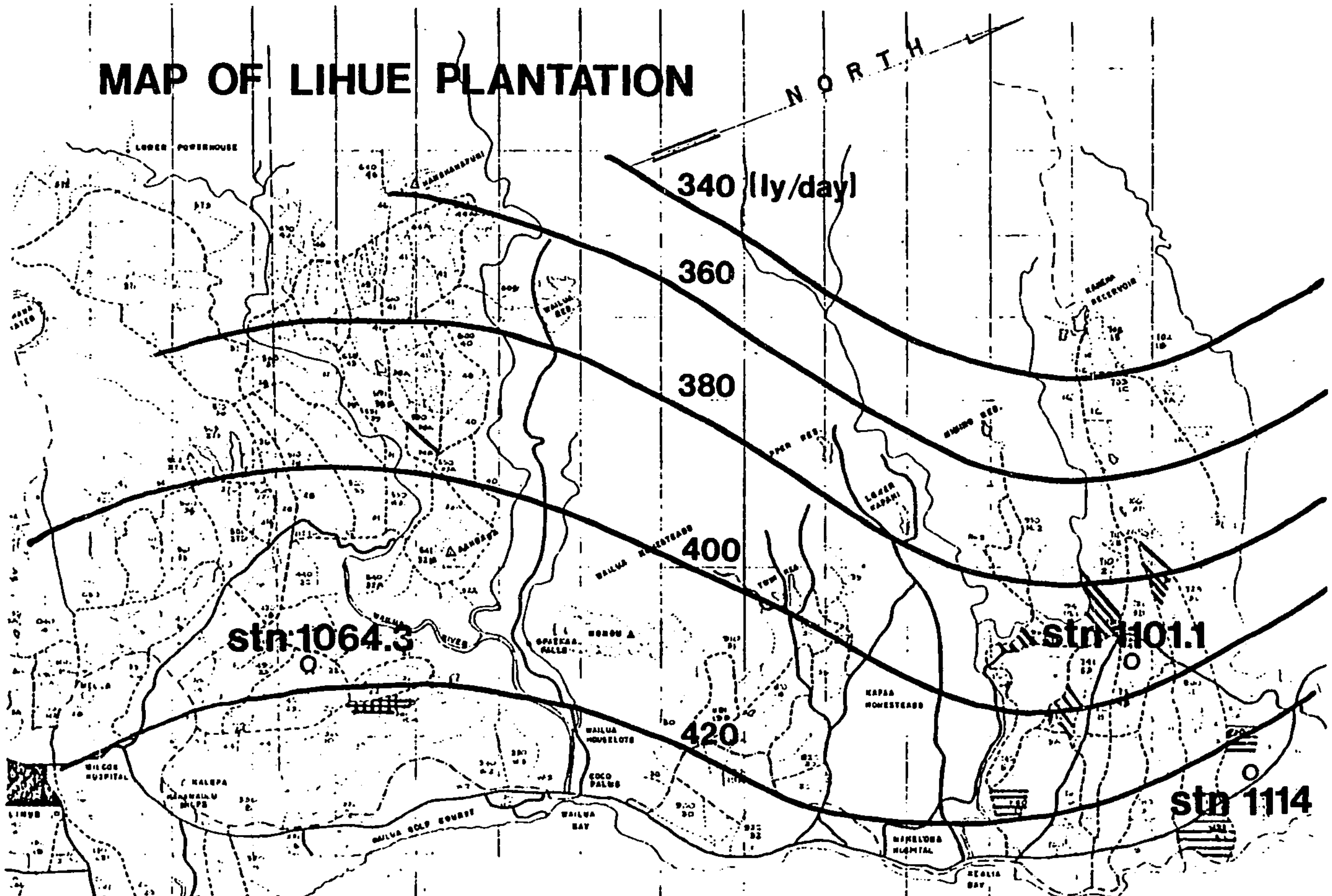

Fig. 1. Map of the Lihue Plantation showing the weather stations (o) and fields (hatched) from which elongation data were used. Isolines of the mean annual solar radiation are also shown.

Evaporation, rainfall and irrigation data, when available, are used to assess soil-moisture conditions.

The ratio of PET measured from lysimeters to evaporation from a Class-A pan installed 5 feet above ground level averaged 1.0 to 1.2 after close-in for furrow irrigated sugarcane (Campbell, 1959; Chang, 1961), and 0.75 to 0.80 for sprinkler- and drip-irrigated sugarcane (Ekern, 1977) on a monthly basis. The evapotranspiration studies in Hawaii were summarized by Jones (1980). The relative water use index, that is the ratio of total water (rainfall plus irrigation) to evaporation, is a measure of the adequacy of soil moisture; a ratio of 1.0 or greater indicates no moisture stress, whereas a ratio of less than 1.0 indicates moisture stress, with stress increasing with decreasing relative use index.

Agronomic Data: Monthly Elongation Data

The agronomic data used for the calibration the validation and testing of the non-linear model consist of monthly elongation measurements obtained from the Lihue Plantation, located on the island of Kauai. The field harvest yield data are also available. This is a unique set of data in that during the past 100 years, there have been only three or four field experiments in Hawaii that provided elongation rate measurements for sugarcane crops started each month of the year. However, there is a difference between the previous sets and the current set of data, the previous sets of data were from experimental plots, whereas the Lihue Plantation data .e from commercial production fields.

The elongation data used for this study were obtained from measurements of the length of sugarcane stalks taken by the Lihue Plantation from 1983 through 1985; elongation measurements for 1982 were available but not used because of the effect of hurricane Iwa. Measurements of cane plants started three to four months after planting and continued on a monthly basis until the crop was about 21 to 23 months old and treated by aerial application of chemical ripeners. The last elongation measurement usually shows a drastic reduction in growth as a result of the effect of the chemical ripener and is, therefore, excluded in this study. The monthly elongation rate for a field is based on an average of ten stalks from different stools for each field, the same stalks being used throughout the measurement periods. In the event that one of the selected stalks showed sign of inflorescence or dying, a representative primary stalk from nearby was used as replacement for the continuation of elongation measurement.

Harvest yield data were also available for fields harvested in 1984 and 1985. The harvest data consist of sugarcane yield in tons of cane per acre (TCA), sugar yield in tons of sugar per acre (TSA), age of cane at harvest in months and date of harvest.

The elongation data used for this study are restricted to cane variety, H62-4671 from irrigated fields (Fig. 1). These two restrictions attempt to eliminate varietal response and the impact of rainfall and soil moisture on growth.

Model Formulation

The monthly elongation data and the corresponding monthly insolation and maximum temperature from a nearby weather station are used as input for a sugarcane growth model using a non-linear model which combines the mechanistic approach and the empirical approach.

The term mechanistic refers to the mechanism of the system, or how the parts of the system work together as they might in a machine. The empirical approach is used to insure that the mathematical function will reasonably fit the experimental observations.

Thornley (1976) stressed that there is no clearly defined dividing line between the two approaches. It is a matter of emphasis. Mechanistic modellers tend to build their models before doing the experiments and are guided by existing data and knowledge. The empirical modeller, on the other hand, may make his guesses about the mechanism after doing the experiment and looking at the data.

At the very least, development of a mechanistic model for plant growth in response to climatic factors and age should be based on qualitative knowledge of the physical relationship between a given variable and growth. The general relationships between plant growth and the environment are in a broad sense well known, but a precise quantitative description of these relationships has not yet been achieved. The response of plants to the environment is complex because of the interaction of many variables and plant factors, all of which affect plant growth. In order to reduce the number of factors affecting growth, the data selected for this part of the study are also restricted to one cane variety from irrigated fields. In this study, growth rate refers to the elongation rate of the primary stalks.

Solar radiation and maximum temperature may be the two most dominating variables when plant-moisture is optimum. This is because photosynthesis rate may be considered synonymous with growth, and the ultimate increase in dry matter production in plants is based on photosynthesis. The age of the crop is one factor known to have significant impact in sugarcane growth. The effects of these factors are discussed below.

Effect of Insolation on Growth

Potential sugarcane yield is determined to a large extent by the amount of solar radiation incident on the plants. Clements (1980) reported a linear relationship between growth and insolation (Fig. 2). The growth unit used by Clements (1980) is defined as the daily increase in cane volume obtained by multiplying the daily elongation rate in centimeters and green weight of the sheaths, in grams, per stalk. The increase in sugarcane growth rate with increasing insolation supports findings by Burr et al. (1957) that sugarcane has a high saturation light intensity, and by Takahashi et al. (1973) and Nickell (1977) that cane yield is proportional to solar radiation incident on the plants.

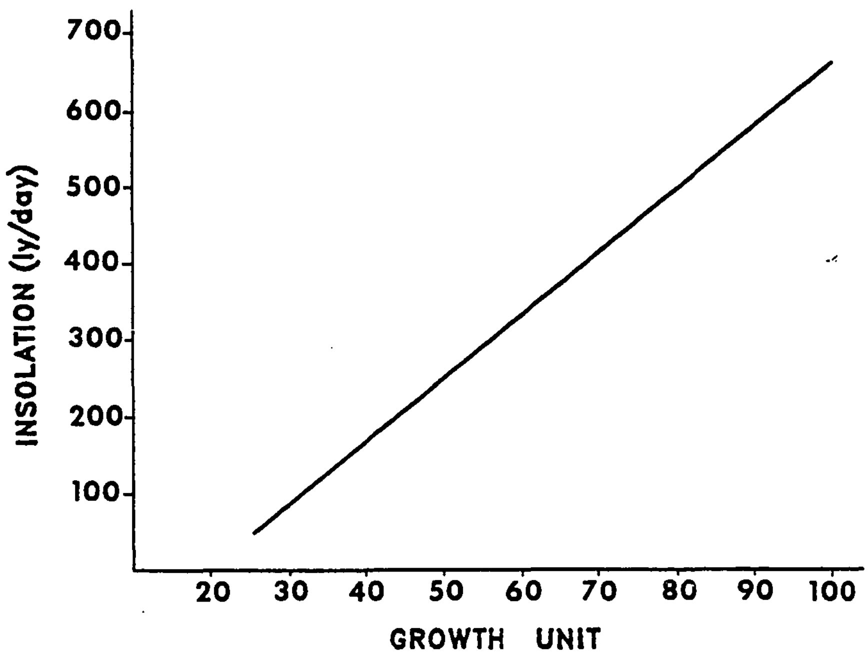

Fig. 2. Relationship between measured sugarcane growth rate and insolation. Redrawn from Clements (1980).

Effect of Temperature on Growth

Sugarcane, like other plants, has a well-defined temperature range for the growth processes. Three cardinal temperatures for sugarcane are known. Clements (1980) obtained a relationship between sugarcane growth and maximum temperature, with growth increasing almost linearly with temperature up to 88°F, after which there is a decline in growth rate.

The maximal temperature above which sugarcane growth is checked is not accurately known, but is estimated to be around 110°F. The optimal temperature which is most conducive to the interactions of all physiological processes, is between 86° to 90°F (Fig. 3, Clements, 1980).

Effect of Age on Growth

Verret and Das (1927), Borden and Denison (1942) and Clements (1980) have shown that sugarcane growth is highly dependent on crop age. Fig. 4 shows the effect of age on elongation rate after removal of the seasonal effects reported by Verret and Das (1927). The elongation data were obtained from monthly measurements of the length of 20 primary stalks for each planting of the experimental plots. Plantings were made each month starting in July for 12 consecutive months. The seasonal effects were removed by monthly averaging of the monthly elongation rates for each crop age between 3 and 17 months by month of the year.

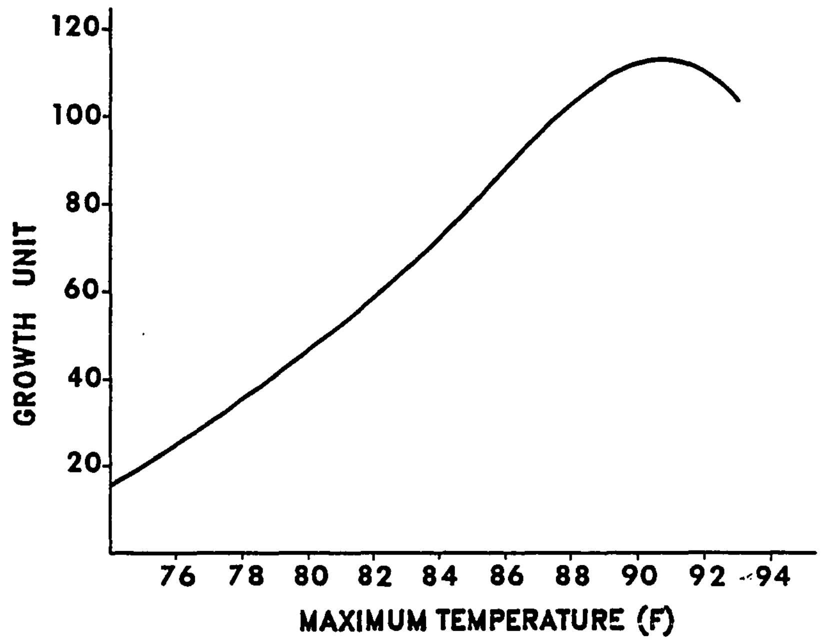

Fig. 3. Relationship between measured sugarcane growth rate and maximum temperature. Redrawn from Clements (1980).

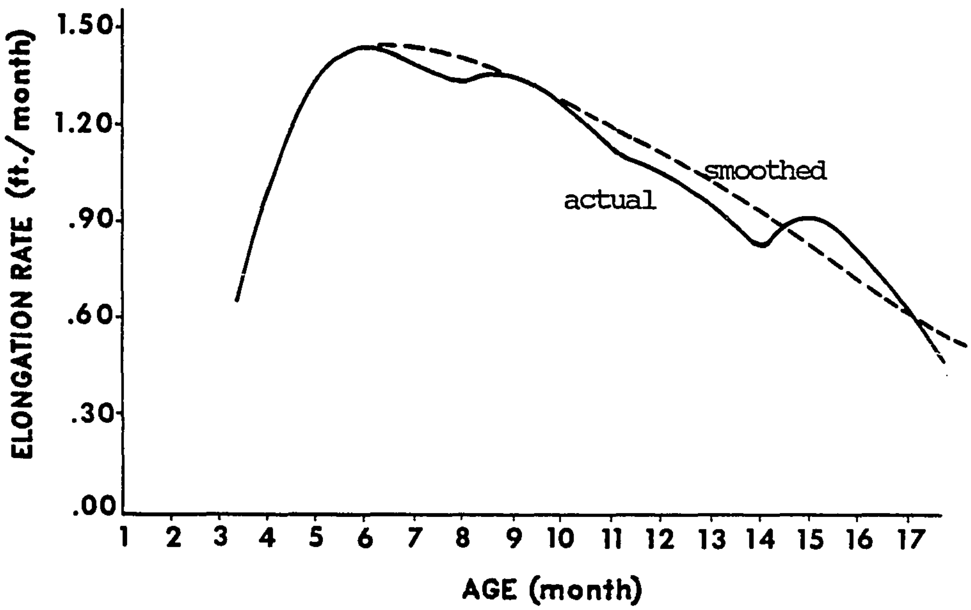

Fig. 4. Relationship between measured sugarcane growth rate and crop age. Redrawn from Verret and Das (1927).

The growth rate of sugarcane is highest between the age of 3 to 12 months with a maximum at 6 months. The growth rate increases between 3 and 6 months, and then decreases rapidly between 6 and 12 months. The decline in growth rate is more gradual one year after planting. The growth rate at 18 months is 40 to 60 percent of the optimum growth rate at 6 months of age depending on variety and other factors. Kortschak and Forbes (1969), reporting on the relationship between photosynthesis rate and crop age, showed a similar trend for individual leaves.

Integrated Effects of Insolation, Temperature, and Age

Studies at the HSPA Experiment Station have shown that the amount of water utilized by individual cane plants has a linear relationship to the total dry weight produced; this relationship was first reported in the 1963 Annual Report of the Experiment Station. Nickell (1968) reported on the relationship between solar radiation, root and air temperatures and water utilization, and showed that sugarcane growth increased with both root and air temperatures up to 75°F in the climate house experiments. A sharp decline in water utilization or growth was noted for root temperatures below 60°F. The increasing growth trend with solar radiation is also clearly demonstrated in that study.

Since sugarcane growth is significantly affected by age, insolation and maximum temperature when soil and plant moisture is not limiting, a realistic growth model should therefore include, as a minimum, the effects of age, insolation and temperature on growth.

Model Development

The effect of insolation on sugarcane growth rate in Fig. 2 may be represented by the following mathematical expression:

$$G_a(I) = \frac{G_o \, Rad(I)}{R_o} \quad (1)$$

Where $G_a(I)$ is the mean growth rate in inch/day for month (I),

Rad(I) is the mean monthly insolation in ly/day, and

G_o and R_o are positive constants.

G_o represents the optimum growth rate at the optimum radiation R_o for a particular soil type. Since this is a linear equation, the optimum insolation is actually the maximum insolation for the region.

The curve representing the relationship between growth and temperature (Fig. 3) is almost like the mirror image of the curve representing the relationship between growth and age (Fig. 4). However, if the shorter end of both curves is extended, the two extended curves are bell-shaped and could be considered similar. Thus, both extended curves may be represented by the same type of mathematical expression. Therefore, the curves shown in Fig. 3 and 4, which are segments of the extended curves, may also be represented by the same type of function.

The curves may be represented by the following mathematical equation:

$$Y = \frac{l}{m+n(X-X_o)^2} \tag{2}$$

Where Y is the dependent variable,

X is the independent variable,

X_o is optimum value of X at which Y is maximum,

and l, m, n are positive constants.

Therefore, the individual and integrated effect of age and maximum temperature on sugarcane growth rate may be represented by:

$$G(I) = \frac{K}{a+b(Age(I)-A_o)^2+c(Temp(I)-T_o)^2} \tag{3}$$

where G(I) is the growth rate for month (I),

Age(I) is age of crop in month,

Temp(I) is the monthly maximum temperature (F),

A_o is the optimum age for maximum growth,

T_o is the optimum temperature for growth, and

k, a, b, c are positive constants.

The interaction of insolation may be integrated into the effect of age and maximum temperature by combining equation (1) and (3) as follows:

$$G_a(I) = \frac{G_o \ \mathrm{Rad}(I)}{aR_o + b(\mathrm{Age}(I) - A_o)^2 + c(\mathrm{Temp}(I) - T_o)^2} \quad (4)$$

where all the terms are as defined above.

Generalized Growth Model

Equation (4) may be simplified by dividing by the coefficient a. Thus, the proposed generalized non-linear model for sugarcane growth rate in response to age, insolation and maximum temperature is

$$G_a(I) = \frac{G_o \ \mathrm{Rad}(I)}{R_o + b(\mathrm{Age}(I) - A_o)^2 + c(\mathrm{Temp}(I) - T_o)^2} \quad (5)$$

where b and c are positive coefficients to be determined empirically.

Generalized Relative Growth Model

If G_o in equation (5) is set to unity, then the model determines the relative growth rate as a function of age, insolation and temperature, and the equation becomes:

$$G(I) = \frac{\mathrm{Rad}(I)}{R_o + b(\mathrm{Age}(I) - A_o)^2 + c(\mathrm{Temp}(I) - T_o)^2} \quad (6)$$

where G(I) is the relative growth rate.

Determination of Coefficients

It is necessary to consider each parameter of the model separately and in conjunction with other parameters to derive the coefficients b and c.

Under optimal temperature and age conditions, the model for relative growth may be written as

$$G(I) = \frac{Rad(I)}{R_o} \tag{7a}$$

and the model for absolute growth is

$$G_a(I) = \frac{G_o \, Rad(I)}{R_o} \tag{7b}$$

Thus, the proposed growth model in response to radiation is a linear model in agreement with Fig. 2 as reported by Clements (1980). According to the model, the growth rate is proportional to the light intensity received by the plant. Similarly under optimum insolation and temperature conditions, the model becomes:

$$G(I) = \frac{R_o}{R_o + b(Age(I) - A_o)^2} \tag{8a}$$

or

$$G(I) = \frac{1}{1 + (b/R_o)(Age(I) - A_o)^2} \tag{8b}$$

and under optimum age and insolation conditions, the model becomes:

$$G(I) = \frac{R_o}{R_o + c(\mathrm{Temp}(I) - T_o)^2} \tag{9a}$$

or

$$G(I) = \frac{1}{1 + (c/R_o)(\mathrm{Temp}(I) - T_o)^2} \tag{9b}$$

Equations (8) and (9) describe what is known qualitatively about the relationships between growth and age, and between growth and maximum temperature.

The value of the coefficients b and c must be such that the results of the model are realistic at least at the optimum conditions and at the two extreme conditions within the ranges of each of the three factors. The optimum values of age, insolation and maximum temperature are known and substituted in the proposed growth model before it is subjected to calibration. The coefficients b and c are determined by the calibration process.

