12-1988

Developing a mathematical model for vegetative plant growth in broccoli

Brian D. Pennell

To the Graduate Council:

I am submitting herewith a thesis written by Brian D. Pennell entitled "Developing a mathematical model for vegetative plant growth in broccoli." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Plant, Soil and Environmental Sciences.

David L. Coffey, Major Professor

We have read this thesis and recommend its acceptance:

Carl Sams, Luther Wilhelm

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

To the Graduate Council:

I am submitting herewith a thesis written by Brian D. Pennell entitled "Developing a Mathematical Model for Vegetative Plant Growth in Broccoli". I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Plant and Soil Science.

David L. Coffey

David L. Coffey, Major Professor

We have read this thesis and recommend its acceptance:

Carl E. Sams

Luther R. Wilhelm

Accepted for the Council:

C W Minkel

Vice Provost
and Dean of The Graduate School

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a Master's degree at The University of Tennessee, Knoxville, I agree that the Library shall make it available to borrowers under rules of the Library. Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of source is made.

Permission for extensive quotation from or reproduction of this thesis may be granted by my major professor, or in his absence, by the Head of Interlibrary Services when, in the opinion of either, the proposed use of the material is for scholarly purposes. Any copying or use of the material in this thesis for financial gain shall not be allowed without my written permission.

Signature ______________________

Date 12/1/88

DEVELOPING A MATHEMATICAL MODEL FOR VEGETATIVE PLANT GROWTH IN BROCCOLI

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Brian D. Pennell

December 1988

ACKNOWLEDGMENTS

I wish to express my appreciation to the following individuals who have provided assistance and support during my graduate program:

Wayne and Elinor Pennell, for their prayers and encouragement.

Dr. David Coffey (major professor), for his guidance and advice.

Dr. Carl Sams and Dr. Luther Wilhelm (committee members), for their suggestions and corrections.

A number of graduate students, faculty and staff of the Department of Plant and Soil Science for their friendship and help.

The Department of Plant and Soil Science of the University of Tennessee, for the use of facilities and equipment for this research.

David Hooten, for encouraging me to return for this degree.

Jesus Christ, for the strength and perseverance to complete the program.

ABSTRACT

Two experiments were conducted during 1987 and 1988 at the University of Tennessee Plant and Soil Science greenhouse. "Premium Crop" broccoli (Brassica oleracea L. Group Italica) plants were grown to develop a database from which an empirical mathematical model for vegetative growth could be developed. A model predicting the time from seeding to visible bud and another model showing the development of the inflorescence were also investigated. Plants were grown in shaded chambers within a greenhouse at 30, 50, 70, and 100% of full sunlight. Light treatments were arranged in a randomized complete block design with 3 replications. The Photosynthetic Photon Flux (PPF) density was recorded at 1-minute intervals in each experimental unit from the time of seedling emergence through inflorescence development using quantum sensors. Growth was defined as the increase in leaf area and leaf number over the duration of the study.

Models that fit the data well were developed. A non-linear model and two linear models described vegetative growth very well, however the non-linear model would be difficult to use and therefore is not recommended. The model predicting the time to visible bud may support evidence of critical minimum light and time requirements. The model describing the inflorescence development did not fit well as seen in a low R^2.

Though the models developed generally fit very well, they were based on a very small database. There was no supporting field and greenhouse data to validate the models. For these reasons, the models developed in this study should be used as guides rather than final predictive models.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

"Premium Crop" broccoli, *Brassica oleracea* L. Group *Italica*, is an annual cool season vegetable crop which has become increasingly popular for its flavor and nutritional value. With the increased popularity of the salad bar, the demand for fresh broccoli has greatly increased. Broccoli has been a risky crop to produce in Tennessee due to the variability of the weather and variability of the crop. For this crop to be more of an economic factor in Tennessee agriculture, a greater understanding of its growth and maturity is necessary.

Three facets of growth in broccoli can be investigated: the vegetative development, the time to visible inflorescence (bud), and reproductive or inflorescence development. The vegetative development is considered to begin at seed germination and continues until the inflorescence is visible. When the inflorescence becomes visible the plant begins to decrease its vegetative growth rate and transfer the energy into reproductive growth; the bud develops into a mature inflorescence which will then bloom if not harvested. Broccoli is highly perishable and remains at optimum quality stage for only a short time, therefore it requires immediate harvest. Since the time to harvest is unpredictable, scheduling labor and markets to coincide with optimum maturity can be difficult.

The purpose of this research is to develop an empirical mathematical model for plant growth in broccoli. A mathematical model is simply a quantitative relationship describing a process. An empirical model is one developed from experimental data of causal and dependent factors (Thornley, 1976). To determine the relationship between the causal factors and the dependent factor the process or relationship must be well studied. Therefore, each one of the factors must be understood before a mathematical equation can be used to estimate the dependent variable.

Plant growth is a natural process that is ideal for mathematical modeling. The characteristics and factors affecting plant growth have been and continue to be studied. When the characteristics and factors are well understood, they can be related in mathematical relationships (models). These models can be incorporated into computer simulations either to predict or to describe the process in question. For effective use of mathematical modeling, the process studied must have characteristics that can be clearly identified and must have stages that can be quantitatively measured. The characteristics and stages can then be related with mathematical relationships. If the relationships are consistent for most plants within a specific cultivar, they can be used to simulate the process.

Plant growth models with a several factors are more accurate, but harder to develop and use than those with few factors because the data are extensive and difficult to obtain. It is doubtful if any model could include all of the factors that influence growth; therefore a mathematical model is only an approximation of reality. Models with only a few factors are much easier to use because data are more readily available. If the model is incorporated in a computer program for growth prediction the simplicity can enhance the utility of the model, leading to wider use and online adjustment during the season.

Growth can be defined as the irreversible increase or development of a living organism (Ting, 1982). Growth is a function of genetic characteristics, nutritional resources, and surrounding climatic conditions. Genetic characteristics determine the maximum potential of the plant. Genotype is expressed in adaptability, vigor, natural resistance, stamina, and a number of other characteristics. Nutrients are vital in the formation, differentiation, elongation, and development of the plant. Nutrients (macro and micro) contribute to the normal, healthy formation of chemical compounds and cell structures. The climatic conditions determine the extent to which the maximum genetic potential is expressed in the plant. Sunlight causes the assimilation of carbons into stored energy in chlorophyll via photosynthesis. Temperature alters both the rates of the natural processes that occur and the elemental phases of the resources used in these processes.

The objectives of the research conducted in this study were to:

1. Determine factors that are required in developing a model.

2. Develop an empirical mathematical model describing the vegetative growth stage of broccoli.

3. Investigate possible models to describe time from seeding to visible bud formation and also describe the inflorescence development.

The following steps indicate the procedure taken in this study to develop an empirical mathematical model (Thornley, 1976) for broccoli growth:

- Determine the factors that influence growth.
- Determine the characteristics to be monitored.
- Perform experiments monitoring the factors and the characteristics.
- Determine the relationships between the growth factors and the plant characteristics.
- Incorporate these relationships into a model that describes or predicts plant growth.
- Validate the model with statistical methods, comparing the actual growth with the predicted growth.