Model Calibration

The model is subjected to a calibration process after a preliminary determination of the coefficients b and c based on the individual relationships between growth rate and solar radiation, between growth rate maximum temperature and between growth rate and age (Figs. 2, 3 and 4). The mean monthly insolation and maximum temperature data for the period of elongation measurements of the three selected fields are used as input to the model. The value G_o, the optimum growth rate for the area, is obtained from the elongation data of the Lihue Plantation. The model is calibrated by making changes to the two coefficients after comparison of the computed growth rates with the mean measured elongation rates from three fields located near the weather station. The process is repeated until a realistic growth curve and reasonably good correlation is obtained.

Model Validation

The calibrated model is then validated using correlation analysis between the measured growth rates and the elongation rates computed by the model with age in month, mean monthly insolation and maximum temperature as input. The model, obtained after calibration, is used without change throughout the entire testing phase and for studies of the interactions of these factors on simulated sugarcane growth.

Growth Simulation

Using the derived mathematical equation developed for the non-linear model, a series of growth simulation curves is generated by computer for a wide range of insolation and maximum temperature, for the ages between 3 to 27 months. These computer simulated growth curves are then used for the analysis of the individual impact of these three factors and of their interactions on sugarcane growth.

CHAPTER IV

RESULTS AND DISCUSSIONS

First-Order Regression Models

The multiple regression models used to investigate the relationship between FT7 cane yields and climatic variables are variations of the following first-order model.

$$\begin{aligned} Y = a &+ b(1)S(1) + b(2)S(2) + \ldots + b(n)S(n) \\ &+ c(1)H(1) + c(2)H(2) + \ldots + c(n)H(n) \\ &+ d(1)M(1) + d(2)M(2) + \ldots + d(n)M(n) \end{aligned} \quad (10)$$

where Y = cane yield in tons per acre (TCA),

S = cumulative insolation (langley),

H = cumulative maximum temperature (F), and

M = cumulative minimum temperature (F);

the cumulative values of the standardized climatic variables are for specified periods within the crop age of each test.

a, b(1) to b(n), c(1) to c(n), and d(1) to d(n) are coefficients to be estimated for each model.

Only linear models are considered because of the constraint of having relatively too few observations and too many predictor variables resulting from the long growing period of the crop which average almost 24 months. Even with linear model, monthly climatic values connot be used. The shortest cumulative period for the climatic variables used for the regression analysis is 3 months.

Ten first-order models with input described in Table 1 were tested.

Table 1. Input to Multiple Regression Models.

Predictand: Harvest yield result in tons of cane per acre (TCA).

Predictors: Standardized cumulative insolation(S), maximum temperature(H) and minimum temperature(M) for periods indicated in month, with or without age(A) of crop in month.

MODEL	AGE	PERIODS OF CUMULATIVE VALUES FOR PREDICTORS
I	no	1st-last month
Ia	yes	same
II	no	1st-18th month
IIa	yes	same
III	no	1st-12th, 13th-last month
IIIa	yes	same
IV	no	1st-6th, 7th-12th, 13-18th, 19th-last month
IVa	yes	same
V	no	1st-3rd, 4th-6th, 7th-9th, 10th-12th, 13th-15th, 16th-18th, 19th-21st month
Va	yes	same

The results of the ten models for the entire set of data are summarized in Table 2, and for each plantation in Tables 3-7. There are only five cases which have R-square values equal to or greater than 0.30. Models IV and IVa, which used 6-month cumulative values of the independent variables, have values of 0.30 and 0.40.

The two highest R-square values of 0.44 and 0.49 are obtained with models V and Va using 3-month cumulative periods. The low R-square values for the multiple regression models indicate that the first-order model would have limited predictive values.

There is a tendency for the values of the coefficient of determination to improve with shorter cumulative periods. This may be an indication that perhaps better association may be obtained if the cumulative periods for the climatic variables can be made to coincide with the critical growth phases of the internodes of the stalks.

Analysis of those models, which have R-square values of 0.25 or greater, gave a confounding picture as to which of the predictor variables are important. For example, out of the 7 models in Table 6, the coefficients for solar radiation for the period of 7th to 12th month are negative for the two models for Wailuku and one for Olokele. This is contrary to known fact that cane growth during this period is near optimum and highly correlated with solar radiation. It appears that some of the models do not have physically meaningful structure. Some of the coefficients appear to be unstable as in the case of the the maximum temperature, H(7-12), which has a negative coefficient in the model for Oahu Sugar Co. and a positive coefficient in the model for Wailuku. Here again, the coefficient for maximum temperature from the 7th to 12th month of the crop should be positive since growth at that stage are known to be positively correlated with maximum temperature. The most unexpected cases are models V and Va for Olokele which have the best associations between cane yield and climatic factors with or without age, but have negative coefficients for insolation for the periods 4-6 months, 10-12 months and 19-21 months. It is highly unlikely that insolation for almost the entire cycle of the crop is negatively correlated with cane yield.

The addition of crop age to the list of predictors increases the R-square values slightly in a few cases, particularly when the values are already above 0.25. This is the only factor which is stable with a consistent positive coefficient when included in a model, indicating that cane yield continued to increase as age of harvested cane increases to its highest age in the set of data analysed.

The first-order models did not demonstrate that a substantial proportion of the cane yield variability could be attributed to insolation, temperature or age of the crop. This may be due to several factors, some of which may be climatic or agronomic, while others may be due to model design. The model may not have been adequate because other climatic or agronomic factors were not included.

Table 2. Results of Stepwise Regression Analysis for the Ten Models for All Data.

Predictand: Harvest yield result in tons of cane per acre (TCA).
Predictors: Standardized cumulative insolation(S), maximum temperature(H) and minimum temperature(M) for periods indicated in month.

Number of observations = 593

Period:	1st-last month
Model I:	TCA=131.42+1.67S(1-L)+1.79M(1-L)
	R^2 = .01
Model Ia:	TCA=-19.97-1.80H(1-L)+6.48A
	R^2 = .10
Period:	1st-18th month
Model II:	No variables met the .15 significance level
Model IIa:	TCA=-9.94+6.05A
	R^2 = .10
Periods:	1st-12th, 13th-last month
Model III:	TCA=131.42+2.46S(13-L)+3.06M(13-L)
	R^2 = .03
Model IIIa:	TCA=-27.52-2.10H(13-L)+6.80A
	R^2 = .10
Periods:	1st-6th, 7th-12th, 13th-18th, 19th-last month
Model IV:	TCA=131.42-3.04S(7-12)+3.10S(19-L) +1.78M(13-18)+1.90M(19-L)
	R^2 = .04
Model IVa:	TCA=-30.65-1.94S(7-12)-2.33H(19-L)+6.94A
	R^2 = .11
Periods:	1st-3rd, 4th-6th, 7th-9th, 10th-12th, 13th-15th, 16th-18th, 19th-21st month
Model V:	TCA=131.41-2.00H(10-12)-3.49M(4-6)+4.35M(16-18)
	R^2 = .02
Model Va:	TCA=44.11-2.89M(4-6)+4.44M(16-18)+3.74A
	R^2 = .05

Table 3. Results of Stepwise Regression Analysis for Model I and Ia by Plantations.

Predictand: Harvest yield result in tons of cane per acre (TCA).

Predictors: Standardized cumulative insolation(S), maximum temperature(H) and minimum temperature(M) for periods of 1st to last month(1-L) of the crop, with or without age(A) of crop in month.

LOCATION	DF	R^2	AGE	MODEL
Ewa	74	.14	no	TCA=148.28+9.12H(1-L)
		.14	yes	same
Oahu	48	-	no	*
		.28	yes	TCA=-45.80+5.04S(1-L)-6.85H(1-L) +7.52A
Waialua	69	.03	no	TCA=136.76+4.59M(1-L)
		.14	yes	TCA=-31.64+7.29A
HC&S	136	.04	no	TCA=125.30+5.36M(1-L)
		.11	yes	TCA= 13.71+4.67M(1-L)+4.76A
Pioneer	69	.12	no	TCA=124.11+5.94S(1-L)-9.15M(1-L) +6.71H(1-L)
		.23	yes	TCA=-89.38+4.83S(1-L)-8.71M(1-L) +9.06A
Wailuku	52	-	no	*
		.15	yes	TCA=-49.06+7.49A
Kekaha	107	.03	no	TCA=128.04-3.53S(1-L)
		.03	yes	TCA= 20.30-6.58S(1-L)+4.68A
Olokele	38	.10	no	TCA=143.72+9.19M(1-L)
		.10	yes	TCA=-92.25+10.04A

* No variables met the 0.15 significance level for entry into the model.

Table 4. Results of Stepwise Regression Analysis for Model II and IIa by Plantations.

Predictand: Harvest yield result in tons of cane per acre (TCA).

Predictors: Standardized cumulative insolation(S), maximum temperature(H) and minimum temperature(M) for periods of 1st to 18th month(1-18) of the crop, with or without age(A) of crop in month.

LOCATION	DF	R^2	AGE	MODEL
Ewa	74	.08	no	TCA=148.28-5.60M(1-18)+6.42H(1-18)
		.13	yes	TCA= 36.49-5.60M(1-18)+7.09H(1-18) +4.69A
Oahu	48	.07	no	TCA=130.80-6.18M(1-18)
		.28	yes	TCA=-46.47+7.55A
Waialua	69	-	no	*
		.15	yes	TCA=-31.64+7.29A
HC&S	136	.05	no	TCA=125.30+7.22M(1-18)
		.14	yes	TCA= 16.51+6.59M(1-18)+4.64A
Pioneer	69	.08	no	TCA=124.11-8.07M(1-18)+7.07H(1-18)
		.19	yes	TCA=-85.36-7.07M(1-18)+8.89A
Wailuku	52	-	no	*
		.15	yes	TCA=-49.06+7.49A
Kekaha	107	-	no	*
		-	yes	*
Olokele	38	-	no	*
		.16	yes	TCA=-63.03+6.83M(1-18)+8.79A

* No variables met the 0.15 significance level for entry into the model.

Table 5. Results of Stepwise Regression Analysis for Model III and IIIa by Plantations.

Predictand: Harvest yield result in tons of cane per acre (TCA).

Predictors: Standardized cumulative insolation(S), maximum temperature(H) and minimum temperature(M) for periods of 1st to 12th month(1-12), and 13th to last month(13-L) of the crop, with or without age(A) of crop in month.

LOCATION	DF	R^2	AGE	MODEL
Ewa	74	.21	no	TCA=148.28-8.91S(13-L)+15.40H(13-L) +15.40H(13-L)
		.21	yes	same
Oahu	48	.23	no	TCA=130.80+8.66S(13-L)-7.76H(1-12)
		.28	yes	TCA=-46.47+7.55A
Waialua	69	.25	no	TCA=136.76+5.21S(13-L)-10.08M(1-12)
		.25	yes	TCA= 43.42-9.27M(1-12)+13.25L(13-L) +4.04A
HC&S	136	.09	no	TCA=125.30-4.07H(1-12)+6.22M(13-L)
		.15	yes	TCA= 24.44-4.18H(1-12)+4.02M(13-L) +4.31A
Pioneer	69	.11	no	TCA=124.11-8.67M(1-12)+5.19H(13-L)
		.21	yes	TCA=-62.48-7.96M(1-12)+7.92A
Wailuku	52	-	no	*
		.15	yes	TCA=-49.06+7.49A
Kekaha	107	.07	no	TCA=128.04-4.28S(1-12)+3.21M(1-12)
			yes	same
Olokele	38	.10	no	TCA=143.72+9.39M(13-L)
		.10	yes	same

* No variables met the 0.15 significance level for entry into the model.

Table 6. Results of Stepwise Regression Analysis for Model IV and IVa by Plantations.

Predictand: Harvest yield result in tons of cane per acre (TCA).

Predictors: Standardized cumulative insolation(S), maximum temperature(H) and minimum temperature(M) for periods of 1st to 6th month(1-6), 7th to 12th month(7-12), 13th to 18th month(13-18), and 19th to last month(19-L) of the crop, with or without age(A) of crop in month.

LOCATION	DF	R^2	AGE	MODEL
Ewa	74	.26	no	TCA=148.28-14.83S(19-L)-7.50M(19-L) +28.00H(19-L)
		.26	yes	same
Oahu	48	.30	no	TCA=130.80+7.96S(13-18)+7.28S(19-L) -5.79M(1-6)-8.89H(7-12)
		.40	yes	TCA=-65.79+8.21S(13-18)-5.77M(13-18) +8.37A
Waialua	69	.20	yes	TCA=136.76-11.60M(7-12)+15.65M(19-L)
		.22	yes	TCA=-17.94-7.59M(1-6)+11.25M(13-18) +6.70A
HC&S	136	.17	no	TCA=125.30+5.56S(7-12)+4.58S(19-L) +11.05M(13-18)-5.86H(13-18)
		.19	yes	TCA= 23.27+11.22M(13-18)-5.97H(13-18) +4.36A
Pioneer	69	.11	no	TCA=124.11+5.42S(19-L)-7.34M(7-12)
		.21	yes	TCA=-60.55-4.70M(1-6)-5.91M(7-12) +7.84A
Wailuku	52	.26	no	TCA=124.42-13.25S(7-12)+13.96H(7-12) -8.50H(13-18)
		.36	yes	TCA=-106.13-8.99S(7-12)-8.15S(19-L) +6.30H(7-12)+9.96A
Kekaha	107	.09	no	TCA=128.04+6.75M(7-12)+13.07H(1-6) -9.88H(13-18)
		.09	yes	same
Olokele	38	.26	no	TCA=143.72-9.95S(7-12)-18.21M(1-6) +22.02M(13-18)
		.20	yes	TCA=-127.75-13.09S(7-12)+11.55A

Table 7. Results of Stepwise Regression Analysis for Model V and Va by Plantations.

Predictand: Harvest yield result in tons of cane per acre (TCA).

Predictors: Standardized cumulative insolation(S), maximum temperature(H) and minimum temperature(M) for periods of 1st to 3rd month(1-3), 4th to 6th month(4-6), 7th to 9th month(7-9), 10th to 12th month(10-12), 13th to 15th month(13-15), 16th to 18th month(16-18) and 19th to 21st month(19-21) of the crop, with or without age(A) of crop in month.

LOCATION	DF	R^2	AGE	MODEL
Ewa	74	.11	no	TCA=147.42+6.05H(13-15)+7.88M(7-9)
		.16	yes	TCA= 49.84+6.85H(13-15)+8.16M(7-9) +4.10A
Oahu	48	.28	no	TCA=130.80-9.34H(10-12)+5.41M(1-3) -7.60M(4-6)-7.57M(13-15)
		.30	yes	TCA= 63.81-5.60H(13-15)-10.09M(7-9) -6.30M(13-15)+2.85A
Waialua	69	.16	no	TCA=136.76-13.74M(7-9)+16.11M(19-21)
			yes	TCA= 61.07-12.66M(7-9)+15.62M(19-21) +3.28A
HC&S	136	.18	no	TCA=125.30-5.65H(1-3)-7.14H(10-12) -3.98M(4-6)+11.28M(13-15)
			yes	TCA= 39.12-6.65H(1-3)-7.56H(10-12) -5.20M(4-6)+11.38M(13-15)+3.68A
Pioneer	69	-	no	* No variables met the 0.15 significance level.
			yes	TCA= -6.70+5.56A
Wailuku	52	.11	no	TCA=124.41-5.76S(10-12)+7.31S(13-15)
		.11	yes	same
Kekaha	107	.11	no	TCA=128.58+10.32H(1-3)-6.70H(13-15) +7.75M(7-9)
		.11	yes	same
Olokele	38	.44	no	TCA=140.96-27.99S(4-6)-19.35S(10-12) -7.77S(19-21)-21.48M(4-6) +31.92M(16-18)
		.49	yes	TCA=-32.93-28.26S(4-6)-20.54S(10-12) -9.28S(19-21)-21.58M(4-6) +30.45M(16-18)+7.4A

Soil moisture is known to have dominant effect on the growth of sugarcane. Nickell (1968), Hilton and Santo (1979) among others reported that cane yields are directly related to the amount of total water applied. This factor could not be included in the model because irrigation data were sparse. Rainfall data by itself is not useful in this study since most of the FT7 tests were conducted in low rainfall areas.

Cane growth is also known to be significantly influenced by amounts and timing of fertilization, and yield response to nitrogen (N) depends on crop water status. Hilton et al. (1980) summarized 105 yield tests harvested between 1960 and 1978 and reported 14 percent increase in cane yield with an average N increase from 250 to 600 lb/acre. He also reported that the yield differences between applied N were frequently insignificant. Thus it appears doubtful that the addition of amounts of N applied will significantly improve the model.

The results of the first-order regression models are comparable to the findings by Oldeman (1971). He used sugar yield data from 97 fields harvested between 1930 to the late 1960's at the Waialua Sugar Co. as the predictand, and nine climatic and eight management variables as predictors in a first-order regression analysis. He reported R-square values of less than 0.30 for regression between TSA and climatic variables or management variables. When both sets of predictors were combined, the highest R-square was 0.45, but when the data were divided into four soil groups, the R-square values were 0.39 to 0.82. Ratooning was reported to have a significant negative impact on yield, which he attributed to soil compaction due to the use of heavy equipment for agricultural operations. Trouse (1964), Humbert (1968) and Trouse et al. (1984) reported serious soil damage and compaction due to heavy equipment operation in cane fields. Yield declined in direct proportion to the number of times the field had been mechanically harvested. Oldeman (1971) also reported a yield decline, which could not be explained, in addition to the decrease due to ratooning.

Another factor which may affect yield significantly is irrigation with saline water. Syed and El-Swaify (1972) reported reductions in mean dry matter yields ranging between 10 to 35 percent with increasing salt concentrations. The green weight yield decreases were 34 percent compared with the yield from the control plants irrigated with tap water. Well water used for irrigation of sugarcane tend to become too brackish during dry years and may significantly affect yields. The problem of salinity becomes more significant when other sources of water is not available because of salt accumulation in the soil.

Bosshart (1979) reported that two of the plantations on the island of Maui were seriously affected by salinity on an acreage basis.

One of the main reasons that the first-order models failed to yield models with reasonable R-square values may be due to model design. The multiple regression analysis using the linear model is designed for independent variables whose effects on the mean response are additive and do not interact. These assumptions are apparently wrong. An implicit assumption of the model is that the individual effects of the climatic variables can be separated. However, insolation and maximum and minimum temperatures are, in most cases, significantly correlated as shown in Table 8.

Table 8. Correlation Analysis of Weather Factors from FT7 Tests.

	<----------CORRELATION COEFFICIENT----------->		
PLANTATION	SOLAR RADIATION / MAXIMUM TEMP.	SOLAR RADIATION / MINIMUM TEMP.	MAXIMUM TEMP. / MINIMUM TEMP.
Ewa	0.65	0.54	0.83
Oahu	0.56	0.51	0.67
Waialua	0.59	0.34	0.41
HC&S	0.55	0.44	0.60
Pioneer	0.46	0.48	0.67
Wailuku	0.48	-0.04	0.17
Kekaha	0.55	0.35	0.70
Olokele	0.64	0.59	0.80

Multicollinearity of the predictor variables is a source of error in statistical models. When independent variables are correlated, the regression coefficient of any independent variable depends on which other independent variables are included in the model. In such a case, a regression coefficient does not reflect the inherent effect of the particular variable on the dependent variable, but only a marginal or partial effect, given whatever other correlated independent variables are included in the model.

Sarker (1963) reported that weather during the tillering phase alone accounted for about 50 percent of the variations in yield. He added that these factors, when combined with the weather factors of the elongation phase, can account for about 80 percent of the variations. However, this is applicable for a one-year crop and does not seem to be applicable to a two-year crop.

The effect of climate, soil and management factors and of their interactions are extremely complex. The weak relationship between final yield of cane and solar radiation and temperatures may be due to the long growing periods of 21 to 26 months. The harvested sugarcane is the end result of a long and complex process of constantly changing environmental and physiological interactions. The final yields of two widely separated fields are often identical even though the physiological or climatic factors during the various stages of growth may be quite different.

For shorter growth periods, Clements (1980) obtained an R-square value of 0.54 using sugarcane growth as the predicted variable and relative humidity, wind, velocity, maximum and minimum temperatures, and solar radiation as the predictor variables. When sheath moisture was added to the list of predictors he obtained an R-square of 0.82, which improved to 0.87 when age was also added. His regression analysis was based on growth units taken every 35-days. This indicates that monthly growth data are more appropriate than final harvest data for crop growth models.

Non-Linear Model

Proposed Growth Model

The proposed model of sugarcane growth in response to age, insolation and maximum temperature is:

$$G_a(I) = \frac{G_o \ Rad(I)}{R_o + b(Age(I) - A_o)^2 + c(Temp(I) - T_o)^2} \qquad (11)$$

where $G_a(I)$ is the absolute growth rate for month(I),

Rad(I) is the mean monthly insolation,

Temp(I) is the mean monthly maximum temperature,

G_o is the optimum growth rate for an area,

R_o is the optimum radiation,

A_o is the optimum age,

T_o is the optimum temperature, and

b and c are positive constants.

Substituting for the optimum values for age, insolation and maximum temperature, the proposed growth model becomes:

$$G_a(I) = \frac{G_o \ Rad(I)}{600 + b(Age(I) - 6)^2 + c(Temp(I) - 86)^2} \qquad (12)$$

As described in the method section, the coefficients b and c are obtained empirically by means of a calibration process using age, insolation and maximum temperature as input to the model. The first estimates of b and c were derived from the relationships shown in Fig. 2, 3 and 4.

The computed growth rates are then subjected to a correlation analysis with the mean measured growth data from three nearby fields. The coefficients b and c were changed according to the results of the correlation analysis and comparison of the computed growth with measured growth. This procedure could be repeated as often as needed until a satisfactory result of the computed growth is obtained. In this study, a satisfactory model was obtained after three trials using the selected data for calibration. The growth model obtained for the Lihue Plantation is:

$$G_a(I) = \frac{G_o \; Rad(I)}{600+4.5(Age(I)-6)^2+5.0(Temp(I)-86)^2} \qquad (13)$$

The weather data used for the calibration of the model, and the computed and measured elongation rates are shown in Table 9 and plotted in Fig. 5. The curve of the growth rates derived from the model is similar in pattern and trend to the curve of the measured growth. During the first year of the crop, the computed growth rates, with few exceptions, are almost identical to the actual growth rates. During the second year, the computed growth rates are all slightly greater than the measured rates, but they are considered acceptable because the discrepencies are not serious and the fields, although irrigated, were not under optimum moisture conditions.

Table 9. Computed and Actual Sugarcane Growth Rates for Fields 712, 770, 952, and Weather Data from Nearby Station No. 1101.1.

YEAR	MONTH	AGE (month)	COMPUTED GROWTH (in/day)	MEAN ACTUAL GROWTH (in/day)	SOLAR RADIATION (ly/day)	MAX. TEMP. (F)	TOTAL RAINFALL (inch)
1983	Apr	3	.455	.283	455.8	78.1	2.03
	May	4	.504	.647	506.7	77.8	3.17
	Jun	5	.633	.637	561.2	79.1	2.27
	Jul	6	.634	.700	546.0	79.4	2.80
	Aug	7	.677	.663	546.4	80.3	4.56
	Sep	8	.609	.623	507.9	80.1	1.74
	Oct	9	.433	.463	416.5	78.6	3.52
	Nov	10	.350	.383	327.7	79.4	1.71
	Dec	11	.299	.187	328.0	77.9	1.24
1984	Jan	12	.247	.190	306.2	76.9	3.97
	Feb	13	.328	.217	414.3	77.3	1.88
	Mar	14	.454	.247	518.7	79.7	0.91
	Apr	15	.392	.303	498.7	79.0	4.31
	May	16	.426	.367	538.2	80.5	1.25
	Jun	17	.410	.260	528.4	82.0	1.58
	Jul	18	.415	.317	563.5	83.1	1.58
	Aug	19	.397	-	580.8	83.6	1.18
	Sep	20	.323	-	516.0	83.4	3.48
	Oct	21	.231	-	400.4	83.3	6.22

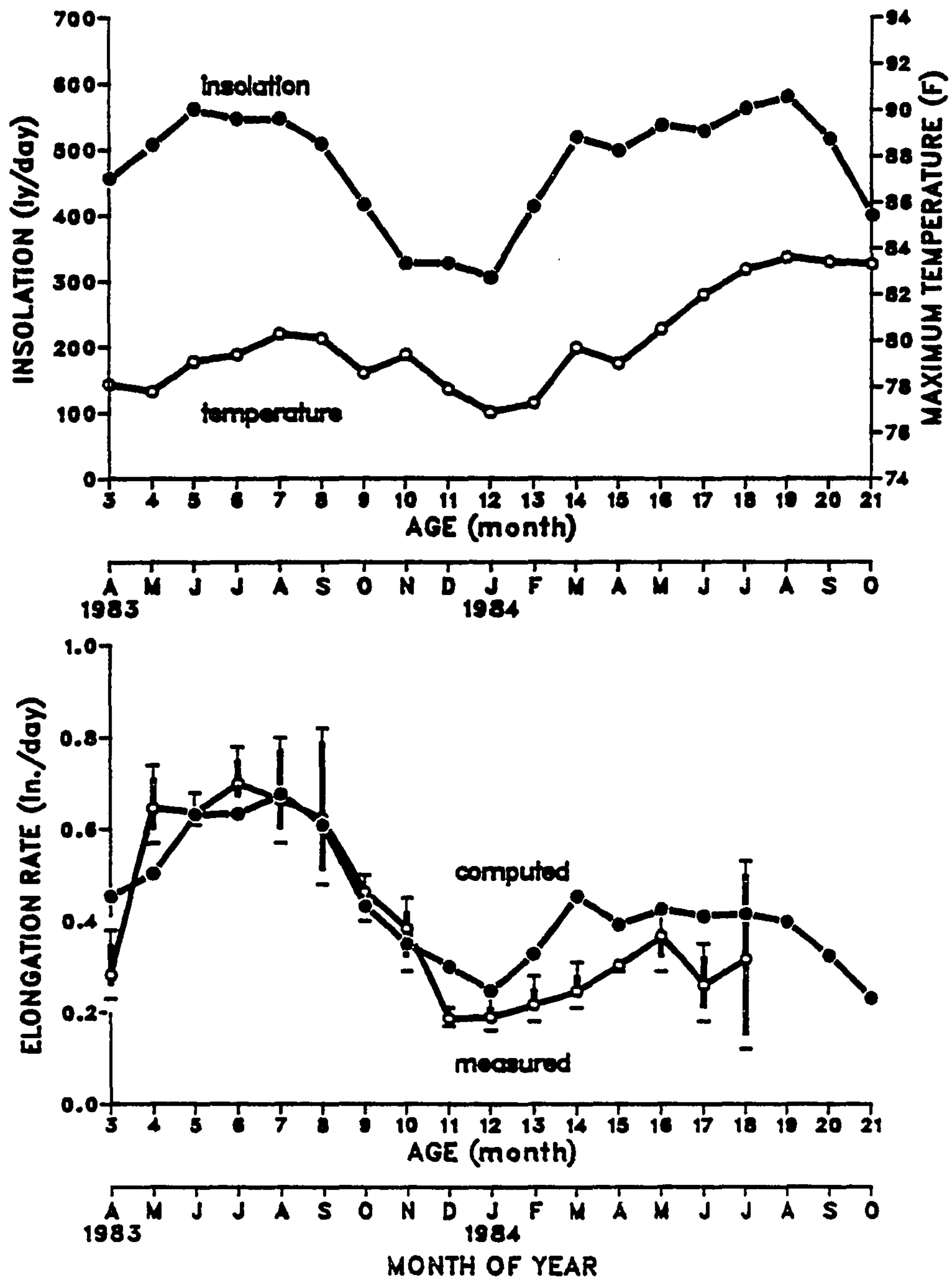

Fig. 5. Comparison of simulated sugarcane growth rates with the mean measured growth rates for fields 712, 770, and 952. The correlation coefficient r=0.89. Length of bar denotes range of measured data. Insolation and maximum temperature data used as input to the model are also plotted.

The shortage of irrigation water was due to widespread drought that prevailed in 1984 (How, 1985). The drought started in early 1983 but was confined to the leeward areas of the state. The percentage of mean rainfall values for four selected stations at the Lihue Plantation (Table 10) clearly shows abnormally low rainfall during the first five months of 1983 and the last four months of 1983. However, rainfall was above or near normal for three summer months during the period of high consumptive use. Irrigation water, which usually comes from watershed areas, was plentifull in 1983, inspite of the dry condition in the low-lying areas.

The drought which started around October 1983 in the low-lying regions extended into the watershed areas in November as shown by rainfall for station number 1092 located in the watershed areas (Fig. 6). The severe drought lasted for almost 12 months, causing severe water shortages from March through October 1984. The end of the driest 24-month period on sugar plantations ended in November 1984 with heavy rainfall in excess of 14 inches.

Table 10. Monthly Rainfall and Percentage of Mean Rainfall for Selected Stations at the Lihue Plantation for 1983-1985.

Station No.		1064.3		1101.1		1114		1092	
YEAR	MONTH	RAIN (inch)	PCM* (%)	RAIN (inch)	PCM* (%)	RAIN (inch)	PCM* (%)	RAIN (inch)	PCM* (%)
1983	Jan	1.52	20	1.41	22	1.22	19	4.15	38
	Feb	0.04	1	0.34	6	0.26	5	0.44	5
	Mar	0.92	14	0.80	18	1.29	23	2.52	23
	Apr	3.64	63	2.03	34	1.34	29	4.97	48
	May	4.34	83	3.17	60	2.03	60	6.49	80
	Jun	2.78	77	2.27	85	2.00	104	5.48	104
	Jul	6.02	132	2.80	92	2.38	101	7.92	122
	Aug	5.33	116	4.56	193	3.47	136	10.25	147
	Sep	3.68	90	1.74	61	1.34	62	5.06	84
	Oct	3.51	57	3.52	96	2.05	47	8.14	97
	Nov	2.21	31	1.71	26	1.64	30	3.76	36
	Dec	1.12	16	1.24	24	1.41	24	1.80	16
1984	Jan	3.35	44	3.97	61	3.35	52	7.46	69
	Feb	3.13	56	1.88	34	1.37	28	6.27	74
	Mar	2.00	31	0.91	20	1.12	20	3.78	35
	Apr	4.67	80	4.31	73	1.93	42	9.62	93
	May	2.49	47	1.25	24	0.76	22	3.03	37
	Jun	2.05	57	1.58	59	1.21	63	4.38	83
	Jul	3.07	67	1.58	52	0.88	37	3.22	50
	Aug	1.03	22	1.18	50	0.73	29	2.30	33
	Sep	5.32	130	3.48	123	2.56	119	5.27	88
	Oct	4.00	65	6.22	170	4.91	112	6.68	80
	Nov	15.33	213	22.85	343	14.47	267	27.90	264
	Dec	6.93	98	9.33	177	8.00	135	9.99	90
1985	Jan	4.19	55	5.63	86	4.95	77	8.51	78
	Feb	8.58	153	5.58	100	4.16	86	9.43	111
	Mar	3.47	53	2.73	61	1.62	29	6.67	62
	Apr	3.39	58	3.94	66	2.29	50	5.75	56
	May	3.20	61	3.31	63	2.01	59	6.42	79
	Jun	1.83	51	0.62	23	0.47	24	2.56	48
	Jul	2.50	55	2.31	76	1.66	70	5.20	80
	Aug	4.64	101	3.91	166	3.39	132	8.76	126
	Sep	3.77	92	2.32	82	1.98	92	6.61	110
	Oct	7.99	130	3.73	102	2.11	48	11.19	134
	Nov	4.61	64	8.35	125	6.17	114	7.56	72
	Dec	1.14	16	0.99	19	0.38	6	1.40	13

* PCM = percentage of mean rainfall

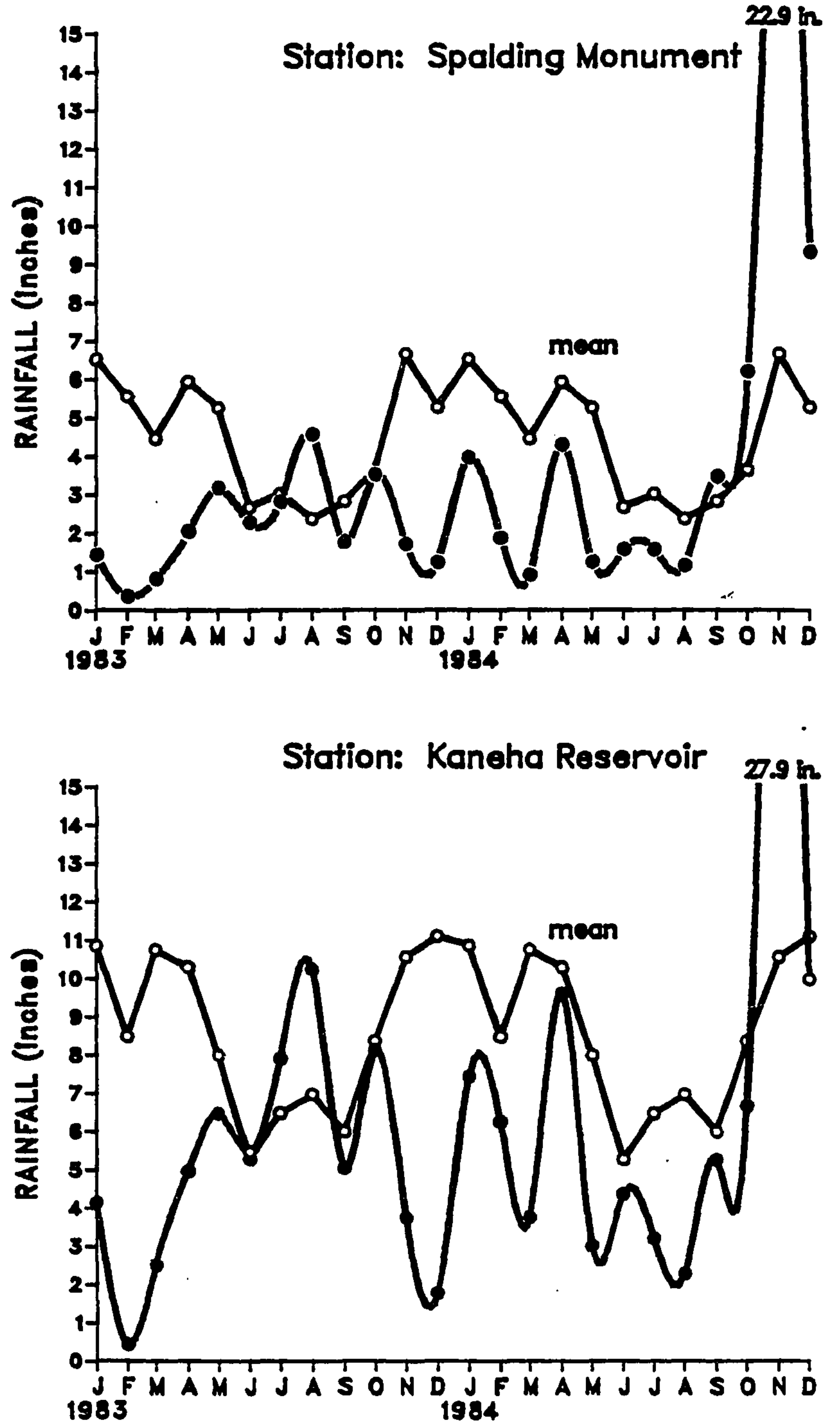

Fig. 6. Actual and mean rainfall for a watershed station, no. 1092--Kaneha Reservoir and for a plantation station, no. 1101.1--Spalding Monument.

The correlation coefficient between the measured and computed growth rates is +0.88. No effort was made to further improve the model because the correlation is considered to be quite good. Moreover, if indeed a near perfect correlation could be achieved, it might be suggestive that age, insolation and temperature may be the only important factors controlling growth, when this is far from being true. Plant growth processes are known to be significantly affected by nutrients, cultivation practices, and soil moisture among other factors.

Fig. 5 shows the dominant effect of insolation during the first year of the crop and the dominant effect of age during the second year. The computed growth curve is quite similar to the insolation curve for the first year indicating that insolation is the controlling factor during that period, provided that the temperature factor is not limiting. The insolation trend during the early part of the second year is also evident from the computed growth although the growth rates are depressed as a result of the age factor. The effect of temperature is less obvious since maximum temperature tends to parallel insolation in Hawaii.

Model Validation and Testing

The model represented in equation (13) was used without change for testing using several sets of data for the purpose of validation. Growth rates are computed from weather data from several stations, and correlation analysis between the computed growth rates and the measured values performed for each set of data. The measured and computed elongation rates and the weather data for four cases are plotted in Fig. 7-10 and shown in Tables 11-14. The computed elongation rates for all cases are reasonable and the related growth curves have realistic shape. The curves follow the radiation curves closely during the first year, whereas the age effect in depressing growth is evident in the second year. Most of the differences in the computed and measured elongation rates may be explained by the moisture stress caused by the severe drought conditions in 1984 as mentioned earlier. Results of each of the four cases used in the testing of the model are discussed.

Analysis of Growth Rates for Field 742

The computed growth rates for field 742 (Fig. 7) are in good agreement with the measured growth rates; the correlation coefficient between them is +0.92. The measured values were slightly below the computed values from age 5 to 7 months and the difference continues to increase in the summer months until September 1984 when a sharp decline in growth rate was measured.

Table 11. Computed and Actual Sugarcane Growth Rates for Field 742 and Weather Data from Nearby Station No. 1101.1.

YEAR	MONTH	AGE (month)	COMPUTED GROWTH (in/day)	ACTUAL GROWTH (in/day)	SOLAR RADIATION (ly/day)	MAX. TEMP. (F)	TOTAL RAINFALL (inch)
1984	Jan	3	.340	.26	305.0	79.5	3.35
	Feb	4	.474	.53	417.1	79.4	1.37
	Mar	5	.749	.60	530.7	82.3	1.12
	Apr	6	.717	.63	529.2	81.5	1.93
	May	7	.817	.73	588.5	82.0	0.76
	Jun	8	.841	.67	564.8	84.0	1.21
	Jul	9	.914	.69	619.8	85.1	0.88
	Aug	10	.873	.61	619.2	85.4	0.73
	Sep	11	.720	.39	540.3	86.0	2.56
	Oct	12	.511	.51	413.8	84.8	4.91
	Nov	13	.324	.32	311.3	81.7	14.47
	Dec	14	.233	.25	277.5	79.0	8.00
1985	Jan	15	.250	.20	322.0	78.3	4.95
	Feb	16	.238	.18	338.6	78.2	4.16
	Mar	17	.265	.17	422.6	77.4	1.62
	Apr	18	.316	.18	501.7	78.8	2.29
	May	19	.299	.26	498.1	79.3	2.01
	Jun	20	.383	-	614.8	83.1	0.47
	Jul	21	.336	-	578.4	83.8	1.66
	Aug	22	.309	-	579.2	83.6	3.39

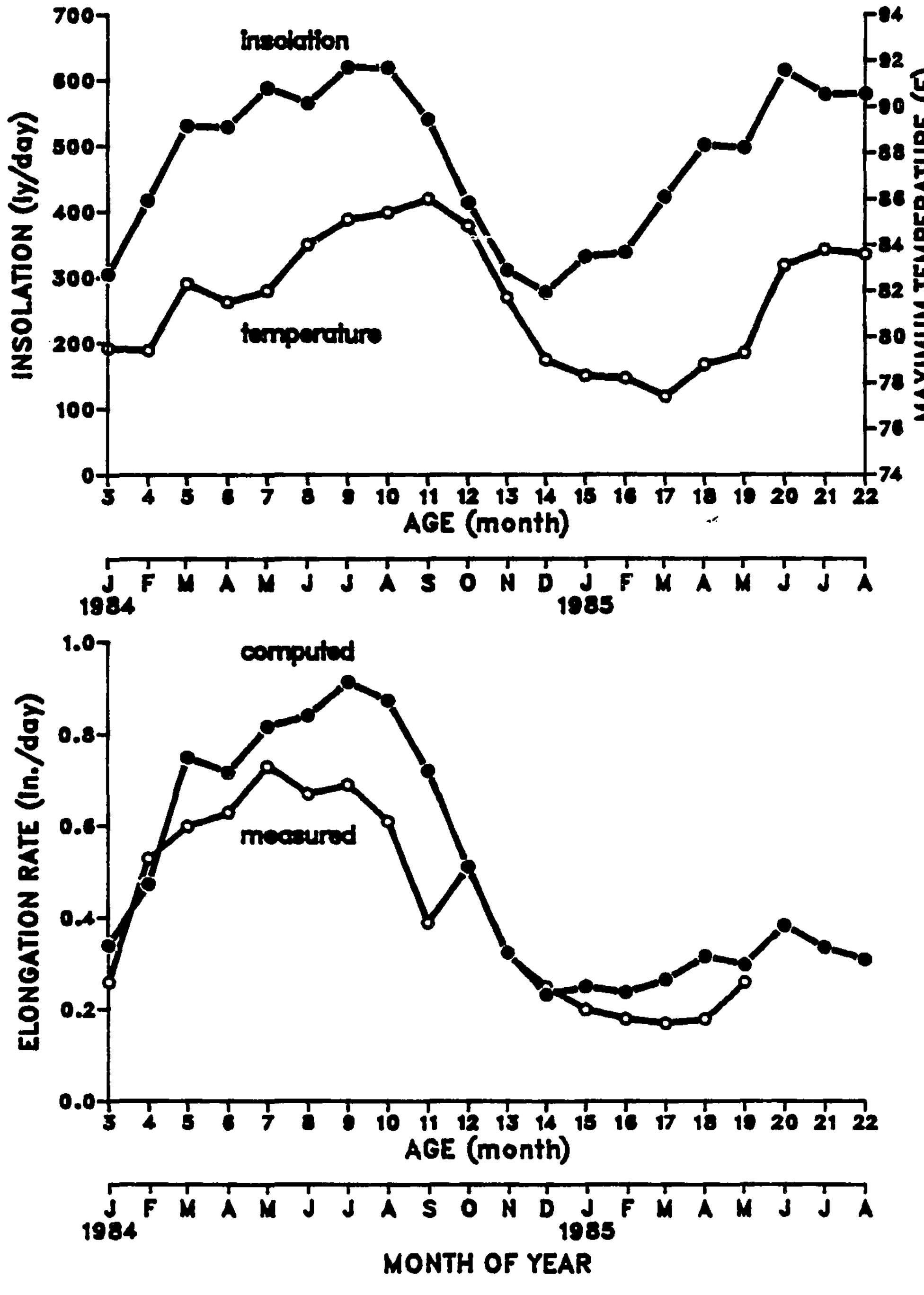

Fig. 7. Comparison of simulated sugarcane growth rates with measured growth rates for field 742. The correlation coefficient r=0.92. Insolation and maximum temperature data used as input to the model are also plotted.