II. LITERATURE REVIEW

Factors That Influence Growth:

Internal and external factors influence the development of plants. The genetic information within the plant is the internal component that influences growth. This genetic information varies somewhat among broccoli cultivars. Some cultivars have a more uniform maturity than others (Hulbert and Orton, 1984). The ability of a model to predict maturity is greatly increased with uniformity. Uniformity can provide the possibility for a once over harvest as opposed to a sequential harvest. Since vigor and uniform maturity are cultivar specific, models initially should be cultivar specific. By using only one cultivar in developing a model, variation among cultivars are alleviated. The external components act on the plant and are independent of the plant. Nutrient and water availability along with climatic factors such as light, temperature, humidity, and daylength comprise the primary external components. Micronutrients, those elements needed in very small amounts, and macronutrients, those elements needed in larger amounts, are essential for plant growth. Micronutrients can be limiting if they are not present in sufficient quantity. Three major macronutrients nitrogen (N), potassium (K), and phosphorus (P) greatly influence plant development.

Nitrogen generally affects the vegetative growth and potassium tends to affect root development in plants (Ting, 1982). Dufault (1988) found this to be true in greenhouse broccoli production. He grew "Southern Comet" broccoli in N and P deficient, soilless mediums to determine its response to these macronutrients. He found that as N levels increased there was a significant decrease in the number of days to bud initiation, the number of days to harvest, but a significant increase in the number of leaves and the total leaf area. Increasing P levels in the growth media did not have a significant effect on any of the above but did significantly increase the root dry weight and the total chlorophyll in the floret.

Magnifico, et al. (1979) determined that in a field planting, a crop of broccoli removed 559, 23, and 723 kg/ha of N, P, K, respectively. This is similar to the amount of these same nutrients absorbed by celery: 314 kg/ha N, 81 kg/ha P, and 712 kg/ha K (Zink, 1962), or the nutrients absorbed by spinach: 180 kg/ha N, 22 kg/ha P, and 289 kg/ha K (Zink, 1965). The demand for these nutrients and water is closely related to plant population density. The higher the population density, the more plants must compete for the nutrients. In broccoli as plant density increases the size of the inflorescence has been found to decrease (Chung, 1986; Chung, 1982; Salter, et al., 1984; Zink and Akana, 1951). Higher plant population densities have been shown to give better uniformity in some cultivars (Salter and Jones, 1975).

The other primary external components affecting plant growth are climatic factors. Two of these, temperature and photosynthetically active radiation (PAR), seem to have the greatest effect upon broccoli growth. These two factors can be related to plant development in two primary ways. The first way is to consider the morphological or structural development as opposed to the physiological or functional development. The second way is to consider the vegetative as opposed to the reproductive growth phase. Light and temperature seem to affect these stages of development in a different manner although the exact relationship between temperature, light and plant growth has not been completely established.

Temperature:

Madriaga and Knott (1951) found that there was a non-linear relationship between temperature and vegetative growth in lettuce. They found that this held true only for plants during the vegetative growth phase. The time from bud to flower in geraniums was negatively correlated to temperature (Armitage, et al., 1981). Although temperature affects the morphological development of broccoli plants, it has not been significantly correlated with the vegetative growth stage (Gauss and Taylor, 1969). Gauss and Taylor also reported that temperature significantly influenced the number of leaves to bud initiation. Results from another study disputed this claim by stating that there was no significant rise in leaf number with increasing temperature (Weibe, 1975). Temperature extremes have an effect on physiological development of the plant. Chung (1986) found that broccoli plants grown in colder weather do not reach physiological maturity and therefore have lower yields than those grown in warmer weather. Gauss and Taylor (1969) found that low temperature alone did not directly affect the chronological time to bud formation, but that it had a profound effect on vegetative growth. Low temperature may indirectly result in earlier morphological flowering. Fontes, et al. (1967) found that high temperatures suppress floral initiation and low temperatures encourage floral induction.

Light:

Gauss and Taylor (1969) stated that temperature influences chronological time to maturity, but that light is the more dominant factor. The reproductive development from floral initiation to maturity seems to be influenced primarily by temperature (Coffey, 1987; Sams, 1987).

Models Describing Growth:

Using the appropriate factors that affect growth, the system can be modeled with mathematical relationships. The model can be very simple involving only one or more factors with simple mathematical functions, or it might involve several factors with complex mathematical functions. An example of a simple model is one used to predict sweet corn harvest date. The harvest date (HD) is calculated as 17 days after 50% of the stalks have silked (50% S) or HD = 50% S + 17 (Dale, et al., 1985). Another fairly simple, yet popular model is the Heat Unit system (HU). In this system, units (degree days) are accumulated until harvest. The amount of HU for a certain crop to reach maturity is assumed constant. The degree days for a specific crop are calculated by taking the maximum and minimum daily temperatures, averaging them, and then subtracting from the average a base or threshold temperature specific for that crop.

$$DD = (T_{min} + T_{max})/2 - T_{base}$$

A form of HU accumulation was used as early as 1730 (_____, 1960). In a more recent application, HU accumulation was used to predict harvest of canning peas, corn, and peanuts (Katz, 1951; Mills, 1964). Katz, 1951 also showed that the relationship between HU accumulation and tenderometer readings of sweet peas is essentially linear.

In using this type of model the base temperature must be determined for each crop. Segmented regression was used to determine a base temperature for sorghum (Gbur, et al., 1978). The HU system treats growth as solely a linear function of temperature. This is not accurate since growth is a function of many variables, however many times the relationship between temperature and growth is strong enough to overcome the influence of the other variables. To attain a greater degree of accuracy, many researchers have included other factors into the HU model to predict plant growth. Perry, et al. (1986) compared 14 methods of calculating HU to find the most accurate method for predicting the day of first harvest for pickling type cucumbers. The method with the lowest coefficient of variation was considered the best of the 14 methods studied. One of the best models in Perry, et al.'s study included daylength as a factor; another good method was based on the assumption that temperatures above a maximum level were detrimental.

Kish, et al. (1971) included soil moisture to improve their HU model for predicting snap bean maturity. Kish, et al. found that inclusion of soil moisture into the HU system proved to be superior to the normal Heat Unit system in prediction of snap bean maturity. Accumulated daily radiation has also been included in a modified HU model to predict maturity on vegetable crops (Scaife, et al., 1986). Photosynthetically Active Radiation (PAR) has also been included in HU models (Smith and Loewer, 1981). PAR is certainly a factor that influences growth since light energy is necessary for photosynthesis. HU models were attempted on broccoli but the results were inconclusive (Chung, unpublished).

More complex models attempt to consider the impact of other factors that greatly influence plant maturity. These models are applicable when the simple model is insufficient in describing development. As seen in the previous paragraph, many HU models have been adapted to include factors other than temperature to improve the predictability of the model. The relationships between these factors and plant growth may be linear or nonlinear but the HU model is based on a linear relationship between growth and maturity and might not be compatible with these other factors.

Achieving the best model depends on more than how many (or which) factors are included. Many limits or thresholds should also be incorporated in models to determine when factors react abnormally or when the model does not apply. In a study of the effects of temperature and PAR on morphological and physiological changes in the vegetative and reproductive phases for geraniums, the vegetative stage appeared to be dependent on PAR at normal temperatures (Armitage, et al., 1981). From bud initiation to flowering, light did not seem to affect morphological changes as long as there was a minimal level available. Temperature extremes lowered photosynthetic efficiency. Temperature had more of an effect on time from bud to flowering than did light. Some models contain a number of factors: PAR, Relative Humidity, CO_2 concentration, irrigation, etc.(Hanks, 1974; Lorber and Haith, 1981; Lumpkin and Bartholomeu, 1984; Smith and Loewer, 1981; Wilkerson, et al., 1983). These comprehensive models are generally incorporated into computer simulations such as for soybeans, SOYGRO (Wilkerson, et al., 1983), for grain sorghum, SORGF (Bender, et al., 1983), for rice, RICEMOD (McMennamy and O'Toole, 1983), and for cereal grains, CERES (Martin, et al., 1985) all of which can be manipulated to predict how crops should perform under different conditions. Whisler, et al, (1986) list 31 such comprehensive models and the crops for which they were designed. These models are generally more accurate than simple models in prediction but are hard to develop and use because the amount and type of data that must be obtained. Often it is much better to use a model for which the data from the factors are readily available. This ease of use can lead to wider use of the model and online adjusting as the season progresses can be accomplished when the model is incorporated in a computer program for growth prediction.

III. METHODS AND MATERIALS

Introduction:

Two experiments were conducted at the Plant Science Greenhouse at The University of Tennessee, Knoxville from September, 1987 to June, 1988. These experiments were conducted to gather data on the growth of broccoli under different lighting conditions.

Structural Setup:

Each experiment consisted of one planting of "Premium Crop" broccoli, *Brassica oleracea* L. Group *Italica*, in the greenhouse. Plants were grown on three 1.06 m by 6.1 m benches (Figure III-1). To support shade cloth for imposing light treatments, angle iron, 1.25 cm by 1.25 cm, was shaped to form arches over the benches forming structures with a maximum height of 1.06 m. This height allowed the plant sufficient space to grow to full height. These angle iron supports were placed approximately every 1.5 m; therefore, five supports were needed for each bench.

Three different weaves of polyvinylchloride (PVC) shade cloth (30, 50, 70 % of transmittance), made by SARLON, covered the angle iron supports to provide different levels of shading for the various light treatments imposed. Hereafter these shade treatments will be referred to as a percentage of full sunlight transmitted. Wire was extended the length of the bench to support the shade cloth and

Figure III-1. A photograph of the structural setup of the shade chambers within the Plant Science Greenhouse at the University of Tennessee.

prevent sagging. The shade cloth was fastened at the top of the arch and allowed to drape on both sides. The bottom edge of the shade cloth was weighted down by wooden strips allowing the entire side to be raised to take data and water or examine the plants.

Instrumentation:

Electronic instrumentation was used to record the average temperature and average accumulative radiation. A Campbell 21X micrologger (Campbell Scientific, Inc., Logan, UT) was selected for the project because it could be programmed to record the instantaneous value, sum, or average of the sensor readings. The unit was programmed to indicate the type and location of the sensor to be read and the form of data to be stored. The micrologger recorded temperature and light readings every 60 seconds during the daylight hours and then averaged or integrated the temperature and light, respectively, and stored the results every hour.

Type "T" thermocouples were used to measure temperature. A thermocouple was made for each of the experimental units, using Copper-constantan wire. The micrologger read the millivolt output from each thermocouple and calculated the temperature from these readings.

Quantum sensors (LI-COR, Inc., Lincoln, NB) were utilized to measure the radiation within the range of 400 to 700 nanometers. This spectrum of radiation is commonly referred to photosynthetically active radiation (PAR). One LI-COR SZ190 quantum sensor was used in each experimental unit. The quantum sensor produced an electrical current output inappropriate for the micrologger; therefore, a 600-ohm resistor was added to the circuit to produce a voltage output. The calibration constant for each sensor was entered into the micrologger prior to field testing. The quantum sensors were all tested under similar conditions recorded consistently within 1% of each other. A LI-COR LI188B Integrating, Quantum Photometer was also compared with these sensors and its readings were also within the same range.

The quantum sensors were mounted in the center of the shade chambers above the canopy of the leaves to measure the radiation within the shade treatment at the top of the canopy. The thermocouples were suspended within the canopy to measure the temperature within the canopy of each treatment. The wires from the thermocouples and the quantum sensors were run through polyvinylchloride (PVC) tubing to prevent deterioration of the wire sheathing.

The internal memory of the micrologger stored approximately 9 days of environmental data. Data were downloaded onto a Tandy cassette tape recorder on a weekly basis. The portable tape recorder, using normal bias tape, was taken to the greenhouse and connected to the micrologger. The data were downloaded to an IBM AT computer equipped with a CAMPBELL extension card which transfers data into an ASCII file.

Physiological Data:

Each experiment utilized a Randomized Complete Block Design consisting of four treatments and three replications. There were four record plants in each experimental unit. Guard plants were placed between each treatment to minimize the border effects on the record plants. The plants were direct-seeded in 19 L pots filled with PROMIX plant medium and were thinned to one plant per pot after plant emergence. The pots were placed at a 0.6 m by 0.3 m spacing within the shade chambers. The spacing was less than the normal Tennessee recommendations for field production but was necessary due to bench space limitations. The plants were maintained within their respective shade treatments from seeding until harvest.

The plants were kept well watered with occasional drying periods to encourage root development. A complete soluble fertilizer (Peters 9-45-15) was applied approximately biweekly. The temperature within the greenhouse was maintained within the critical range for broccoli (5°C to 30°C) with a heating system in the winter and an evaporative cooling system in the spring and early summer. Temperature was approximately uniform across all treatments, therefore temperature was not a variable among treatments.

The physiological characteristics measured to estimate plant growth were: leaf number, leaf length and width, stalk diameter, and the inflorescence diameter. The yield was taken at harvest to compare with other field studies. The leaf number recorded was the total number of leaves, including the senesced leaves. The leaves were counted when they had attained a area of approximately 1 cm^2 unless they were pin leaves around the inflorescence. Leaves were removed as they senesced. The length and width of each leaf were recorded to determine the total leaf area. Also by maintaining records on the individual leaves, the development of the leaves could be monitored. The length was measured from the base of the continuous portion of the leaf blade to the tip. The width was measured about half way down the leaf. Both measurements were made to the nearest 5 mm. The area of the leaf was estimated by representing the leaf as an ellipse with the length and width being the major and minor axes.

The stalk diameter and the inflorescence diameter were measured with a caliper to the nearest 0.1 mm. The stalk was measured directly above the cotyledonary leaves while the inflorescence diameter was measured at the top of the head. The heads were harvested when the inflorescence began to loosen and the beads began to separate.

The physiological data were taken approximately weekly in the fall and every 3 to 4 days in the spring. The fall crop was under lower light intensities and cooler temperatures so development was relatively slow, therefore weekly measurements were sufficient to record the changes in plant development.

Statistical Analysis/Modeling:

Upon completion of the experiments the data were analyzed with a number of statistical procedures in SAS (SAS Institute, Inc., Cary, NC) and STATGRAPHICS (STSC, Inc., Rockville, MD). Initially a general linear models procedure was run in SAS to determine if the differences between the experiments, replications, treatments, and individual plants were statistically significant. Within this study 'significant' denotes testing at an alpha level of 0.05. Plots of the various factors were generated in SAS, STATGRAPHICS, and LOTUS 123 (Lotus Development Corporation, Cambridge, MA) so that the relationships could be studied.

When the plots were examined, mathematical equations were selected that responded similarly to the growth data. Nonlinear models were used for the growth prior to bud initiation and the time to bud initiation. Nonlinear regression procedures in SAS and STATGRAPHICS were used to determine the coefficients that gave the model the best fit. An 'R^2 like' statistic was calculated to compare the nonlinear models by dividing the regression sum of squares by the uncorrected total sum of squares and multiplying it by 100. An 'R^2 like' statistic is a measure of the variation in the dependent variable that can be accounted for by the model similar to a true R^2. Linear models were investigated for all three facets of growth investigated. Linear models were considered with the following variables: potential PAR received, time from seeding, photosynthetic photon flux (PPF), and temperature degree day accumulations. The models selected were those that had the highest R^2 value. Linear regressions were run on the models selected to determine the coefficients and see if the variables significantly contributed to the model. The predicted models were plotted where possible.