Investigation of low growth rate in September revealed that rainfall for most of that month was low (2.5 in.) which followed several very dry months. The soil moisture stress was the culmination of an extensive drought which started in 1983 in the leeward areas of the state and which extended into the watershed areas in 1984. The drought effect in 1984 was much more significant because there was also a shortage of irrigation water.

The growth rates measured in summer 1984 were, in all probability, below optimum, thus accounting for the differences between measured and computed elongation rates.

Analysis of Growth Rates for Fields 821 and 830

The mean measured growth rates (Table 12, Fig. 8) for fields 821 and 830, planted in July 1983, show the severity of moisture stress during the first summer months of the crop. The low growth in August 1984 is again indicative of the effect of the extensive drought prevailing since 1983. It results from the lack of rainfall and irrigation water (Table 13, Fig. 9) during a period of high consumptive water need when high temperature and insolation levels prevailed. The relative water index indicates the severe moisture stress in fields 821 and 830 during the summer months of 1984.

The index of relative water is used for the ratio of total water, that is, rainfall plus irrigation to evaporation. It is used as an indicator of soil moisture condition. A value of 1.0 or greater represents no moisture stress, whereas a value below 1.0 represents stress condition, with stress increasing with decreasing relative water index. The sharp increase in measured growth rate in November 1984 is the growth response of the moisture-stressed sugarcane to heavy rainfall, which exceeded 14 inches during that month. This is an example of compensatory growth, a feature which is not accounted for in the model.

With the knowledge of the severe moisture-stressed conditions of the cane in fields 821 and 830, it is not surprising that the correlation between measured and computed growth rates is only +0.34. This does not invalidate the model. The computed elongation rates are reasonable. It is a reminder that the proposed model is applicable to estimating growth in response to age, insolation and temperature under otherwise optimum conditions.

Table 12. Computed and Actual Sugarcane Growth Rates for Fields 821, 830 and Weather Data from Nearby Station No. 1114.

YEAR	MONTH	AGE (month)	COMPUTED GROWTH (in/day)	MEAN ACTUAL GROWTH (in/day)	SOLAR RADIATION (ly/day)	MAX. TEMP. (F)	TOTAL RAINFALL (inch)
1983	Oct	3	.587	.615	423.3	83.0	2.05
	Nov	4	.483	.730	338.4	82.9	1.64
	Dec	5	.426	.445	331.6	80.8	1.41
1984	Jan	6	.357	.450	305.0	79.5	3.35
	Feb	7	.482	.360	417.1	79.4	1.37
	Mar	8	.734	.375	530.7	82.3	1.12
	Apr	9	.678	.430	529.2	81.5	1.93
	May	10	.743	.435	588.5	82.0	0.76
	Jun	11	.733	.355	564.8	84.0	1.21
	Jul	12	.767	.385	619.8	85.1	0.88
	Aug	13	.715	.105	619.2	85.4	0.73
	Sep	14	.578	.310	540.3	86.0	2.56
	Oct	15	.405	.355	413.8	84.8	4.91
	Nov	16	.259	.600	311.3	81.7	14.47
	Dec	17	.190	.280	277.5	79.0	8.00
1985	Jan	18	.204	.195	332.0	78.3	4.95
	Feb	19	.193	.225	338.6	78.2	4.16
	Mar	20	.217	.180	422.6	77.4	1.62
	Apr	21	.255	.160	501.7	78.8	2.29
	May	22	.239	-	498.1	79.3	2.01
	Jun	23	.301	-	614.8	83.1	0.47
	Jul	24	.264	-	578.4	83.8	1.66

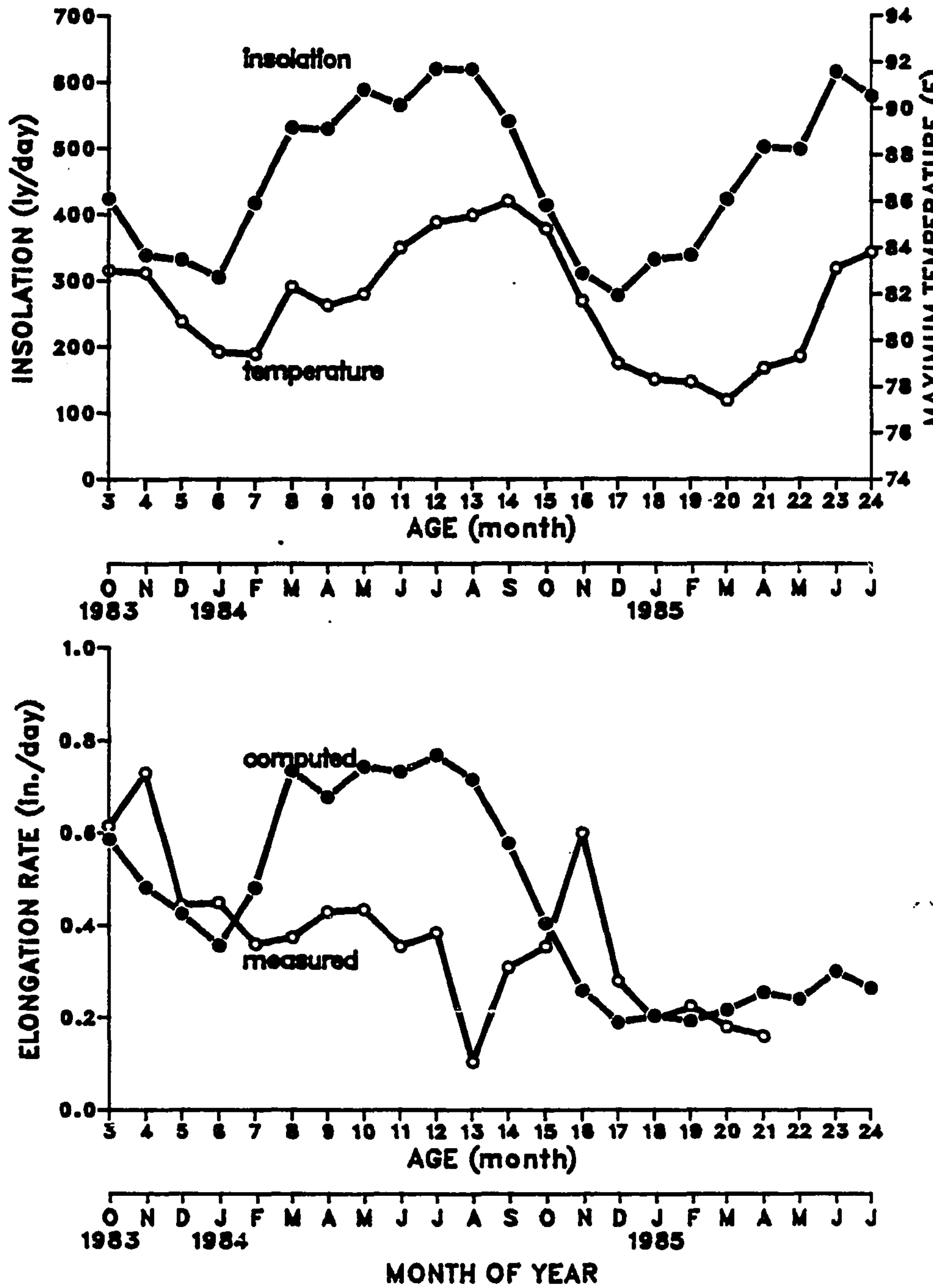

Fig. 8. Comparison of simulated sugarcane growth rates with mean measured growth rates for fields 821 and 830. The correlation coefficient r=0.34. Insolation and maximum temperature data used as input to the model are also plotted.

Table 13. Monthly Rainfall, Irrigation, Evaporation and Relative Water Index for Fields 821, 830.

YEAR	MONTH	RAIN (inch)	IRRIGATION[1] (round)	TOTAL[2] WATER (inch)	EVAPORATION (inch)	RELATIVE[3] WATER INDEX
1983	Oct	2.05	2.6	9.85	7.35	1.34
	Nov	1.64	1.7	6.74	4.83	1.40
	Dec	1.41	2.4	8.61	4.73	1.82
1984	Jan	3.35	1.3	7.25	4.35	1.67
	Feb	1.37	1.6	6.17	5.64	1.09
	Mar	1.12	1.2	4.72	7.19	0.66
	Apr	1.93	1.3	5.83	6.88	0.85
	May	0.76	2.0	6.76	8.20	0.82
	Jun	1.21	0.9	3.91	7.17	0.55
	Jul	0.88	0.7	2.98	8.06	0.37
	Aug	0.73	0.1	1.03	9.09	0.11
	Sep	2.56	0.6	4.36	7.32	0.60
	Oct	4.91	0.5	6.41	6.13	1.05
	Nov	14.47	1.1	17.77	5.09	3.49
	Dec	8.00	1.6	12.80	4.60	2.78
1985	Jan	4.95	1.0	7.95	4.65	1.71
	Feb	4.16	1.0	7.16	4.66	1.54
	Mar	1.62	1.2	5.22	6.00	0.87
	Apr	2.29	0.5	3.79	6.20	0.61

[1] Each irrigation round is equivalent to 3 inches of rain.
[2] Total water = rain + irrigation.
[3] Relative water index = ratio of total water applied to evaporation.

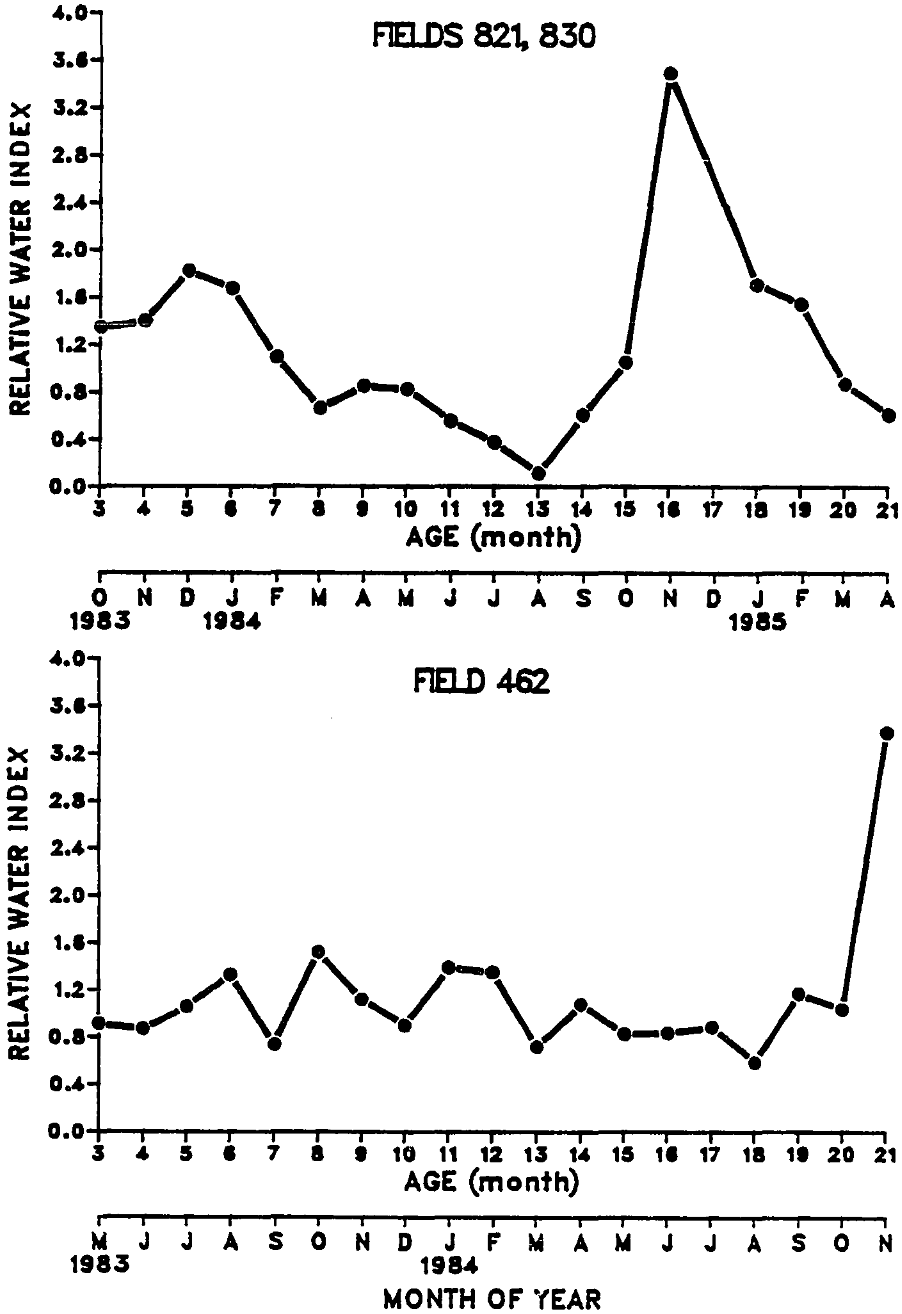

Fig. 9. Monthly relative water index for fields 821 and 830, and for field 462.

Analysis of Growth Rates for Field 860

The computed growth curve, as in previous cases discussed above, has a realistic pattern and compares well with the measured growth curve, except for the summer months of the first year of the crop (Table 14, Fig. 10). Actual growth was significantly affected by moisture stress during those months, as depicted by the abnormal depression of the curve. Drought conditions during the second year had much less impact on growth because of the dominant effect of the age factor in reducing growth. The correlation between the computed and the measured elongation rates is reasonable (0.78) inspite of the discrepencies caused by moisture stress.

Analysis of Growth Rates for Field 462

The measured growth rates for field 462 (Table 15 and Fig. 11) follow closely the computed growth rated for the entire crop age and the correlation coefficient is 0.74. The curve for the measured growth is quite similar to the computed growth curve; the measured values being slightly greater than the simulated values during the first year. These observations indicate that the sugarcane plants in field 462 did not suffer from moisture stress as most of the other fields investigated. Table 16 and Fig. 9 clearly show that field 462 had only a slight moisture stress for just a few months as shown by the relative water index.

Table 14. Computed and Actual Sugarcane Growth Rates for Field 860 and Weather Data from Nearby Station No. 1114.

YEAR	MONTH	AGE (month)	COMPUTED GROWTH (in/day)	ACTUAL GROWTH (in/day)	SOLAR RADIATION (ly/day)	MAX. TEMP. (F)	TOTAL RAINFALL (inch)
1984	Feb	3	.462	.77	417.1	79.4	1.37
	Mar	4	.734	.75	530.7	82.3	1.12
	Apr	5	.712	.80	529.2	81.5	1.93
	May	6	.822	.69	588.5	82.0	0.76
	Jun	7	.859	.55	564.8	84.0	1.21
	Jul	8	.947	.58	619.8	85.1	0.88
	Aug	9	.916	.74	619.2	85.4	0.73
	Sep	10	.764	.65	540.3	86.0	2.56
	Oct	11	.546	.28	413.8	84.8	4.91
	Nov	12	.346	.22	311.3	81.7	14.47
	Dec	13	.247	.26	277.5	79.0	8.00
1985	Jan	14	.266	.23	332.0	78.3	4.95
	Feb	15	.254	.25	338.6	78.2	4.16
	Mar	16	.283	.22	422.6	77.4	1.62
	Apr	17	.340	.36	501.7	78.8	2.29
	May	18	.321	.37	498.1	79.3	2.01
	Jun	19	.416	-	614.8	83.1	0.47
	Jul	20	.365	-	578.4	83.8	1.66
	Aug	21	.335	-	579.2	83.6	3.39

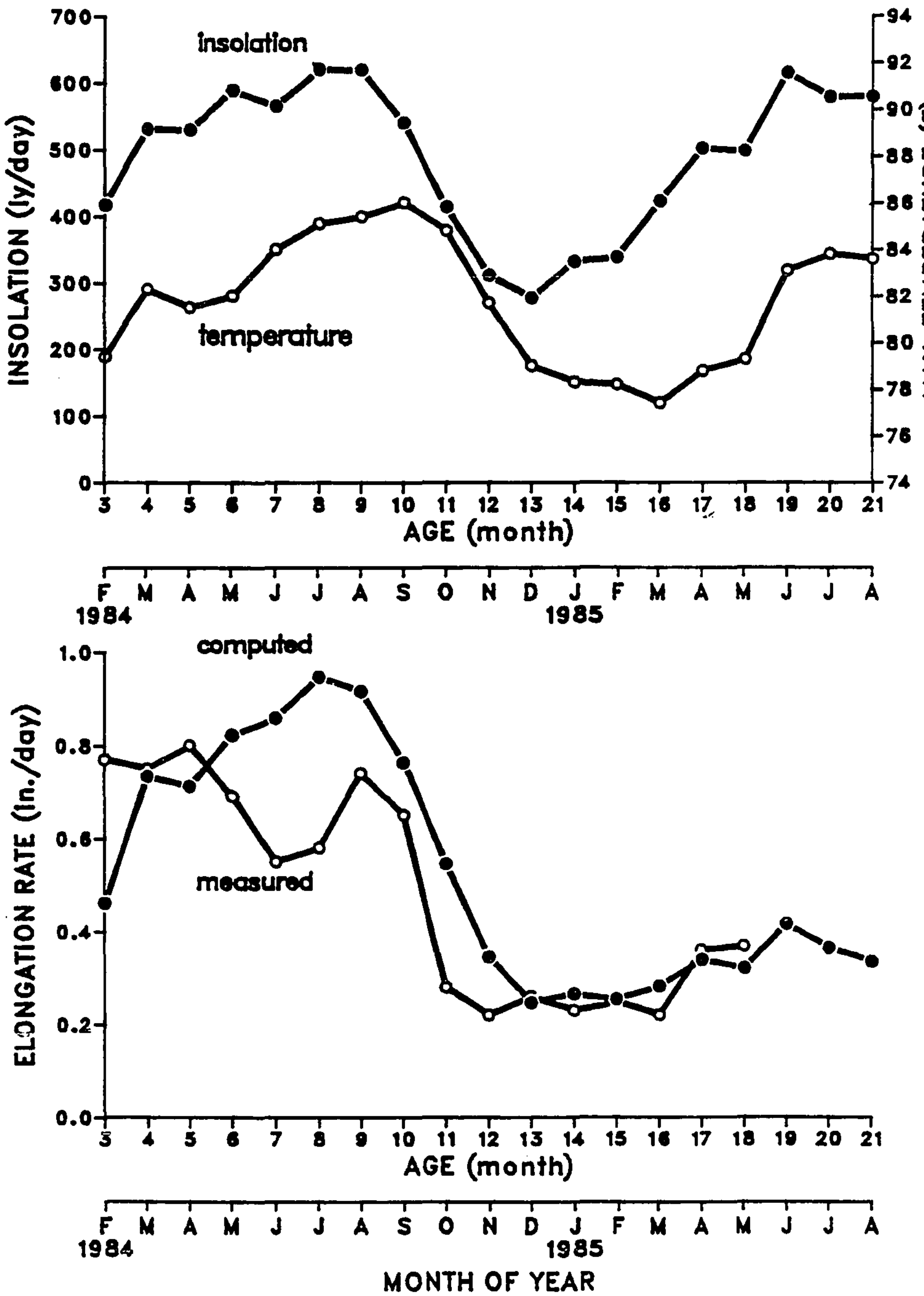

Fig. 10. Comparison of simulated sugarcane growth rates with measured growth rates for field 860. The correlation coefficient r=0.78. Insolation and maximum temperature data used as input to the model are also plotted.

Table 15. Computed and Actual Sugarcane Growth Rates for Field 462 and Weather Data from Nearby Station No. 1064.3.

YEAR	MONTH	AGE (month)	COMPUTED GROWTH (in/day)	ACTUAL GROWTH (in/day)	SOLAR RADIATION (ly/day)	MAX. TEMP. (F)	TOTAL RAINFALL (inch)
1983	May	3	.495	.54	454.4	79.2	4.34
	Jun	4	.576	.67	480.1	80.1	2.78
	Jul	5	.548	.70	463.1	79.7	6.02
	Aug	6	.589	.67	487.3	79.9	5.33
	Sep	7	.581	.63	480.1	80.0	3.68
	Oct	8	.386	.58	374.7	78.2	3.51
	Nov	9	.294	.50	295.2	78.1	2.21
	Dec	10	.251	.32	299.0	76.4	1.12
1984	Jan	11	.216	.23	269.5	76.3	3.35
	Feb	12	.257	.26	366.9	75.1	3.13
	Mar	13	.454	.24	478.2	80.0	2.00
	Apr	14	.410	.39	473.9	79.5	4.67
	May	15	.476	.50	536.1	81.4	2.49
	Jun	16	.439	.44	522.5	82.0	2.05
	Jul	17	.450	.46	562.1	83.1	3.07
	Aug	18	.434	.44	580.6	83.9	1.03
	Sep	19	.339	.44	498.2	83.3	5.32
	Oct	20	.246	.40	387.2	84.3	4.00
	Nov	21	.144	.36	275.4	79.7	15.33
	Dec	22	.125	-	264.3	78.8	6.93
1985	Jan	23	.137	-	324.8	77.7	4.19
	Feb	24	.127	-	323.3	77.2	8.58

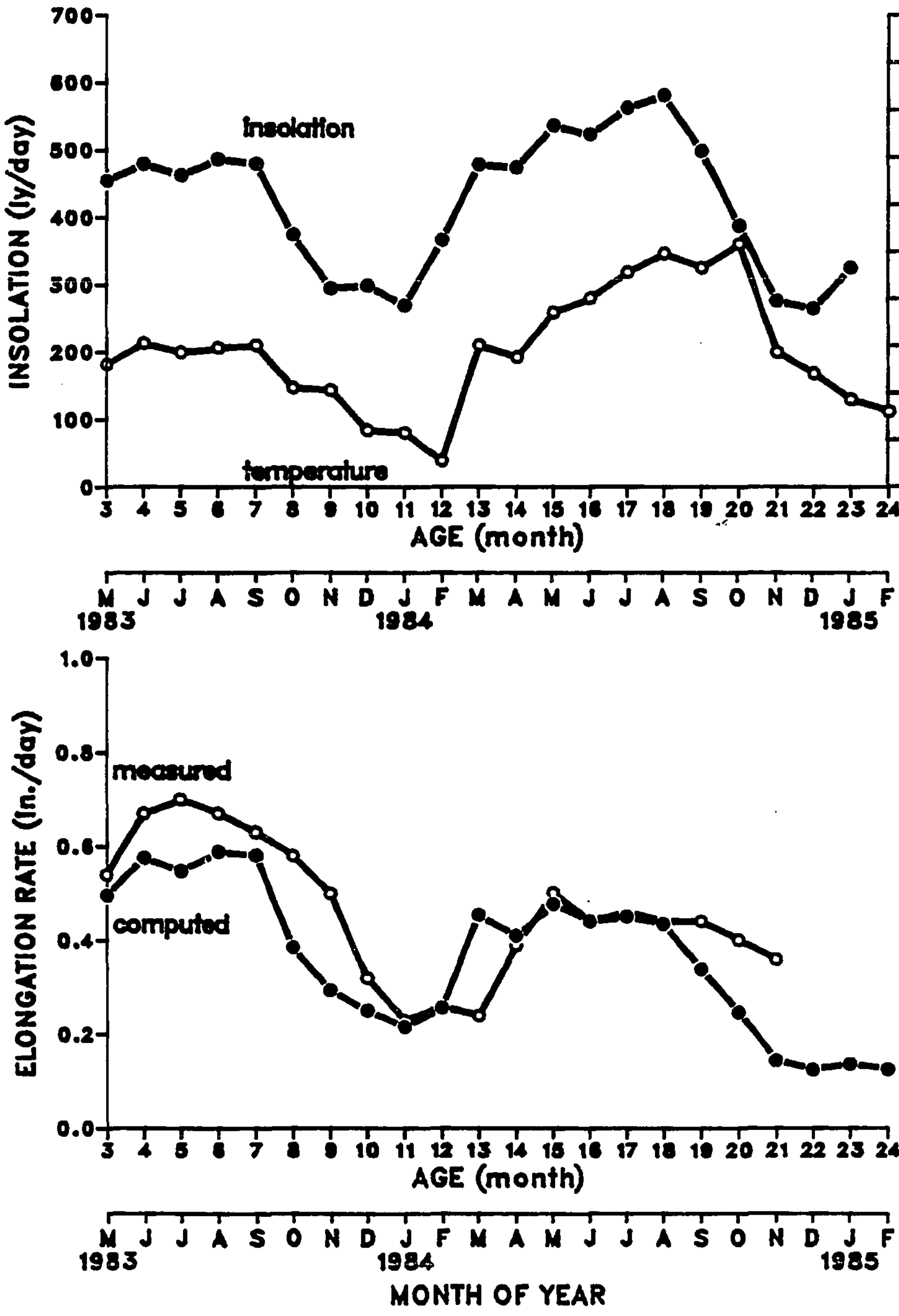

Fig. 11. Comparison of simulated sugarcane growth rates with measured growth rates for field 462. The correlation coefficient r=0.74. Insolation and maximum temperature data used as input to the model are also plotted.

Table 16. Monthly Rainfall, Irrigation, Evaporation and Relative Water Index for Field 462.

YEAR	MONTH	RAIN (inch)	IRRIGATION[1] (round)	TOTAL[2] WATER (inch)	EVAPORATION (inch)	RELATIVE[3] WATER INDEX
1983	May	4.34	1.0	7.34	8.08	0.91
	Jun	2.78	1.7	7.88	9.01	0.87
	Jul	6.02	1.0	9.02	8.47	1.06
	Aug	5.33	2.0	11.33	8.54	1.33
	Sep	3.68	1.0	6.68	9.02	0.74
	Oct	3.51	3.0	12.51	8.21	1.52
	Nov	2.21	1.0	5.21	4.66	1.12
	Dec	1.12	1.2	4.72	5.22	0.90
1984	Jan	3.35	1.0	6.35	4.56	1.39
	Feb	3.13	1.8	8.53	6.31	1.35
	Mar	2.00	1.0	5.00	6.96	0.72
	Apr	4.67	1.4	8.87	8.25	1.08
	May	2.49	1.6	7.29	8.75	0.83
	Jun	2.05	1.7	7.15	8.56	0.84
	Jul	3.07	1.5	7.57	8.54	0.89
	Aug	1.03	1.0	4.03	6.84	0.59
	Sep	5.32	1.2	8.92	7.60	1.17
	Oct	4.00	0.6	5.80	5.56	1.04
	Nov	15.33	0.8	17.73	5.24	3.38

[1] Each irrigation round is equivalent to 3 inches of rain.
[2] Total water = rain + irrigation.
[3] Relative water index = ratio of total water applied to evaporation.

Soil moisture exerts a dominant influence on cane elongation. Sun and Chow (1949) found a high positive correlation between the rate of stalk elongation and rainfall in Taiwan. Cornelison and Humbert (1960) reported uniform cane elongation as long as the soil moisture tension was within the range of field capacity to approximately 4 atmosphere tension. The elongation rates were reduced to one-half of the normal at this tension which is equivalent to a soil moisture depletion of about two-thirds of the available moisture.

Growth Simulation Curves

A major role of any mathematical model is its ability to generate various cause and effect relationships for the entire range of the factors. The quality of the simulated data is, of course, dependent on the accuracy of the model and assumes that the model has been successfully tested and validated. In the case of a plant growth model, much needed growth estimates may be generated and used for the study of the interactions of the various factors included in the model.

The model proposed in equation (7) is used to compute relative growth estimates in response to age, insolation and maximum temperature. The input data are solar radiation intensities from 200 to 600 ly/day in intervals of 50 ly/day and maximum temperatures from $60^{o}F$ to $96^{o}F$ in intervals of $2^{o}F$ for the monthly age of the cane crop from 3 to 27 months.

Two-dimensional Growth Curves

Selected results of the simulated growth are presented in Fig. 12 to 15. The optimum growth rate at 6 months of age is distinct at the higher temperature (Fig.12). The curve is rather flat for $70^{o}F$ indicating that there is little growth at this low daytime temperature at any age. The growth rate at 300 ly/day is one-half of the growth rate at 600 ly/day for the same temperature.

Growth rate is maximum at the age of 6 months with high radiation and temperature levels (Fig. 13). When either the maximum temperature or the insolation drops to a lower value, growth is significantly reduced.

The growth curves in Fig. 14 show growth increasing from the minimal temperature of 60^{o} to $86^{o}F$, the optimal temperature, and decreasing thereafter to $96^{o}F$. The computation is not extended to the estimated maximal temperature of $110^{o}F$ since the maximum temperature in Hawaii seldom exceeds $90^{o}F$. The growth rates at 18 months of age are significantly lower than the rates at 6 months indicating the dominant effect of age on sugarcane growth. Again the growth at the higher insolation is twice as much for the same age.

Simulation also shows growth rates vary linearly with insolation but at low temperature, growth is severely depressed and the effect of high insolation is minor (Fig. 15). At high temperature and insolation, growth increases with maximum growth at 6 months. The growth for the 18-month old cane is about one-half of the optimum growth rate.

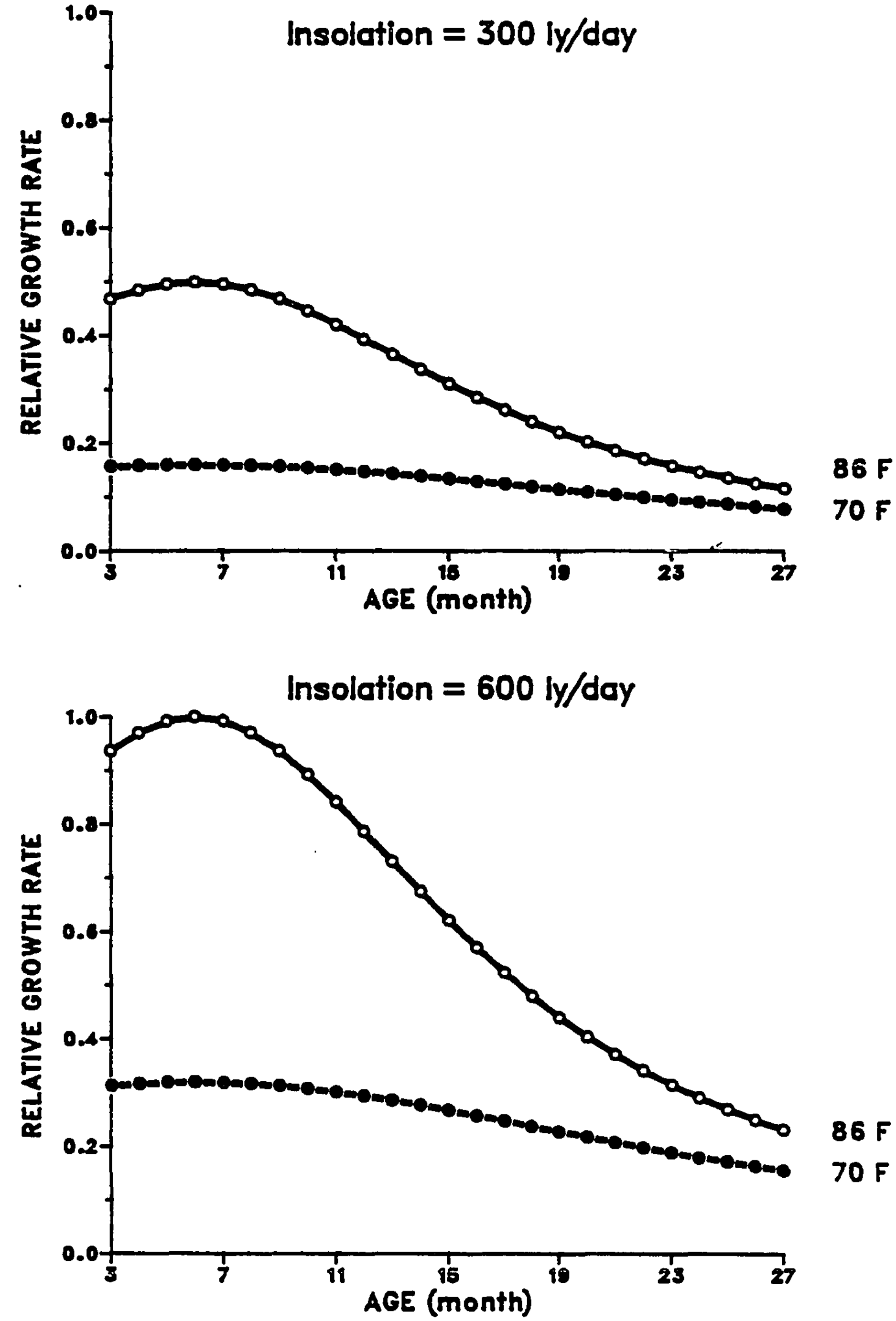

Fig. 12. Simulated response of sugarcane elongation rate to age at insolation of 300 ly/day and 600 ly/day, and maximum temperatures 70°F and 86°F. Growth rate is relative to the monthly growth at optimal conditions of 600 ly/day, 86°F, and crop age of 5 months to 6 months.

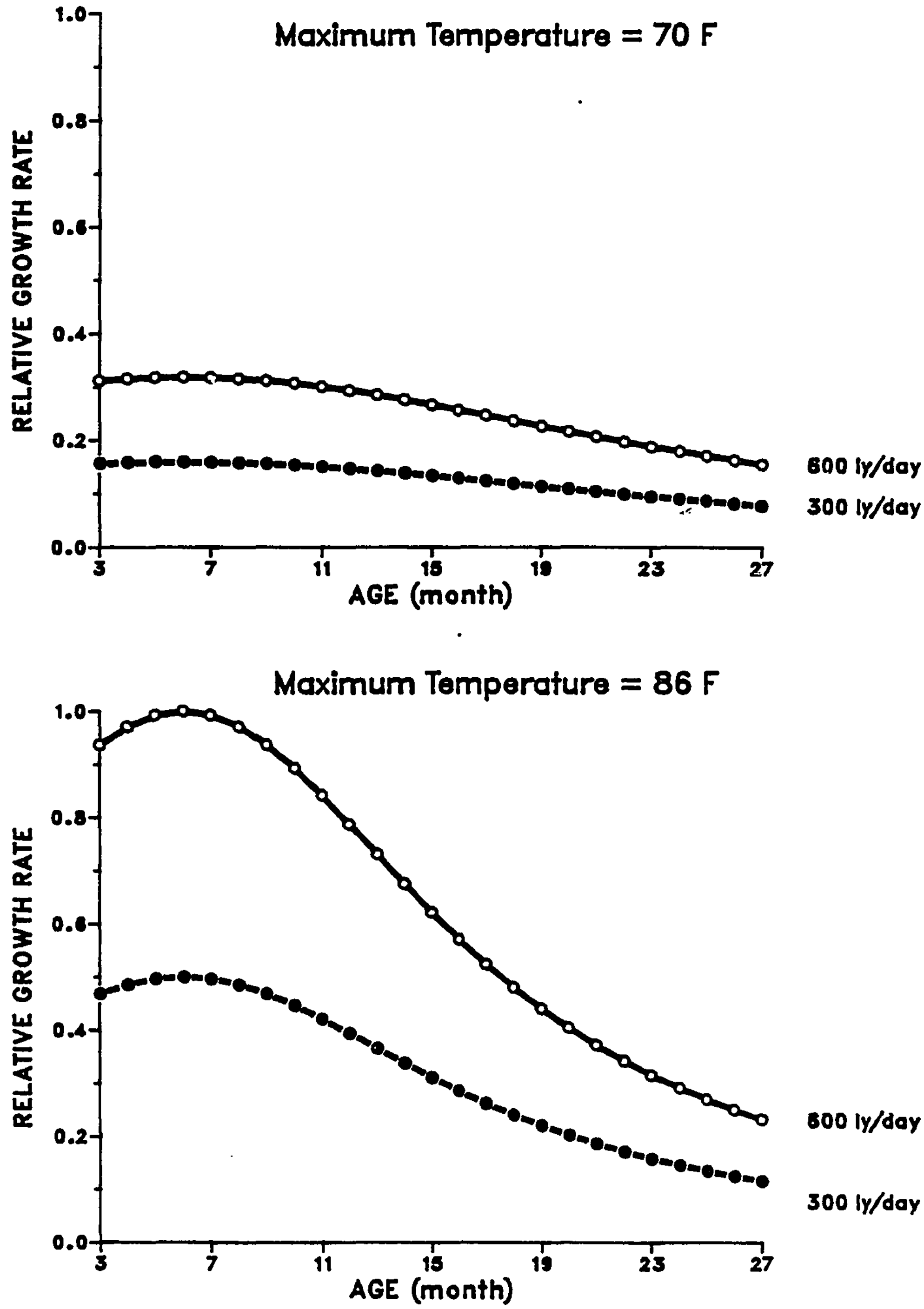

Fig. 13. Simulated response of sugarcane elongation rate to age at maximum temperature of 70°F and 86°F, and insolation of 300 ly/day and 600 ly/day. Growth rate is relative to the monthly growth at optimal conditions for 600 ly/day, 86°F, and crop age of 5 months to 6 months.

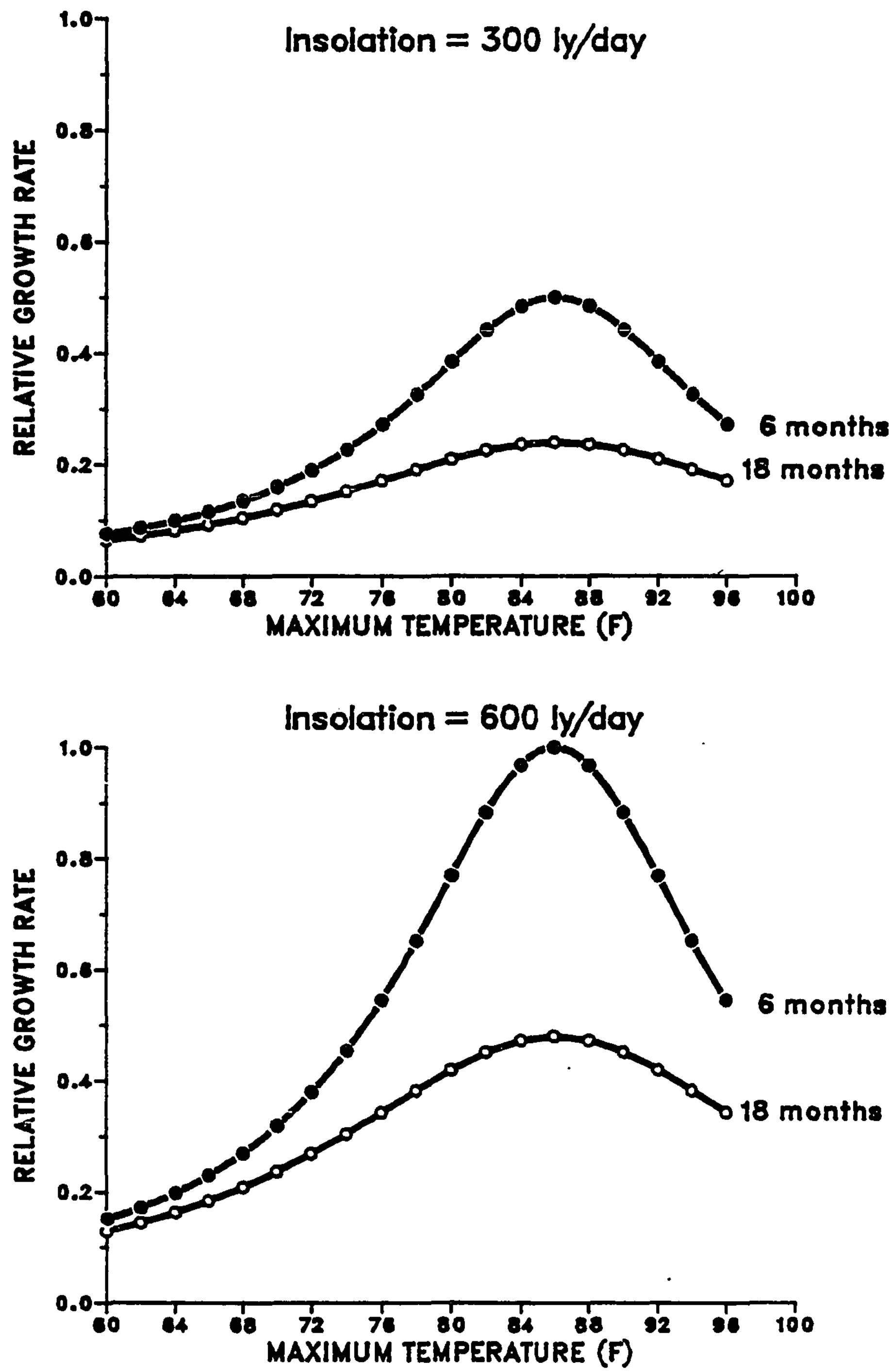

Fig. 14. Simulated response of sugarcane elongation rate to maximum temperatures at insolation of 300 ly/day and 600 ly/day and at crop age of 6 months and 18 months. Growth rate is relative to the monthly growth at optimal conditions of 600 ly/day, 86°F, and crop age of 5 months to 6 months.