IV. RESULTS/DISCUSSION

Introduction:

Two broccoli crops were grown, one in the fall, one in the spring, with the intention of combining the data from the two crops to form an empirical model which would describe plant growth as a function of light and time. However, the patterns of growth in the fall and spring were very dissimilar as might be expected. The fall crop, planted under higher light intensities and higher temperatures matured as the light intensities, daylength, and temperatures decreased. The reverse was true for the spring crop. The fall crop matured very slowly while the spring crop matured much more rapidly. Therefore, separate models for the two crops were developed, as well as, a single comprehensive model.

Statistical analyses of the data from both experiments showed that there were significant differences between the two experiments. The different climatic conditions in the fall and spring greatly affected the crop. The primary differences between the two seasons were the daylength, light intensity, and temperature. These climatic differences altered the rate of development of the two crops.

There were also significant differences among the light treatments for both experiments. The four light treatments were 100%, 70%, 50%, and 30% of the sunlight coming through the greenhouse glass. Plant responses were noticeably different among light treatments. The treatment influence on leaf area made it possible to model the effects of light on plant growth.

The differences among replications were also significant. Each replication was comprised of a bench in the center section of the greenhouse. The greenhouse is oriented east-southeast to northwest-west. Replications 1, 2, and 3 were the northern side, the center, and the southern side, respectively, of the greenhouse. The greenhouse trusses provided shading which explained some of the variation among replications. Figure IV-1 shows the averages of the light received under all treatments for the three replications. The data for this figure represented two typical days in the spring study. It graphically illustrates the Photosynthetic Photon Flux (PPF) measured in moles of photons per second per square meter as a function of time. For both days there was a dip in the radiation received in the middle of the day. This was attributed to shading effect from the heat ductwork and structural framework in the ceiling of the greenhouse. The greatest variation among replications occurred between replication 1 and the other two replications. During the morning the plants in replication 1, located on the northern side of the greenhouse, received more radiation than the other

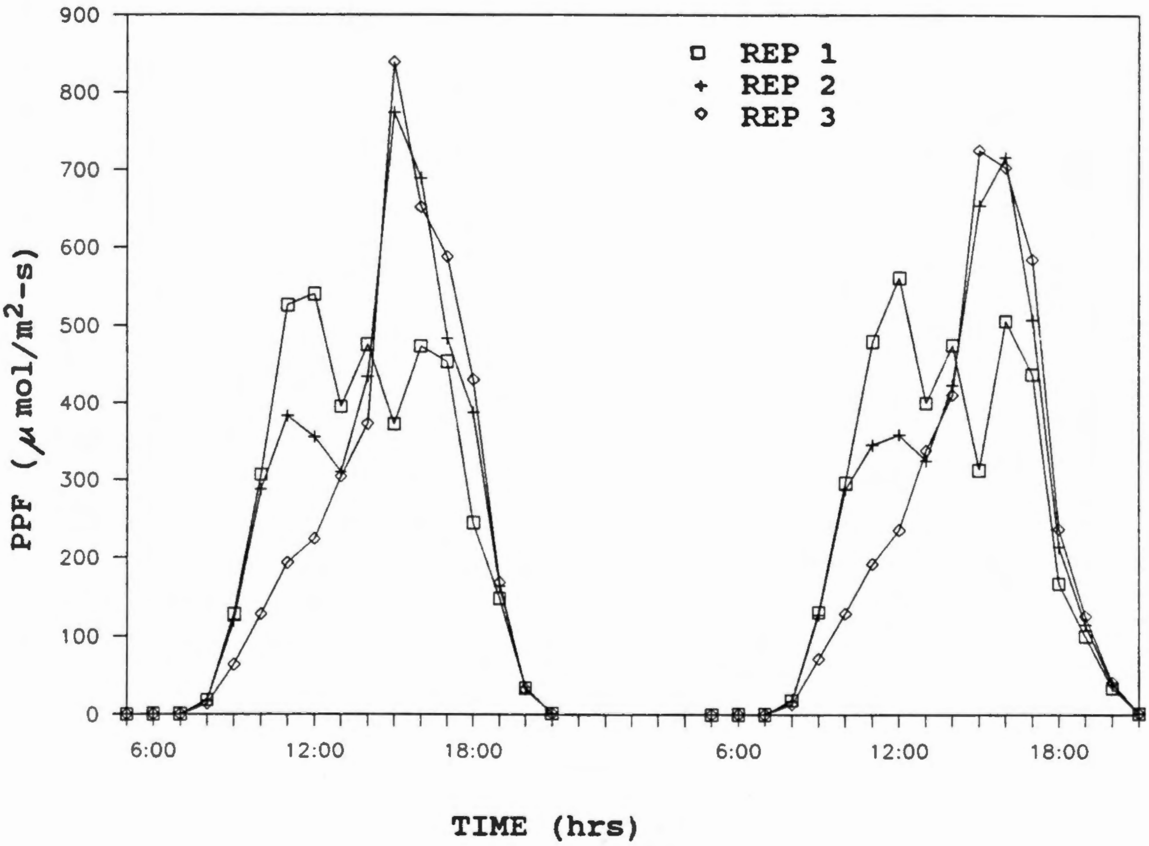

Figure IV-1. Mean PPF readings of the light treatments for the 3 replications on 2 representative days within the greenhouse in the spring.

plants, but during the afternoon as the sun reached the southwest side, the plants in replication 1, received less radiation than the those in the other two replications.

For all replications the lowest light treatment (30% light) was affected the least by the light blocked by the greenhouse trusses. The plants under 70% light also had a greater variation in leaf area than the plants at the other light levels. Figures A.4-A.11 showing the plant growth in each replication under each light treatment appear in the appendix.

The three aspects of plant growth in broccoli investigated in this study were: Seeding to visible bud, time to visible bud, and inflorescence development. The primary emphasis of this study was from seeding to visible bud, the vegetative growth stage.

Seeding to Visible Bud:

The first experiment was carried out in the fall of 1987 and winter of 1988. Seeds were planted October 1, 1987 and the experiment was terminated February 3, 1988. The development was very much as expected. The seedlings under 100% light were shorter and had more rapidly developing leaves and thicker stems than seedlings under lower light intensities. Seedlings in the lower light levels were progressively etiolated as light decreased. The first true leaf appeared first on plants in the 100% light treatment then appeared progressively later on seedlings at lower light levels. Growth, which here is defined as the increase in plant size, leaf number, and leaf area, increased as light level increased.

The second experiment was carried out in the spring of 1988. The seed were planted March 5 and the experiment was terminated on June 18. The rate of plant growth was different than in the first experiment in that the plants under the three highest light levels (100%, 70%, 50%) responded very similarly, and grew faster than the plants in the 30% light level.

The light intensities in the spring were much higher than the light intensities in the fall. The rate of plant development in the spring was much greater than the rate of plant development in the fall. The increased spring growth rate was associated with the higher light intensities and higher temperatures in the spring.

Growth Relationships:

Figure IV-2 shows the increase of leaf area over time in experiment one. The figure represents the average leaf growth of all plants within each treatment. The leaf area of plants under 100% light increased at the most rapid rate and reached an area of approximately 0.82 m^2/plant at visible bud around the 80th day. The plants under 70% light responded in much the same manner with the rate of increase

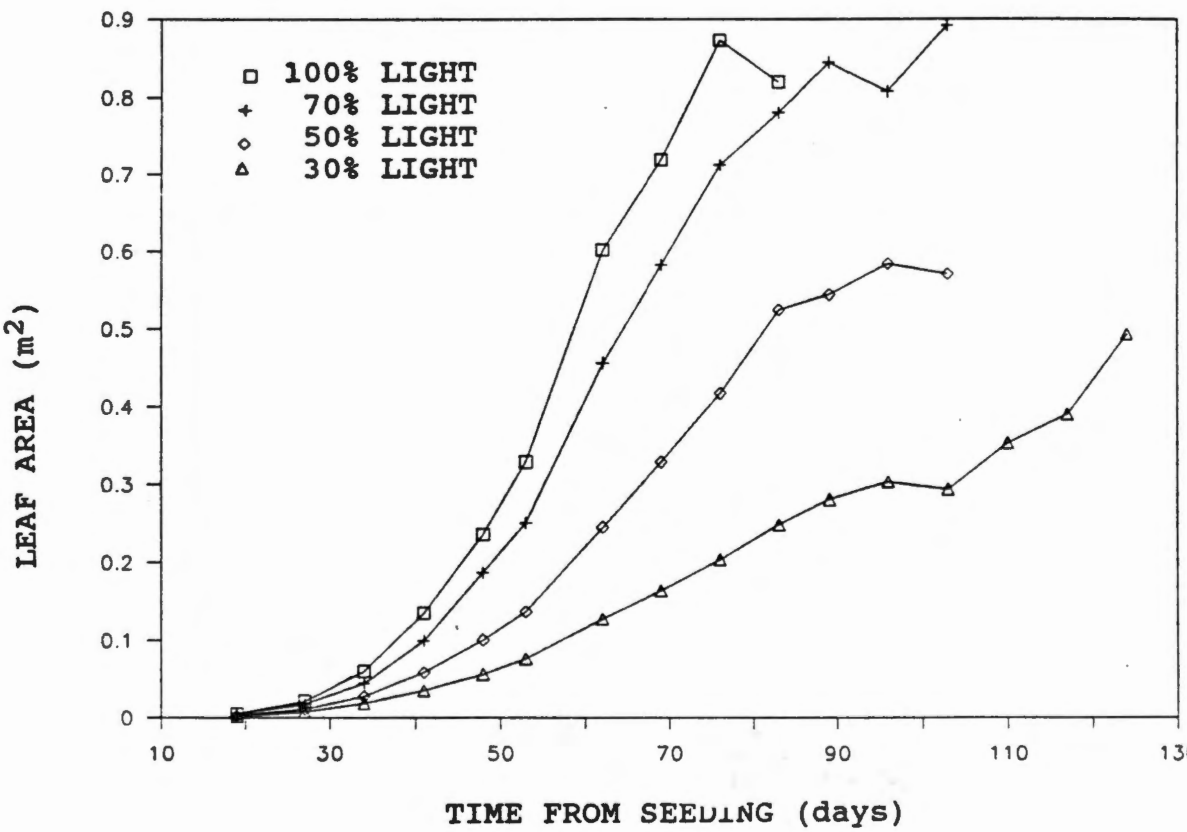

Figure IV-2. The effect of light treatments on leaf area of broccoli plants from seeding to visible bud in the fall experiment.

being only slightly less than those under 100% light attaining a leaf area of about 0.88 m^2/plant and requiring about 102 days to visible bud. Plants under 50% light exhibited a slower rate of growth, a flatter curve and a smaller leaf area at visible bud. Plants in this treatment had a leaf area of about 0.58 m^2/plant at visible bud which required around 105 days. The plants grown under the lowest light level, 30%, never developed a harvestable head. The growth curve on Figure IV-2 for this treatment was almost linear with the plants failing to attain a leaf area greater than 0.5 m^2 by the 117 day. There did not seem to be enough light to promote bud development during the fall.

The growth curve of the plants within the experiments followed that of normal growth response; there was a period of slow growth, a period of rapid growth, then a decline in the rate of plant growth. Under the lower light levels, the plants responded less like the normal growth curve than at the higher light levels. The plants under 30% full light did not have enough light to change from slow growth to rapid growth. There were occasions near the end of the experiments that the total leaf area actually decreased because of senescence.

The spring crop (Figure IV-3) reflected an increase in leaf area over time as with the fall crop, but at a higher rate. In this experiment as in the fall experiment there were three growth phases; slow, rapid, then declining.

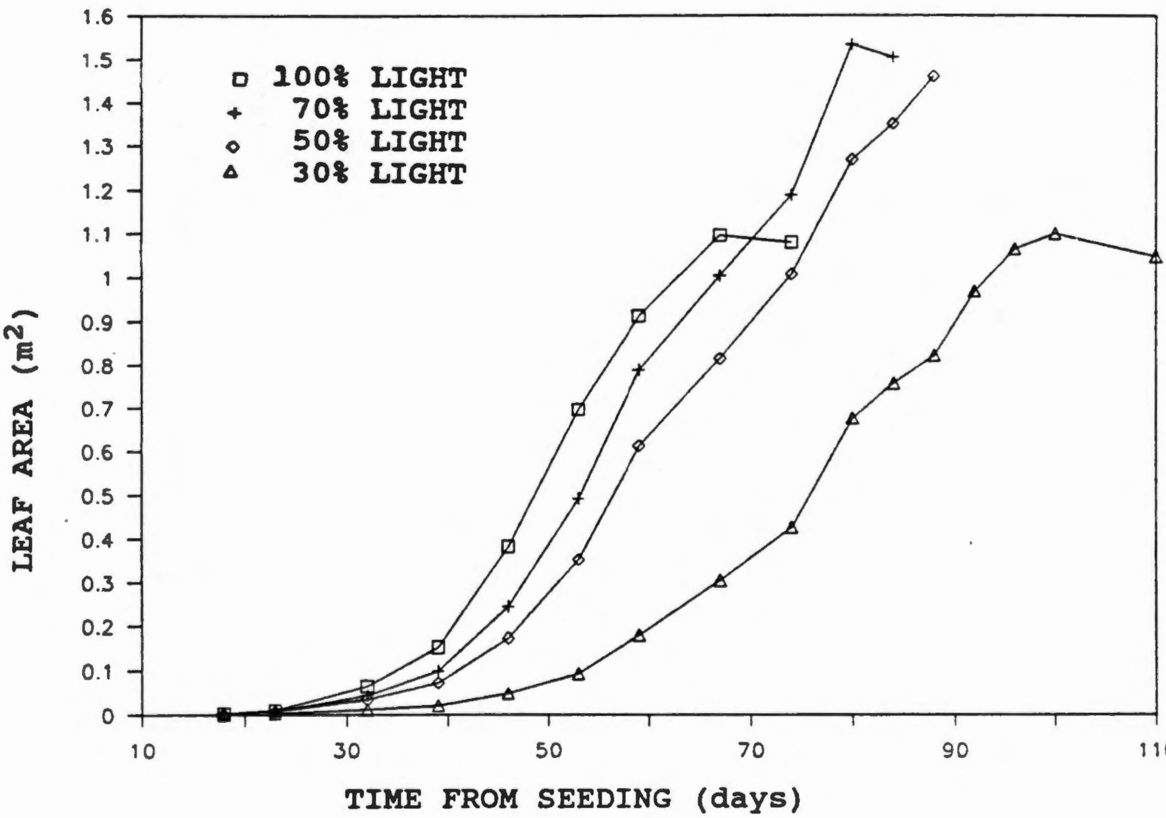

Figure IV-3. The effect of light treatments on leaf area of broccoli plants from seeding to visible bud in the spring experiment.