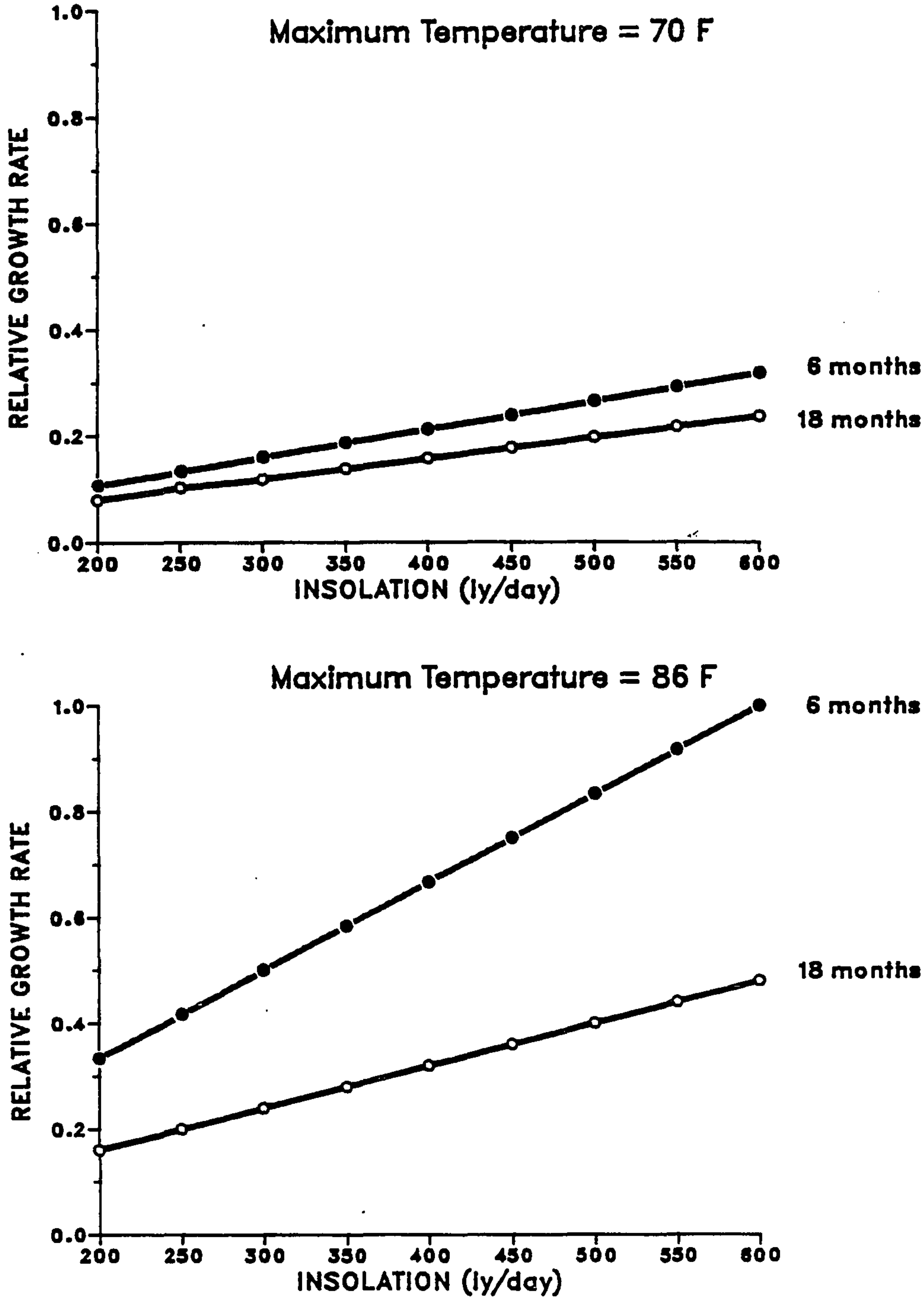

Fig. 15. Simulated response of sugarcane elongation rate to insolation at maximum temperature of 70°F and 86°F and at crop age of 6 months and 18 months. Growth rate is relative to the monthly growth at optimal conditions of 600 ly/day, 86°F, and crop age of 5 months to 6 months.

Three-dimensional Growth Curves

A more effective means of presentation of the interactions of age, insolation and temperature on sugarcane growth is in three-dimensional plots (Fig. 16-23). These figures provide a comprehensive summary of the growth response to age, insolation and temperature, and a simple and convenient approach for the analysis of the individual and of the integrated impact of these factors on growth.

Comparisons of Fig. 16, 18, 20 and 22 with Fig. 17, 19, 21 and 23 show at a glance that the sugarcane growth is reduced to one-half or less of the maximum when one of the following conditions is present: (1) maximum temperature is equal to 70°F or less, (2) insolation is equal to 300 ly/day or less and (3) the crop is 18 months or older. These results are in agreement with results reported by Clements (1980), Verret et al. (1927) and Borden et al. (1942). Growth is at a minimum when each of the three factors is at minimal condition and acting simultaneously.

Fig. 16, 18, 20, and 22 show that growth is optimum when the individual factors of age, temperature and insolation is at optimum condition and acting simultaneously on regulating plant growth.

Comparison of Fig. 16 and 17 shows that the effect of temperature at constant age is smallest in weak light and maximum in strong light, in agreement with Glasziou et al.

(1965) and Hartt (1965). The effect of temperature on growth is more pronounced at high radiation intensities than at low intensities, and on young cane than on older cane.

Comparison of Fig. 18 and 19 shows that the effect of insolation is weak at low daytime temperature and high at high temperature. The effect of age on growth is small under low temperatures but is significantly higher under high temperature and insolation conditions.

The growth effect due to the interactions of insolation and temperature are shown in Fig. 20-23. Comparisons of Fig. 20 and Fig. 21, and of Fig. 22 and Fig. 23, clearly show that the growth rates at 18 months of age is less than 50 percent the growth rates at 6 months of age. The effect of insolation on growth of young canes is small at low temperatures and much higher at high temperatures. Similarly, the effect of maximum temperature on young canes is small at low insolation and much higher at high insolation levels.

The three-dimensional growth curves clearly show that age, solar radiation and maximum temperature must be at optimum and acting simultaneously for maximum growth. Whenever one of the factors is limiting, the limiting factor plays a significant role in reducing growth.

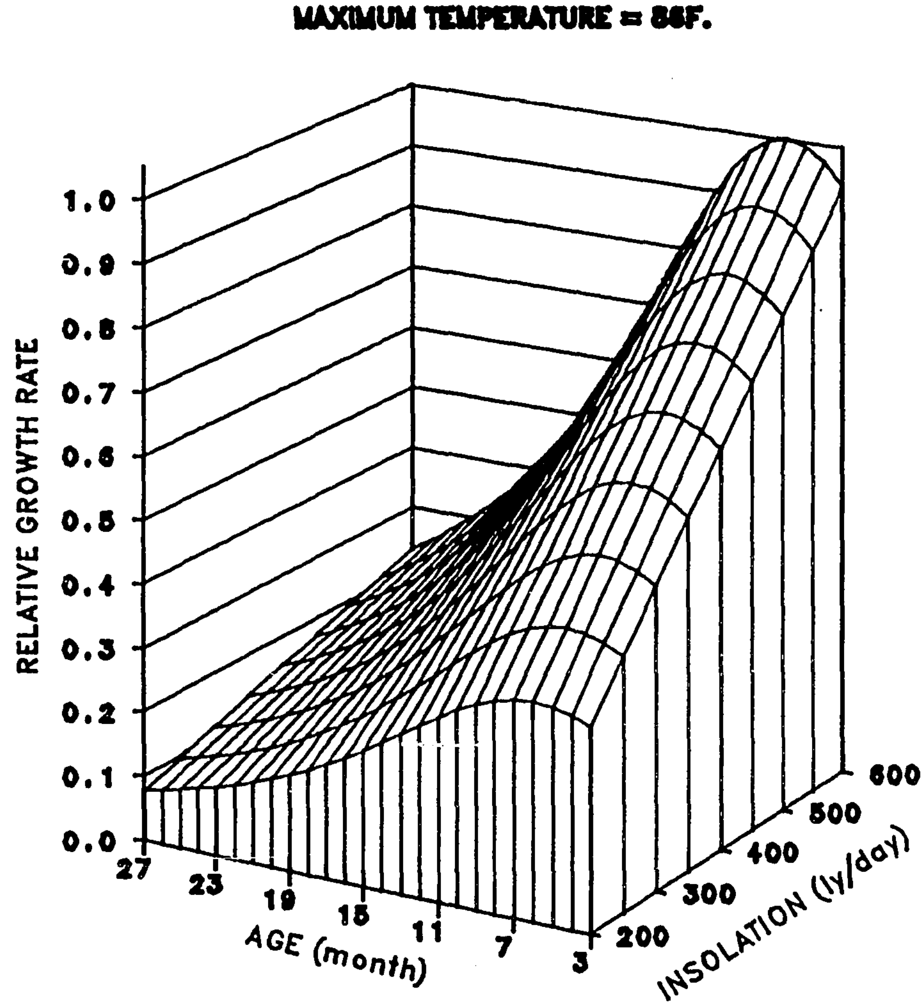

Fig. 16. Simulated interaction of age and insolation on sugarcane elongation rate at maximum temperature of 86°F. Growth rate is relative to the monthly growth at optimal conditions of 600 cal/cm^2/day, 86°F, and crop age from 5 months to 6 months.

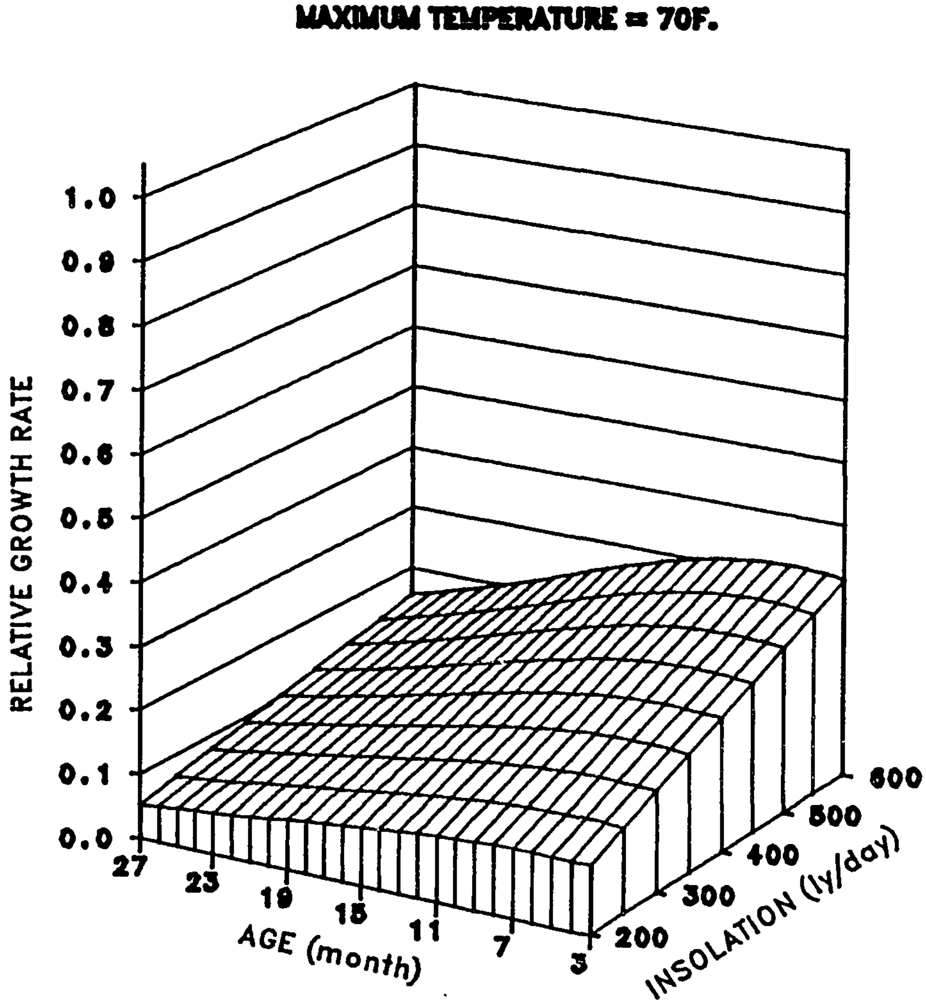

Fig. 17. Simulated interaction of age and insolation on sugarcane elongation rate at maximum temperature of 70°F. Growth rate is relative to the monthly growth at optimal conditions of 600 cal/cm^2/day, 86°F, and crop age from 5 months to 6 months.

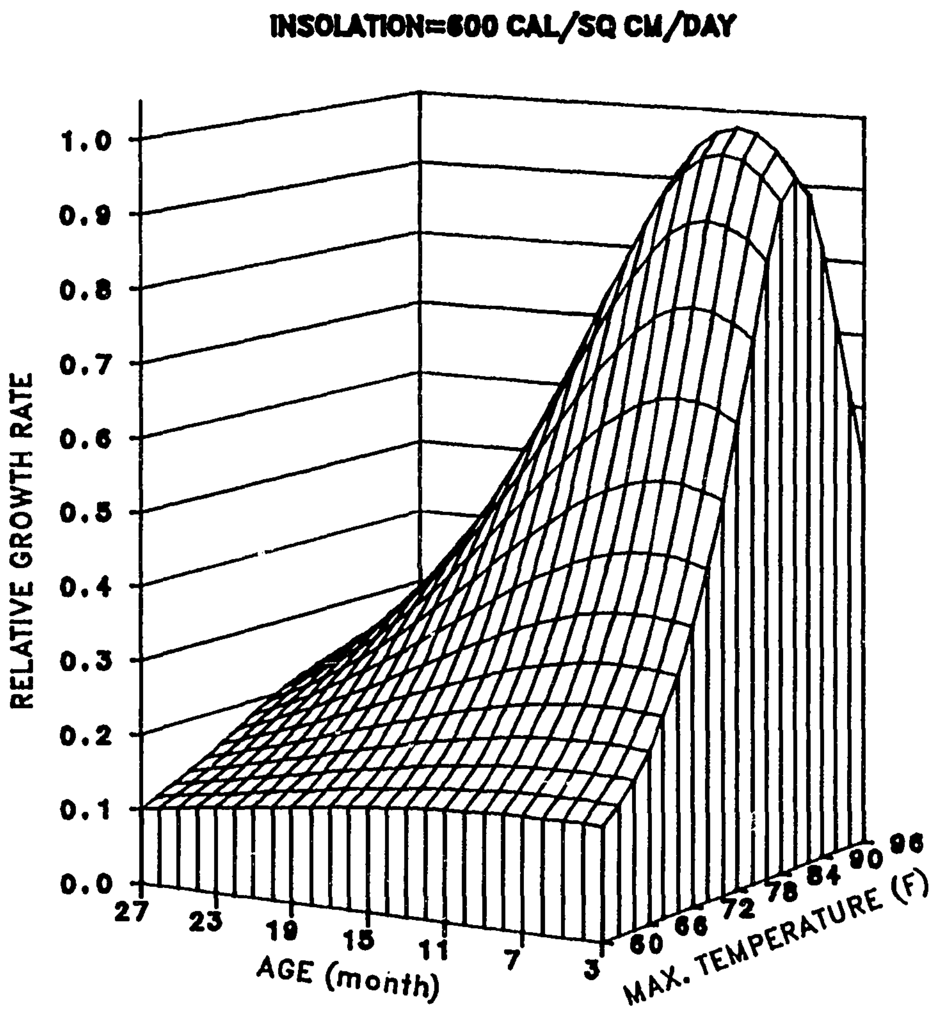

Fig. 18. Simulated interaction of age and maximum temperature on sugarcane elongation rate at insolation of 600 cal/cm^2/day. Growth rate is relative to the monthly growth at optimal conditions of 600 cal/cm^2/day, 86^{o}F, and crop age from 5 months to 6 months.

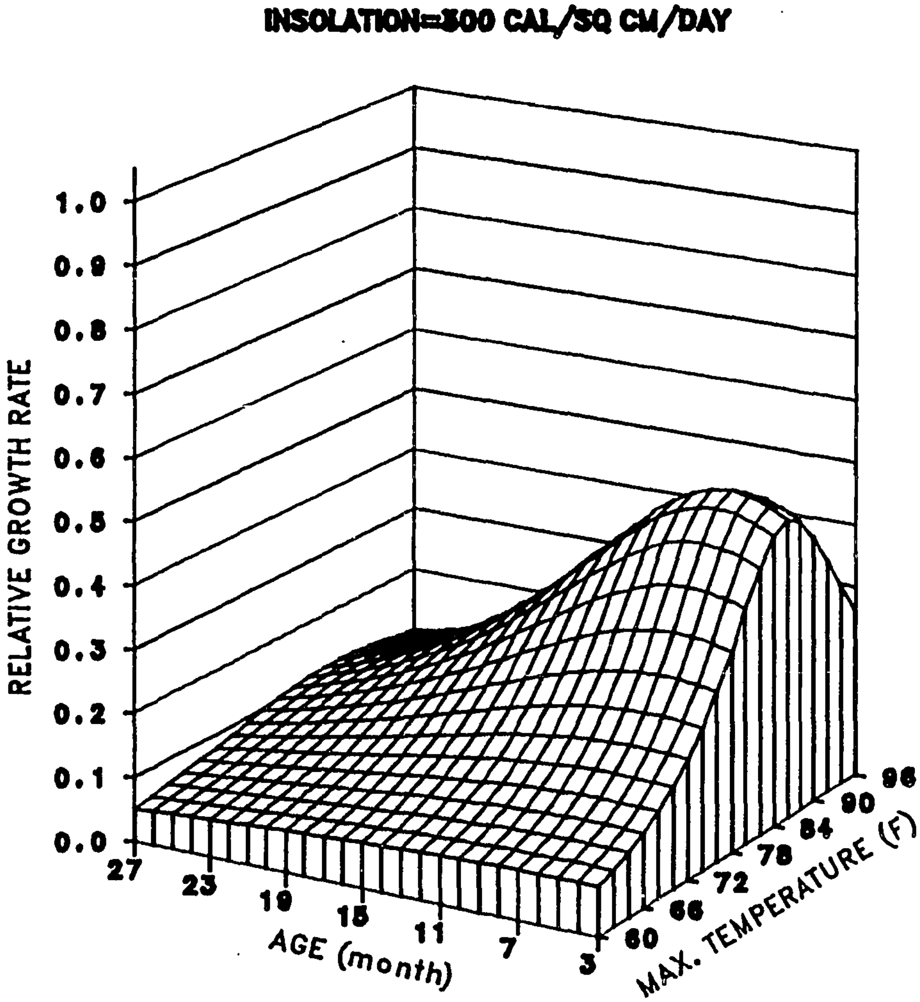

Fig. 19. Simulated interaction of age and maximum temperature on sugarcane elongation rate at insolation of 300 cal/cm^2/day. Growth rate is relative to the monthly growth at optimal conditions of 600 cal/cm^2/day, 86^{o}F, and crop age from 5 months to 6 months.