Again it was true that growth was more rapid under the higher light levels and less under the lower light levels. The plants under 100% light reached a leaf area of about 1.1 m^2/plant in 75 days. The plants under 70% light and 50% light had a much higher leaf area at visible bud than did the plants under 100% light, about 1.45 m^2/plant, and required about 145 days to reach that stage. The plants under the lowest light level still had a much slower rate of increase than the plants under the other three light levels; the plants reached a leaf area of 1.0 m^2/plant and visible bud in 110 days. Plants under 100% light exhibited inflorescence at a leaf area substantially lower than those under 70% and 50% light. This was probably due to the high light intensities in the spring. Phytochrome might be responsible for such a response.

Phytochrome is a chromoprotein which exists in two forms; one that is responsive to red light (P_r), and one that is responsive to far red light (P_{fr}). Red light causes the P_r form to convert to the P_{fr} form. A buildup in the concentration of one form or the other could induce a premature morphological change. Some similar type of response might have occurred with the plants under 100% light. They had progressed from the period of rapid growth to the period of declining growth and initiated inflorescence at a leaf area much less than the plants under 50% and 70% light.

Disregarding time, development can be directly related to the PAR received. Plant growth can be related to the actual PAR received by the plant or the PPF on the plant. There was no way to measure the actual PAR received by the plant because of leaf shading and unknown angle of incidence of the sun due to the angle and orientation of the leaves. Instead, a potential cumulative PAR received was calculated by multiplying the leaf area by the PPF. The actual PAR received would be less than the potential PAR received because of shading and angles of incidence of solar radiation being less than optimal on the leaves.

The relationship between potential PAR received by the plant (moles) and the total leaf area (m^2) is demonstrated in Figure IV-4. With increasing total PAR the total leaf area increased up to a certain point. There was essentially no difference between leaf area of plants under 100% light and those under 70% light. At both of those light levels the final leaf area was around 0.9 m^2/plant. For each light level, the relationship between leaf area and the total potential PAR received by the plant was essentially linear. This is not surprising since the total PAR received by the plant is a function of leaf area.

The potential cumulative PAR received would not be a practical factor in building a model that predicts leaf area because the leaf area must already be known. It is better to use a factor that is independent. The other way of

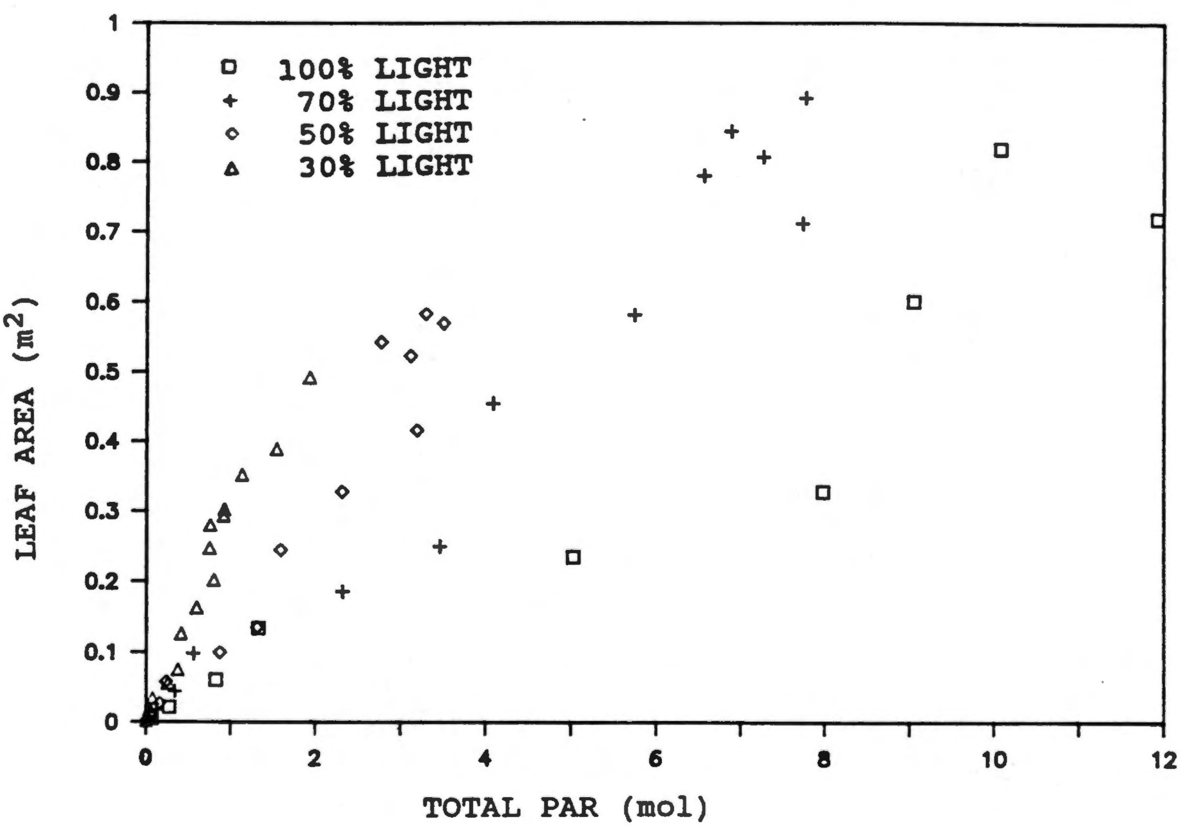

Figure IV-4. The relationship between the total potential PAR received and the leaf area of the fall broccoli crop for each light treatment.

determining the effects of light on growth is relating leaf area to PPF. Figure IV-5 shows the relationship between the PPF and leaf area for the first experiment. At each of the four light levels the relationship is nearly linear, with the plants under 30% light and 100% light higher and lower, respectively, than the plants under the other two light levels.

Figure IV-6 shows the relationship in the spring crop between leaf area and potential PAR received. The differences between the light levels were less than in the fall, but for each light level the relationship between potential PAR and leaf area was still basically linear. It is clear that there is an effect of the light treatments on the development of leaf area of the plant.

The relationship between leaf and PPF for the spring was very different than in the fall. The different light levels were quite distinctive (Figure IV-7). The relationship in the spring was not linear but definitely sigmoidal. That would suggest that the effect of PPF on leaf area in the fall was sigmoidal but that low light intensities received in the fall resulted in a slow rate of growth such that the relationship was almost linear when plotted in this manner.

Empirical models were developed from the data to describe growth as a function of several environmental factors. Models were developed looking at two parameters of leaf growth, area and number. The predictor factors

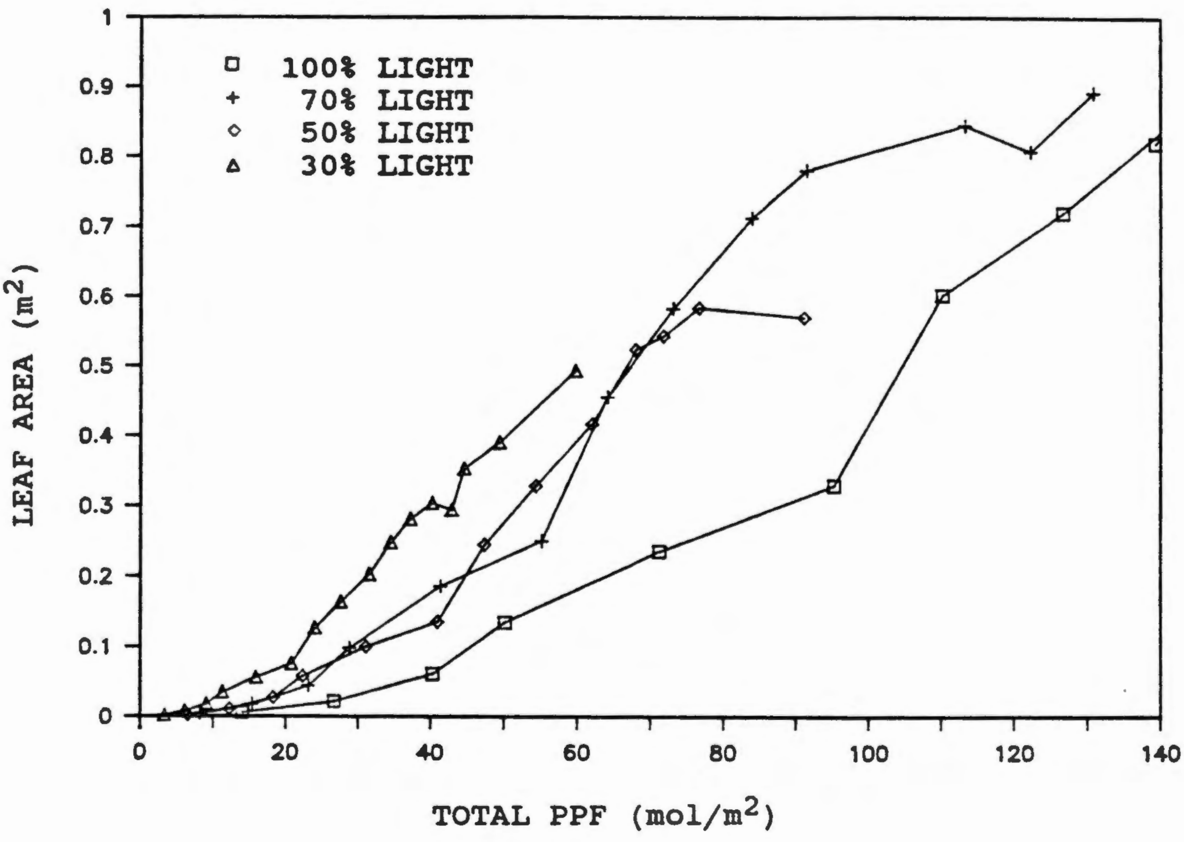

Figure IV-5. The relationship between the total PPF and the leaf area of the fall broccoli crop for each light treatment.

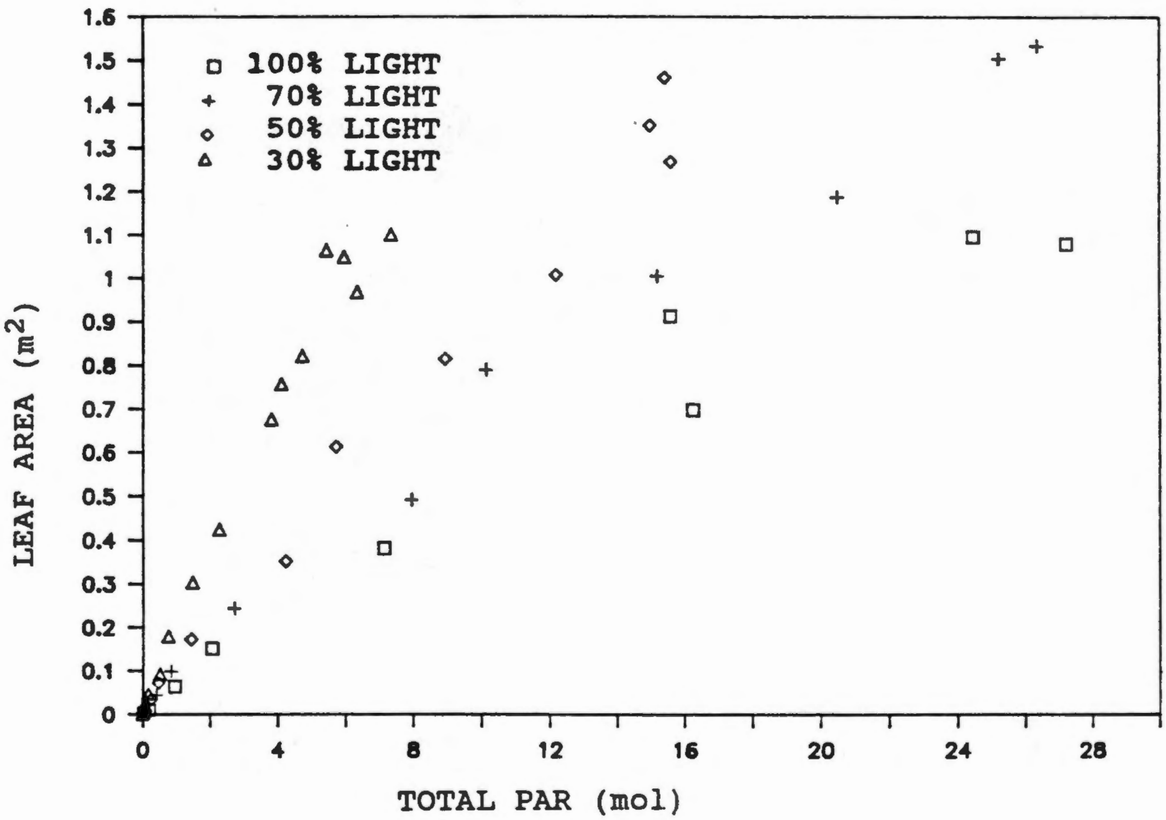

Figure IV-6. The relationship between the total potential PAR received and the leaf area of the spring broccoli crop for each light treatment.