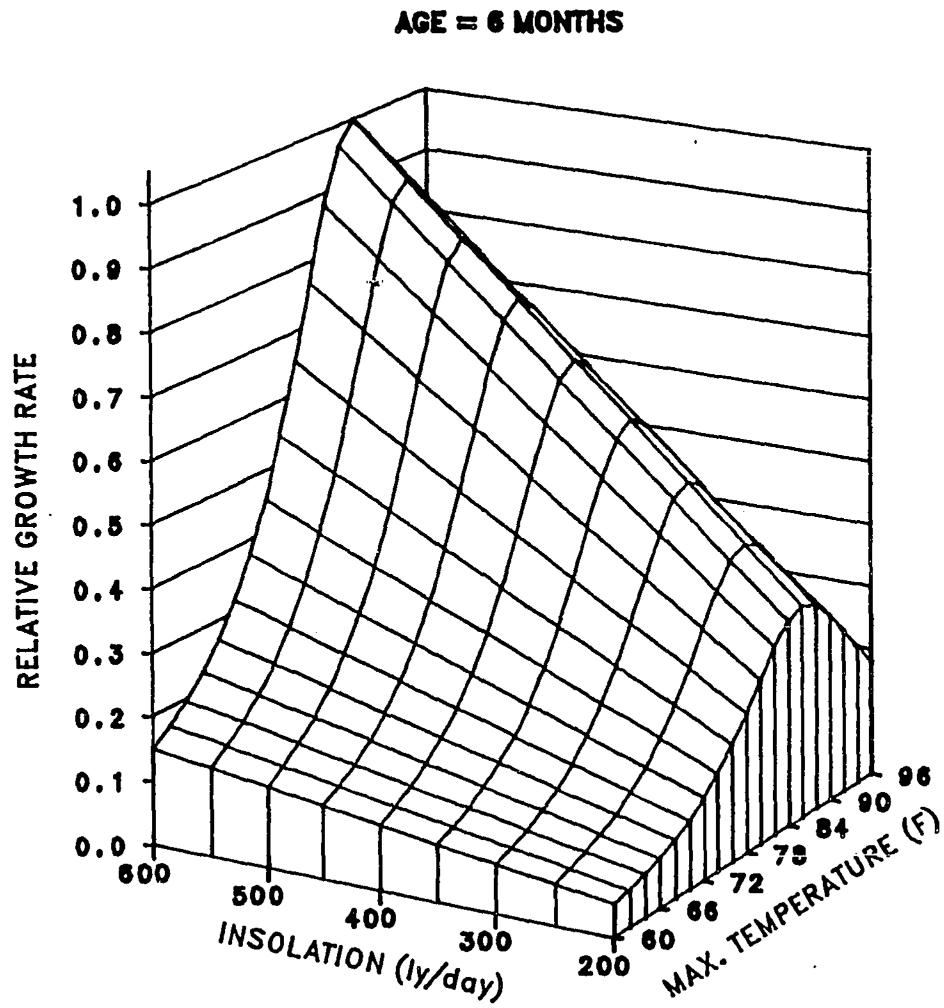

Fig. 20. Simulated interaction of insolation and maximum temperature on sugarcane elongation rate form age 5 months to 6 months. Growth rate is relative to the monthly growth at optimal conditions of 600 cal/cm^2/day, 86^{o}F, and crop age from 5 months to 6 months.

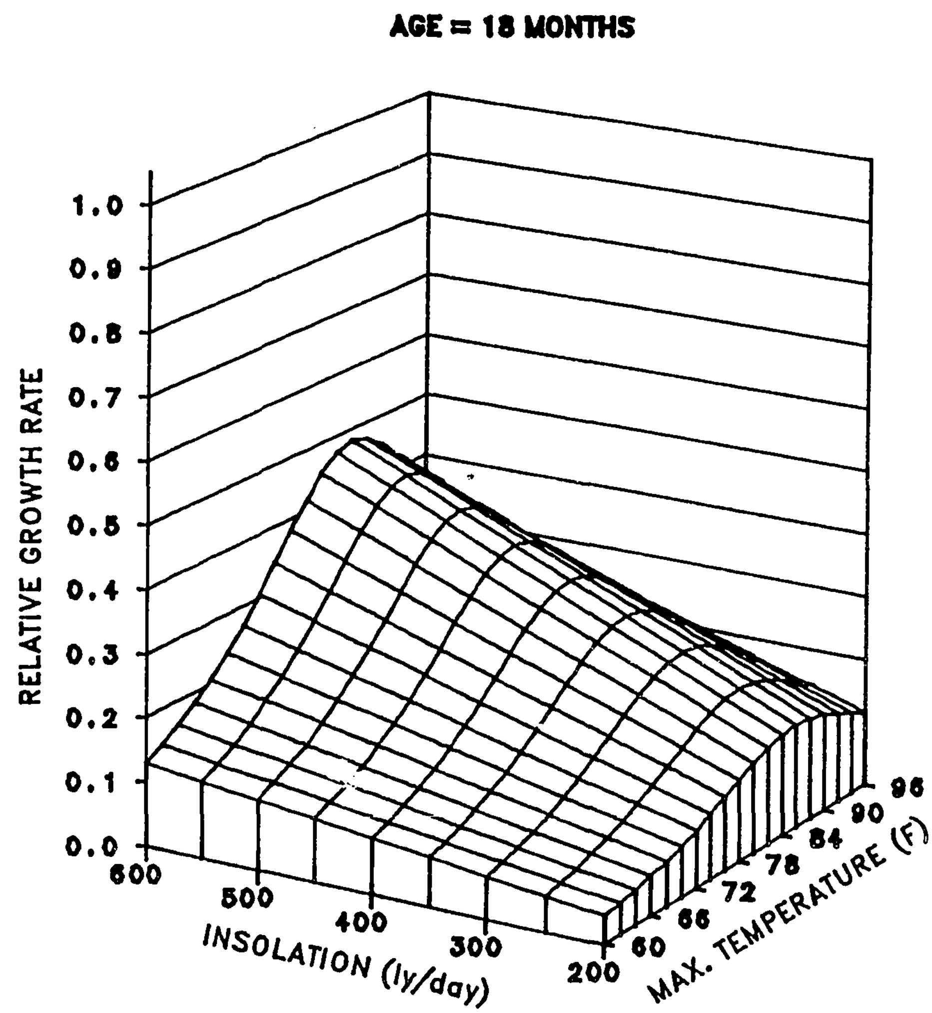

Fig. 21. Simulated interaction of insolation and maximum temperature on sugarcane elongation rate from age 17 months to 18 months. Growth rate is relative to the monthly growth at optimal conditions of 600 cal/cm^2/day, 86^{o}F, and crop age from 5 months to 6 months.

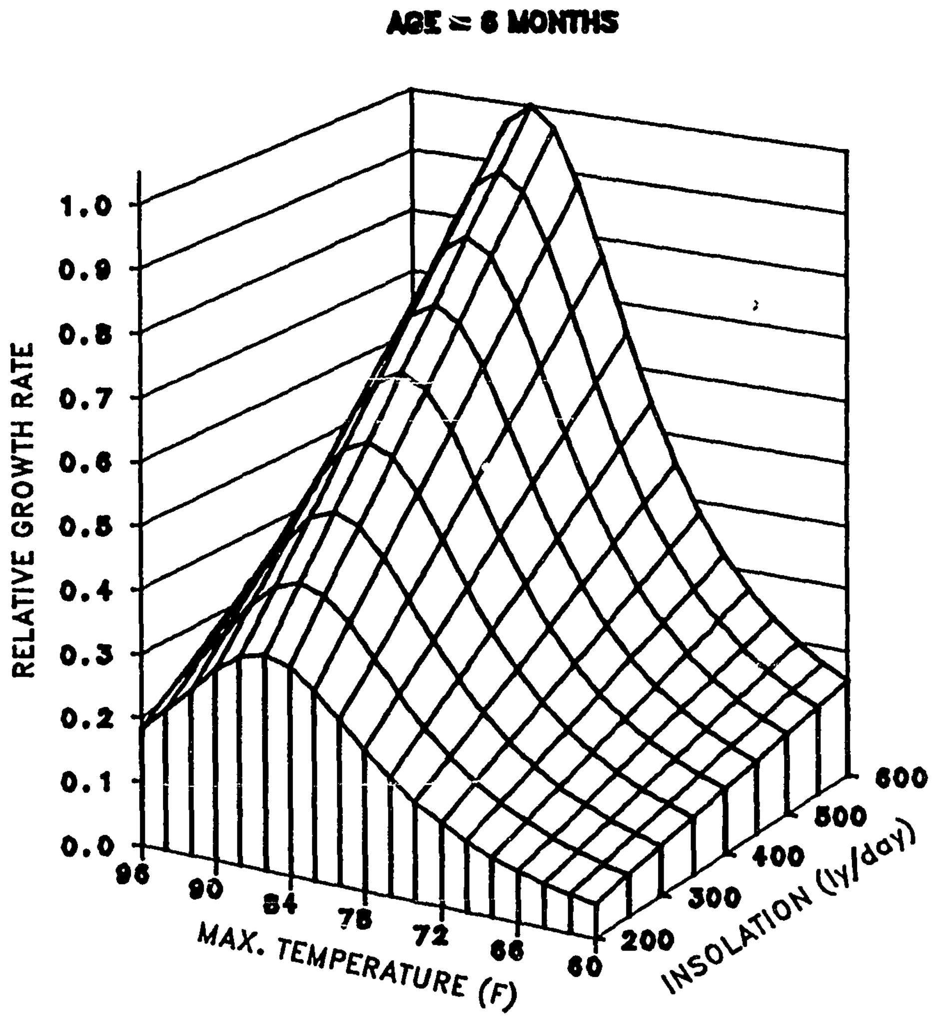

Fig. 22. Simulated interaction of maximum temperature and insolation on sugarcane elongation rate from age 5 months to 6 months. Growth rate is relative to the monthly growth at optimal conditions of 600 cal/cm^2/day, 86°F, and crop age from 5 months to 6 months.

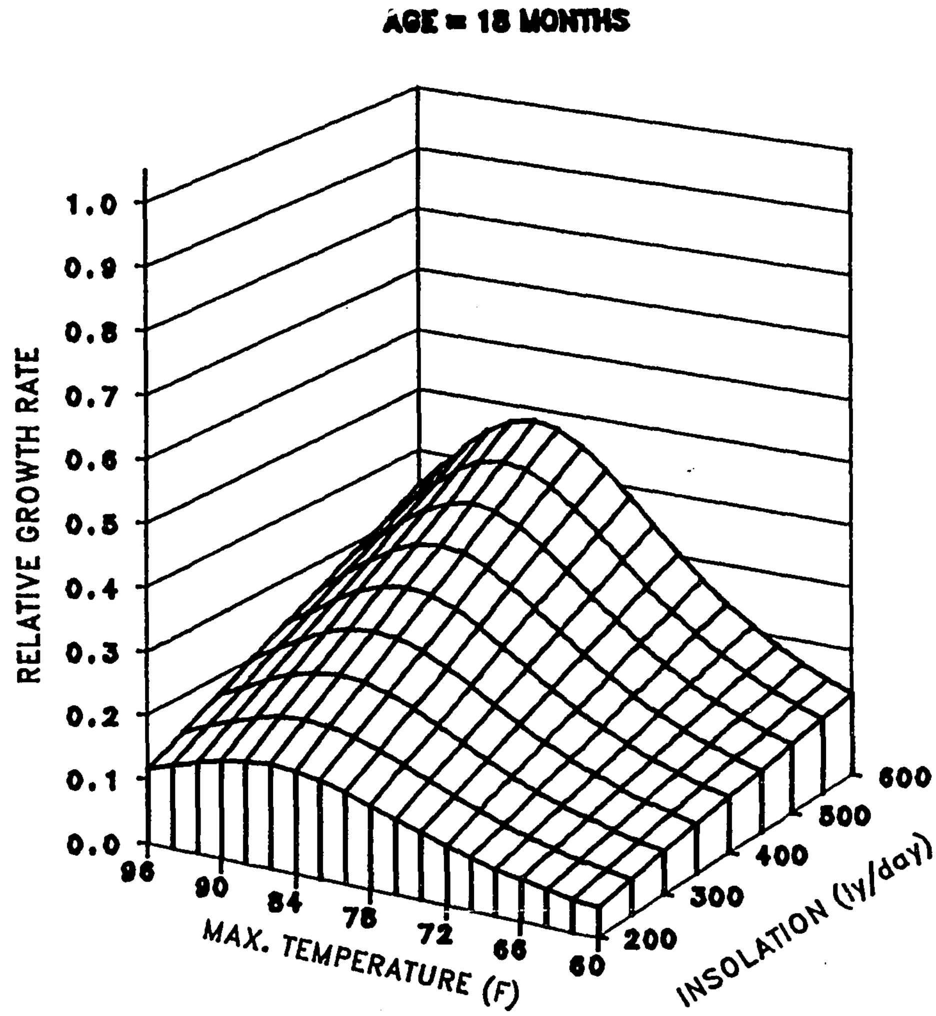

Fig. 23. Simulated interaction of maximum temperature and insolation on sugarcane elongation rate from age 17 months to 18 months. Growth rate is relative to the monthly growth at optimal conditions of 600 cal/cm^2/day, 86°F, and crop age from 5 months to 6 months.

The three-dimensional representations of the individual and combined effects of age, solar radiation and maximum temperature show evidence that growth of sugarcane is not controlled by one factor alone, as claimed by Blackman (1905), nor by a set of factors present in relative minima, as claimed by Harder (Singh et al., 1935). The model shows that each factor have some definite influence on growth rate, depending upon the intensities of the other factors. However, only one limiting factor is required to cause the growth rate to be greatly reduced. That is, the one factor that is limiting controls growth to a greater extent. These facts lead to the conclusion that when investigating growth rate of sugarcane, the simultaneous effect of age, insolation and maximum temperature must be taken into consideration.

The Age Factor

The non-linear model simulates the effect of age, insolation and maximum temperature on sugarcane growth and gives reasonable results for sugarcane grown in Hawaii. These results are also in agreement with results of the elongation rates measured in South Africa by Gosnell (1968), who conducted an extensive experiment to study the effect of increasing age on sugarcane. He reported elongation rates during the second year of 39 to 53 percent of that during the first year for plots which were respectively unirrigated and irrigated during the second year. This shows that irrigation will cause a lesser decrease but it cannot overcome the impact of increasing age to any significant degree.

This study and Gosnell's are mainly interested on the effect of increasing age of sugarcane crop in contrast to that of a single cane plant or group of plants that are widely spaced. The study of age effect on sugarcane crops is much more complex because of the numerous other interactions in addition to the effect of physiological aging of the plants. However, it is the age effect on a crop that is of greater importance because of its overall impact on yields.

The effect of aging is expressed in a significant decrease of the plant's ability to response to external factors. The response of the cane plant to fertilizers and irrigation is greater during the first year than the second year of the plant. The modelling results and the actual growth rates in this study show that the plants' ability to respond to climatic factors is also greatly reduced in the second year. Borden (1945) reported the highest total green weight accumulation during the first year of the crop. He also reported that higher amounts of nitrogen have not only produced more green tops, but have maintained more tops throughout the second year of growth, but these amount was still one third less than during the first year.

His findings lend support to the non-linear model which shows that age effect is indeed significant in reducing growth during the second year.

Dark respiration is a major factor in the decrease of the growth rate of sugarcane with age. According to Glover (1973), the leaves are the main source of respiration loss during the early life. Then, as the stalks grow and the canopy closes, the new leaves are borne as a crown of the developing stalks and stalk respirations gradually becomes dominant. He attributed the 40 percent decrease in the final yield in the second year over the yield during the first year to an increase in respiration loss. This is due to the increasing size of the stalks which contribute nothing to photosynthesis, whereas the leaf area being relative constant once the full canopy is established.

Sugarcane Growth and Final Yield

The model may also be useful to determine final cane yield if elongation rates can be related to yield, when combined with information on stalk population. Several studies on stalk population have shown that a sugarcane crop usually started out with a much larger population than it is able to maintain, and by the time the canopy was closed-in some mortality of smaller stalks was apparent (Borden, 1945). Nickell (1967) reported a rapid increase of stalk population at 3 to 9 months of age and a decrease of about 50 percent in stalk population at harvest at 18 to 22 months of age. This means that twice as many stalks were produced but due to light competition a significant number of stalks died.

There are many situations in which light may be the only factor for which there is competition, as in well-fertilized crops of irrigated areas or of high rainfall regions. Even in regions where there is acute competition for water during dry parts of the year, light may be the sole basis of competition during the wet season. Even where water and nutrients impose some limit on growth rate, competition for light is still almost certain to be of importance (Donald, 1958). It has been emphasized (Donald, 1951; Blackman and Black, 1959) that if water and nutrients are in adequate supply, then light will become the limiting factor controlling growth and the production of dry matter.

Watson (1947) showed the great importance of leaf area index (LAI) as a factor governing production. Maximum productivity is achieved when LAI is optimum. Donald (1961) discussed in detail the concept of ceiling LAI in relation to the optimum LAI. When LAI increases beyond the optimum, the low light intensity at the base of the canopy and the weak photosynthesis of the lowest leaves lead not only to a negative contribution by these leaves but to a rapid loss of weight and eventually to their death. The rate of death of leaves increases with increasing LAI until it equals the rate of production of new leaves. The ceiling LAI is the LAI when it is static. The whole foliage, however, still make a positive contribution and the dry weight of the crop continues to increase.

Although there was a significant association between photosynthetic rate and number of sugarcane stalks, and between photosynthetic rate and sugar content, Rosario (1972) did not obtain an association between photosynthetic rate and yield of cane or sugar per hectare. Irvine (1975) reported that photosynthetic rates per unit leaf area did not increase with increasing yield but photosynthetic rates per unit land area were related to yield of sugarcane. LAI was positively associated with cane yield. He mentioned that under traditional cultivation practices, maximum yield is achieved by a large LAI and many horizontal leaves to promote early canopy closure. However, his findings indicate that maximum yield may be obtained by more efficient row geometries which encourage higher LAI.

Studies on stalk density of sugarcane at various crop ages by Nickell (1967) and Van Dillewijn (1952) lend support to the existence of a ceiling LAI in sugarcane. However, it should be pointed out that ceiling LAI in sugarcane depends on soil moisture and levels of nitrogen fertilizer applied as reported by Borden (1945). This is also supported by studies reported by How and Hilton (1979) who obtained significantly higher cane yield from plots irrigated by sewage effluent, which is rich in nutrients, than yield from plots irrigated with ditch water over a two-year period. It should noted that although N increases cane yield, it is standard practice to restrict fertilization to the first year of the crop in order to improve cane quality and sugar yield. For the same reasons, water application for irrigated fields is gradually reduced several months before harvest.

According to Van Dillewijn (1952), numerous field experiments in Java have proved that there is an optimum row spacing for each variety at which it produced its maximum yield of cane and sugar. He concluded that the ultimate number of millable stalks which a cane crop is able to carry under a set of conditions is fixed within a narrow range. Hilton (1982) analysed 80 experiments in row spacing and concluded that sugar yields decreased for all increases in width from the standard 5-foot row spacing, that is, closer row spacing resulted in greater sugar yield. Kosaka (1961) observed that stalk length and the number of stalks per unit area were major factors determining yield.

It appears from results of previous studies that the combination of stalk elongation rates with stalk population counts can be used to predict final yield. This was tested using the Lihue Plantation data on density of millable stalk at the age of 6 months and the measured total cane length for the five cases studied. The result (Fig. 24) shows a linear increase in cane yield (TCA) with the total stalk length with a correlation coefficient of +0.96. Total length per acre was computed from stalk density measured at 6 months of age, length of stalks prior to harvest and length of planting rows per acre. This is in agreement with Santo and Bosshart (1982) who reported that stalk elongation and cane volume measurements taken during the first year correlated very well with cane yield at harvest. They suggested using growth measurements to assess the effects of water treatments on yield without making plot harvest. The non-linear model proposed in this study may be used to predict potential sugarcane growth under optimum moisture condition.

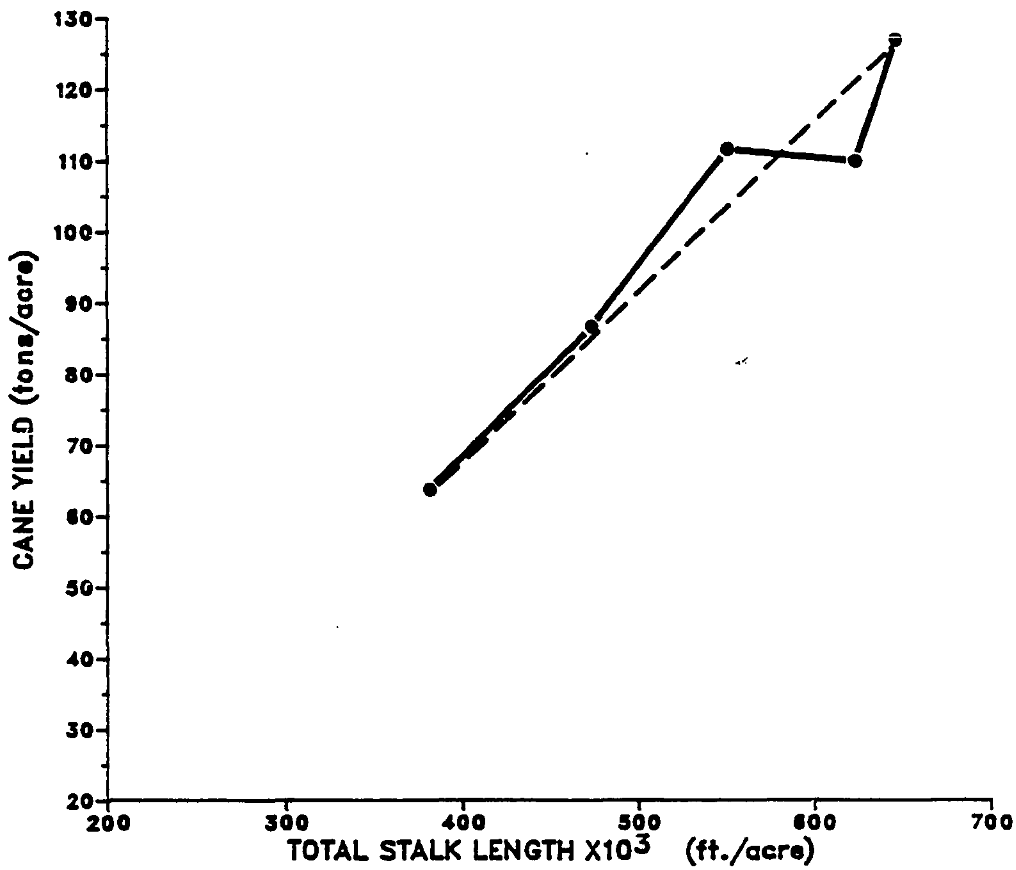

Fig. 24. Relationship between sugarcane yield (TCA) and total stalk length per acre. Dashed line represents fitted curve. Correlation coefficient r=0.96.

V. SUMMARY AND CONCLUSIONS

1. This study has experimented with two methods, namely the first-order regression approach and a non-linear functional approach, of describing sugarcane growth in response to age, insolation and temperature by using harvest or growth data from irrigated fields.

2. Ten first-order models are investigated using stepwise multiple regression analysis. The predictand is cane yield obtained from 600 field tests conducted between 1959 and 1978. The predictors are cumulative values of insolation, maximum temperature and minimum temperature for 3, 6, 12, 18 months, or for each crop period derived from weather observations made at stations near the test plots.

3. The low R-square values of the ten first-order models indicate that the models have limited predictive values and could not account for a substantial proportion of the variations of cane yield.

4. Several factors could be responsible for the low coefficients of determination: (i) moisture stress was not included in the models but could have significantly affected growth, (ii) the long growing period of 20 to 26 months is, undoubtedly, a major

factor because the effect of the multitude of weather and plant factors on plant growth is quite different at various conditions and stages on the crop, (iii) the choice of linear models, imposed by the constraint of too many independent variables and too few observations, may have been inappropriate since the effect of age and of the individual climatic factors are not additive but interactive, and (iv) ratooning, irrigation with saline water and miscellaneous plant, climatic or management factors could have also significantly affected yield but were not included in the models.

5. The non-linear model in based on known relationships between (i) growth and insolation, (ii) growth and maximum temperature and (iii) growth and age of crop. A mathematical expression that integrates the effect of insolation, maximum temperature and age on growth is developed.

6. The sugarcane growth model was successfully tested and validated. The model simulates realistic growth patterns from records of insolation and maximum temperature, and with age as the third factor. Measured and computed growth rates are highly correlated as long as the sugarcane plants did not suffer from soil moisture stress.

7. Simulated growth data were used for the study of the interactions of the factors included in the models.

8. The non-linear model provides a means of studying the interactions of these important factors affecting sugarcane growth, thus overcoming one of the major difficulties in plant growth studies.

9. Three-dimensional plots of the growth curves in relation to age, insolation and maximum temperature are produced. This type of presentation provides a simple and convenient means for the analysis of sugarcane growth in response to the interactions of age, and climatic factors.

10. The model may prove to be useful in estimating growth and used for assessing the growth performance of sugarcane crop on a monthly basis.

11. When combined with data on stalk population between 6 and 12 months of age, the model has the potential of predicting final cane yields.

12. The model helps focus on the importance of high insolation, and maximum temperature, and on the negative impact of increasing age on sugarcane growth. In the search for higher yielding cane, it emphasizes the importance of varieties that are less

susceptible to the age effect, and more tolerant to lower temperatures.

13. The model shows that each factor have some definite influence on growth rate, depending upon the intensities of the other factors. However, only one limiting factor is required to cause the growth rate to be greatly reduced. That is, the one factor that is limiting controls growth to a greater extent. These facts lead to the conclusion that when investigating growth rate of sugarcane, the simultaneous effect of age, insolation and maximum temperature must be taken into consideration.

SUGGESTIONS FOR FUTURE RESEARCH

The non-linear model should be further tested using stalk elongation measurements and weather data from other plantations. Where irrigation of cane fields is practiced, there should be a set of measurements from fields that are maintained at optimum soil moisture throughout the crop cycle. Changes to the optimum growth rate and the estimates of the two coefficients will be required.

Future work should be aimed at improving the non-linear model to include the effect of moisture stress and of fertilization amounts and timing. The factor of moisture stress should be based on effective water application from rainfall and irrigation, and on evapotranspiration and changes in soil moisture. Effort should also be made to develop a model that would be related to sugarcane variety and soil type.

The usefulness of the non-linear model as a predictive tool for cane yield will require additional evaluation. Information on stalk population density will probably be a crucial factor. The method and timing of stalk count will, no doubt, be of considerable importance.

LITERATURE CITED

Ashton, F.M. 1956. Effects of a series of cycles of alternating low and high soil water contents on the rate of apparent photosynthesis in sugarcane. Plant Physiol. 31: 266-273.

Baier, W. 1979. Notes on the terminology of crop-weather models. Agr. Meteorol. 20: 137-145.

Begg, J.E. and N.C. Turner. 1976. Crop weather deficits. In: Advances in Agronomy. (N.C. Brady, Ed.), Academic Press, New York. 18: 161-207.

Benci, J.,E. Runge, R. Dale, W. Duncan, W. Curry and L. School. 1975. Effects of hypothetical climatic changes on production and yield of corn. CIAP Monograph 5, Department of Transportation, DOT-TST-75-55 (Part 2), 4.3-4.37.

Blackman, F.F. 1905. Optima and limiting factors. Annals Bot. 19: 281-295.

Blackman, G.E. and J.N. Black. 1959. Physiological and ecological studies in the analysis of plant environment. XII-The role of the light factor in limiting growth. Ann. Bot. NS23: 131-145.

Borden R.J. 1945. The effect of nitrogen fertilization upon the yield and composition of sugarcane. Haw. Plant. Rec. 49: 259-312.

Borden, R.J. and F.C. Denison. 1942. A study of optimum crop length. Haw. Plant. Rec. 40: 119-137.

Bosshart, R.P. 1979. Changes in soil salinity and sodicity at HC&S Company and Pioneer Mill Company. HSPA Experiment Station Annual Report 1979: 17-18.

Brodie, H.W. 1964. Instruments for measuring solar radiation: Research and evaluation by the Hawaiian sugar industry 1928-1962. Haw. Plant. Rec. 57: 159-196.

Brodie, H.W. 1965. The Wig-Wag -- an inexpensive instrument for measuring solar radiation. Solar Energy 9: 27-31.

LITERATURE CITED

Burr, G.O., C.E. Hartt, H.W. Brodie, T. Tanimoto, H.P. Kortschak, D. Takahashi, F.M. Ashton, and R.E. Coleman. 1957. The sugarcane plant. Ann. Rev. Plant Physiol. 8: 275-308.

Campbell, R.B. 1967. Sugarcane. In: Irrigation of agricultural lands. (R.M. Hagan et al., Eds.), Agronomy Series, Am. Soc. Agron., Madison, Wis. 11: 649-653.

Campbell, R.B., J.H. Chang, and D.C. Cox. 1959. Evapotranspiration of sugarcane in Hawaii as measured by in-field lysimeter in relation to climate. Proc. 11th Congr. Int. Soc. Sugar Cane Technol. 637-649.

Chang, J.H. 1961. Microclimate of sugar cane. Haw. Plant. Rec. 56: 195-223.

Chang, J.H. 1968. Climate and Agriculture: An Ecological Survey. Aldine Publishing Co., Chicago: 304pp.

Chang, J.H., R.B. Campbell, and R.E. Robinson. 1963. On the relationship between water and sugar cane yield in Hawaii. Agron. J. 55: 450-453.

Chang, J.H., H.W. Brodie and L.D. Baver. 1965. Evapotranspiration research at the HSPA Experiment Station. Proc. 12th Congr. Int. Soc. Sugar Cane Technol: 10-24.

Clements, H.F. 1964. Interaction of factors affecting yield. Ann. Rev. Plant Physiol. 15: 409-442.

Clements, H.F. 1980. Sugarcane crop logging and crop control. The University Press of Hawaii, Honolulu, 520pp.

Clements, H.F. and S. Nakata. 1967. Minimum temperatures for sugarcane germination. Proc. 12th Congr. Int. Soc. Sugar Cane Technol: 554-560.

Cornelison, A.H. and R.P. Humbert. 1960. Irrigation internal control in the Hawaiian soils. Haw. Plant. Rec. 54: 205-209.

Das, U.K. 1933. Measuring production in terms of temperature. Haw. Plant. Rec. 37: 32-52.

LITERATURE CITED

Das, U.K. 1936. The day-degree in Mauritius. Haw. Plant. Rec. 40: 103-104.

Donald, C.M. 1951. Competition among pasture plants. I. Intra-specific competition among annual plants. Aust. J. of Agric. Res. 2:355-376.

Donald, C.M. 1958. The interaction of competition for light and for nutrients. Australian J. Agric. Res. 9:421-435.

Donald, C.M. 1961. Competition for light in crops and pastures. Soc. Expt. Biol. Symp. 15: 282-313.

Ekern, P.C. 1970. Consumptive use of water sugarcane in Hawaii. Water Resources Center, University of Hawaii Tech. Report No 37: 193pp.

Ekern, P.C. 1977. Drip irrigation of sugarcane measured by hydraulic lysimeter, Kunia, Oahu. University of Hawaii, Water Research Center. Technical Report No. 109: 99pp.

Gates, D.M. 1968. Transpiration and leaf temperature. Ann. Rev. Plant. Physiol. 19: 211-238.

Glover, J. 1973. The dark respiration of sugarcane and the loss of photosynthate during the growth of a crop. Ann. Bot. 37: 845-852.

Glasziou, K.T., T.A. Bull, M.D. Hatch and P.C. Whiteman. 1965. Physiology of sugarcane VII. Effects of temperature, photoperiod duration, and diurnal and seasonal temperature changes on growth and ripening. Aust. J. Biol. Sci. 18 (1): 53-66.

Gosnell, J.M. 1968. Some effects of increasing age on sugarcane growth. Proc. 13th Congr. Int. Soc. Sugar Cane Technol: 499-513.

Halais, P. 1935. Un nouvel indice de climatalogie agricole. Rev. Agric. Maurice, No. 80: 44-49.

Hanshuncheong, K. 1974. The measurement of global total radiation by Wig-Wag integrators. Preprint. Int. Tropical Meteor. Meeting, Jan. 31-Feb. 7, 1974, Nairobi, Kenya: 8pp.

LITERATURE CITED

Haun, J.R. 1974. Prediction of spring wheat yields from temperature and precipitation data. Agron. J. 66: 405-409.

Hartt, C.E. 1965. The Effect of temperature upon Translocation of 14C in sugarcane. Plant Physiol. 40: 74-81.

Hartt, C.E. 1967. Effects of moisture supply upon translocation and storage of 14C in sugarcane. Plant Physiol. 42: 338-346.

Hilton, H.W. 1982. An analysis of the influence of row spacing and seed spacing on sugarcane yield in Hawaiian cane. Haw. Plant. Rec. 59: 265-272.

Hilton, H.W. and L.T. Santo. 1979. An attempt to measure TSAM as a function of crop age. Unpublished HSPA data. Agronomy Report 30, October 1979: 4pp.

Hilton, H.W. and R.J. Mackenzie. 1980. The response of varieties to amounts of applied nitrogen as measured by yield tests -- 1960 to 1978. Unpublished HSPA data. Agronomy Report 62, March 1980: 9pp.

How, K. 1985. 1983-1984: Driest two-year period on the sugar plantations. Unpublished HSPA data. Agronomy Report 63, April 1985: 10pp.

How, K. and H.W. Hilton. 1979. Sewage effluent for furrow irrigation of sugarcane. Unpublished HSPA data. Agronomy Report 29, July 1979: 8pp.

Hsiao, T.C. 1973. Plant responses to water stress. Ann. Rev. Plant Physiol. 24: 519-570.

Hsiao, T.C. and E. Acevedo. 1974. Plant responses to water deficits, water-use efficiency and drought resistance. In: Plant modification for more efficient water use. (J.F. Stone, Ed.), Agric. Met., Special Issue, 14(112): 59-84.

Humbert, R.P. 1968. The growing of sugarcane. Elsevier Pub. Co., New York: 779pp.

Irvine, J.V. 1975. Relations of photosynthetic rates and leaf and canopy characters to sugarcane yield. Crop Sci. 15: 671-676.

LITERATURE CITED

Jackson, W.A. and R.J. Volk. 1970. Photorespiration. Ann. Rev. Plant Physiol. 21: 385-432.

Jensen, R.E. 1975. A summary of estimated impacts of climatic change on crop production. Proc. of the Fourth Conf. on Climatic Impact Assessment Program. Nat. Tech. Inf. Sci. Service, Springfield, Va. :87-96.

Jones, C.A. 1980. A review of evapotranspiration studies in irrigated sugarcane in Hawaii. Haw. Plant. Rec. 59:195-214.

Komatsu, S., S. Ozawa, and Y. Makino. 1933. Biochemical studies on the maturity of sugarcane. Mem. Coll. Sci. Kyoto Imp. Univ., Ser. A 16: 1-125.

Kortschak, H.P. 1968. Photosynthesis in sugarcane and related species. Photosynthesis in sugarcane, Proc. Int. Symposium June 12 and 13, 1968, Royal Lancaster Hotel, London: 18-29.

Kortschak, H.P. and A. Forbes. 1969. The effects of shade and age on the photosynthesis rate of sugarcane. Prog. Photosynth. Res. 1: 383-387.

Kosaka, L. 1961. Line spacing experiment at HC&S Co. Ltd. Haw. Sugar Technol. 1961 Reports: 106-110.

Kramer, P.J. 1969. Plant and soil water relationships: A modern synthesis. McGraw-Hill Book Co., New York: 482pp.

Leeper, R.A., E.C. Runge and W.M. Walker. 1974. Effect of plant available stored moisture on corn yields. Agron. J. 66: 723-733.

Lemon, E., D.W. Steward, and R.W. Shawcroft. 1971. The sun's work in a corn field. Science 174: 371-378.

McQuigg, J.D. 1976. Modelling the impact of climatic variability for the purpose of estimating grain yields. Proc. of Climate-Plants-Soils Symposium, University of Guelph, April 20-21, 1968: 4-18.

LITERATURE CITED

Meek, D.,J. Hatfield, T. Howell, S. Idso and R. Reginato. 1984. A generalized relationship between photosynthetically active radiation and solar radiation. Agron. J. 76:939-945.

Mongelard, J.C. and K. How. 1976. Automatic control for subsurface irrigation using tensiometers and evaporation pan for basic plant-water studies. Haw. Sugar Technol., 1976 Reports: 187-191.

Mongelard, J.C. and L. Mimura. 1971. Growth studies on the sugarcane plant. I. Effects of temperature. Crop Sci. 11: 795-800.

Mongelard, J.C. and L.G. Nickell. 1972. The sugarcane plant in the soil-plant-atmosphere continuum. Proc. 14th Congr. Int. Soc. Sugar Cane Technol.: 827-840.

Moss, D.N. 1962. The limiting carbon dioxide concentration for photosythesis. Nature 193: 587.

Nickell, L.G. 1967. Agricultural aspects of transplanting and spacing. Haw. Sugar Technol., 1967 Reports: 147-155.

Nickell, L.G. 1968. Water Utilization: I. Basic Plant-water studies. Proc. 13th Congr. Int. Soc. Sugar Cane Technol: 38-48.

Nickell, L.G. 1977. Sugarcane. In: Ecophysiology of tropical crops. (Alvim P. and Kozlowski T., eds), Academic Press: 89-110.

Oldeman, L.R. 1971. Analysis of sugarcane production in relation to climate, soil and management. Unpublished Ph.D dissertation, University of Hawaii.

Rawlins, S.L. and P.A.C. Raats. 1975. Propects of high frequency irrigation. Science 188: 604-610.

Rosario, E.L. 1972. Physiological aspects of photosynthesis differences in relation to yield exhibited by some sugarcane varieties. Cornell Univ. Diss. Abstr. Int. 33: 2,895-B.

Sakamoto, C.M. 1981. The Technology of crop/weather modelling. In: Food-Climate interactions. (W.Bach, J. Pankrath and S.H. Schneider, eds), D. Reidel Publishing Co. : 383-398.

LITERATURE CITED

Santo, L.T. and Bosshart R.P. 1982. Amounts of water versus yield relationships of drip-irrigated sugarcane. Unpublished HSPA data. Irrigation Report 81. September 1982: 7pp.

Sarker, R.P. 1964. A curvilinear study of yield with reference to weather - sugarcane. Indian J. Met. Geophys., 15: 103-110.

Singh, B.N. and K.N. Lal. 1935. Limitations of Blackman's law of limiting factors and Harder's concept of relative minimum as applied to photosynthesis. Plant Physiol. 10: 245-268.

Slatyer, R.O. 1967. Plant-water relationships. Academic Press, New York: 366pp.

Snee, R.D. 1973. Some Aspects of nonorthogonal data analysis - Part I. Developing prediction equations. J. Quality Technology 5: 67-79.

Stender, H.K. 1924. Some sugarcane growth measurements. Haw. Plant. Rec. 28: 472-495.

Sun, V.G. and N.P. Chow. 1949. The effect of climatic factors on the yield of cane on Taiwan, Part 2. Report Taiwan Sugar Expt. Sta. 4: 1-40.

Sutcliff, J. 1968. Plants and Water. E. Arnold, London: 81pp.

Syed, M.M. and S.A. El-Swaify. 1972. Effect of saline water irrigation on N.Co. 310 and H50-7209 cultivars of sugar-cane. I. Growth parameters. Tropical Agriculture (Trinidad): 337-346.

Szeicz, G. 1974. Solar radiation for plant growth. J. Appl. Ecol. 11: 617-636.

Takahashi, D. and L.G. Nickell. 1973 Annual Report, Experiment Station, Hawaiian Sugar Planters' Association: 10-11.

Thompson, G.D. 1965. The relationship of potential evaporation of sugarcane to environment factors. Proc. 12th Congr. Int. Soc. Sugar Cane Technol: 3-9.

Thompson, G.D. 1976. Water use by sugar cane. Part 2. South Afr. Sug. J. 60: 627-635.

LITERATURE CITED

Thompson, G.D. 1977. Irrigation of sugarcane. The South Afr. Sug. J., March: 126-131; April: 161-174.

Thompson, L.M. 1969. Weather and technology in the production of corn in the U.S. corn belt. Agron. J. 61: 453-456.

Thompson, L.M. 1975. Weather variability, climatic change, and grain production. Science 188: 535-541.

Thornley, J.H. 1976. Mathematical models in plant physiology: a quantitative approach to problems in plant and crop physiology. Academic Press, New York: 318pp.

Trouse, A.C. Jr. 1964. Effects of soil compression on some subtropical soils on soil properties and upon root development. Unpublished Ph.D. dissertation, University of Hawaii.

Trouse, A.C. Jr., R.P. Bosshart, K.T. Ingram and L.T. Santo. 1984. Tillage and traffic of Hawaii's sugarcane soils, Parts I-IV. Unpublished HSPA data. Agronomy Reports 55-58: August 1984: 19pp.

Van Dillewijn, C. 1952. Botany of sugarcane. The Chronica Botanica Co., Mass., USA: 371pp.

Veihmeyer, F.J. and A.H. Hendrickson. 1950. Soil moisture in relation to plant growth. Ann. Rev. Plant Physiol. 1: 285-304.

Verret, J.A. and U.K. Das. 1927. Rate of cane growth at various ages. Haw. Plant. Rec. 31: 314-320.

Vong, N.Q. and Y. Murata. 1977. Studies of the physiological characteristic of C_3 and C_4 crop species. I. The effects of air temperature on the apparent photosynthesis, dark respiration, and nutrient absorption of some crops. Jpn. J. Sci. 46: 45-52.

Walter, A. 1910. The sugar industry of Mauritius: A study in correlation. Arthur L. Humphreys, London: 228pp.

LITERATURE CITED

Watson, D.J. 1947. Comparative physiological studies on growth of field crops. Ann. Bot. NS11: 41-76.

Zelitch, I. 1967. Water and CO_2 transport in photosynthetic process. In: Harvesting the Sun (San Pietro, A., F.A. Greer and T.R. Army, eds), Academic Press, New York, N.Y.: 231-249.