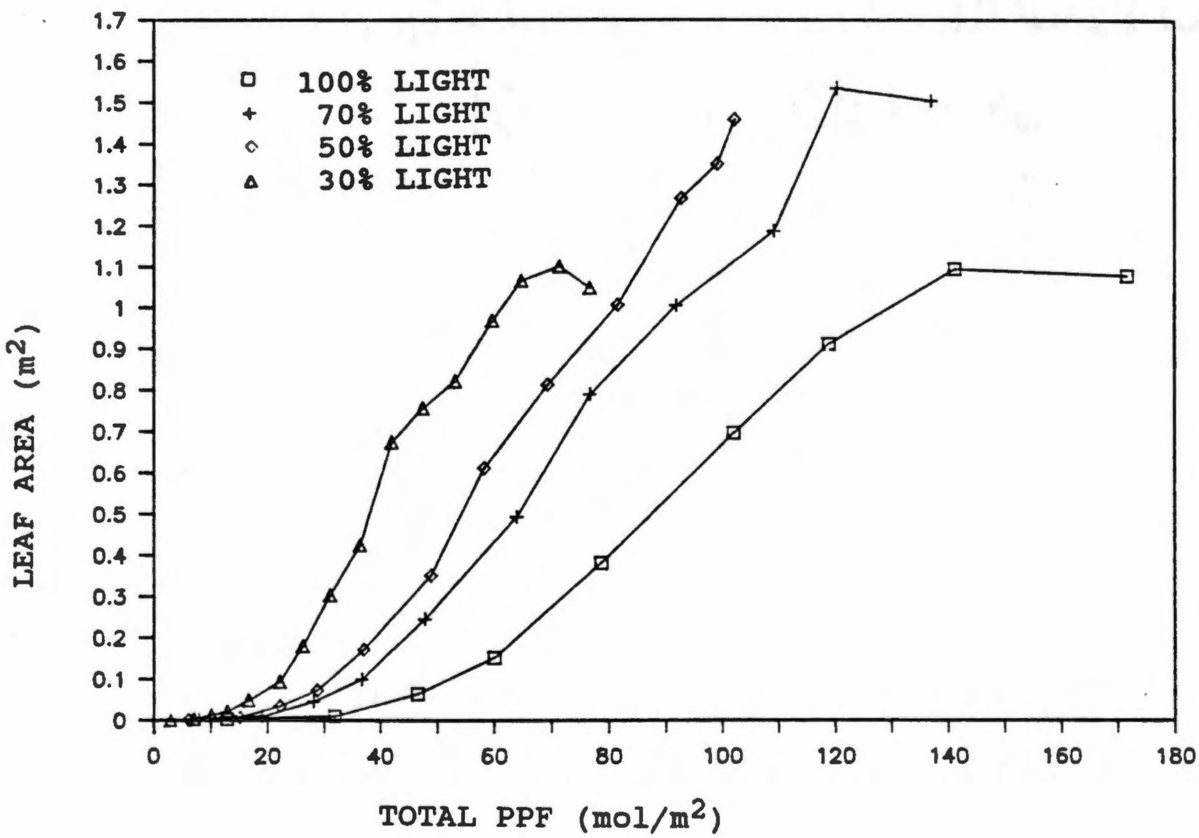

Figure IV-7. The relationship between the total PPF and the leaf area of the spring broccoli crop for each light treatment.

examined for use in modelling were time, total potential PAR, PPF, and heat units (HU). Although the total potential PAR was more highly correlated to leaf area than PPF, potential PAR was left out of these models because it was a function of leaf area. The heat unit calculations used base temperature of 10° C (50° F). This base temperature explained more of the variation in the data than other base temperatures tried. Temperature varied only slightly among treatments, and therefore could not be used to explain the variation among treatments.

Table IV-1 lists the models developed from the data for the fall and spring individually and with the data combined. A non-linear model was developed predicting leaf area as a function of time. This model predicted leaf area very well, as seen in the high 'R^2 like' statistic. Figure IV-8 shows the predictive growth for the fall and Figure IV-9 for the spring. By comparing Figure IV-8 to Figure IV-2 (p. 26) and Figure IV-9 to Figure IV-3 (p. 28) it can be seen that Model 1 fits the data well, particularly in the early stage of growth. Though this model fits the data well, it is difficult to use to predict leaf area; it requires that the user estimate the amount of light received at a certain time during the season as a percentage of the known light from this model. This model provides a graphical solution to predict leaf area that requires considerable calculation and a good understanding of its use. Model 1 for the combined

Table IV-1. Empirical models developed to predict leaf area (LA) for the vegetative growth stage of broccoli depending on the variables time from seeding (TIME) in days, photosynthetic photon flux (PPF) in mol/m^2, and Heat Unit summation with a 10^{o} C base (DD50) in degree days.

Model	Equation	R^2
Fall		
1	LA = A - A * EXP(K * TIME)^U [1]	
2	LA = -.16 + .0029 TIME + .0053 PPF	0.84
3	LA = -.15 + .003 TIME + .005 PPF - .00004 DD50	0.84
Spring		
1	LA = A - A * EXP(K * TIME)^U [1]	
2	LA = -.42 + .010 TIME + .0064 PPF	0.88
3	LA = -.42 + .011 TIME + .006 PPF - .00008 DD50	0.88
Combined		
1	LA = A - A * EXP(K * TIME)^U [1]	
2	LA = -.270 + .0056 TIME + .0065 PPF	0.74
3	LA = -.31 - .006 TIME + .0057 PPF + .0014 DD50	0.84

[1] Coefficients for Model 1

	Tmt	A	K	U	R^2 [a]
Fall					
	1	1.02	0.048	16.13	0.98
	2	1.00	0.052	19.57	0.96
	3	0.98	0.046	17.07	0.97
	4	0.90	0.024	5.93	0.91
Spring					
	1	1.00	0.084	53.41	0.98
	2	1.02	0.056	23.76	0.98
	3	1.05	0.041	14.84	0.99
	4	1.00	0.057	65.00	0.98
Combined					
	1	1.00	0.093	84.99	0.93
	2	1.00	0.085	81.52	0.89
	3	1.00	0.099	204.17	0.80
	4	1.00	0.032	11.43	0.76

[a] 'R^2 like' statistic

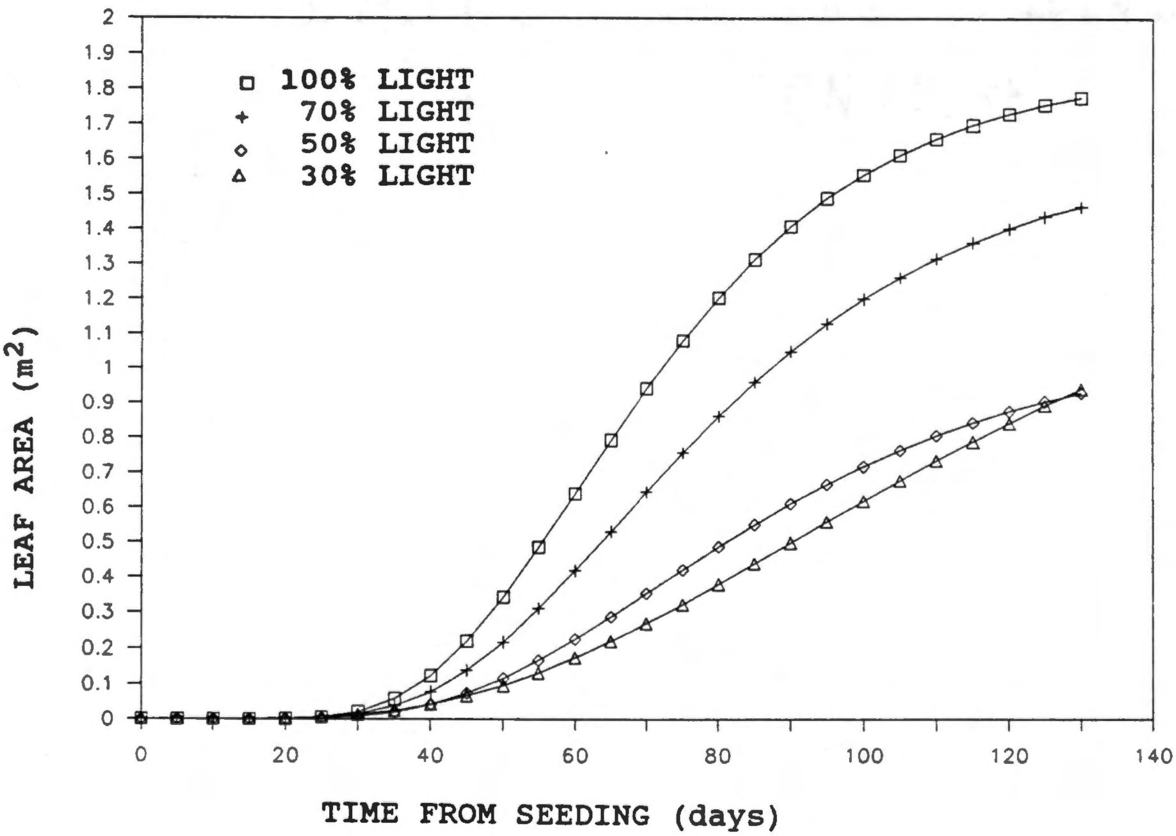

Figure IV-8. The predicted leaf area as a function of time for the fall crop calculated with Model 1 on Table IV-1 using the appropriate coefficients for each light level.

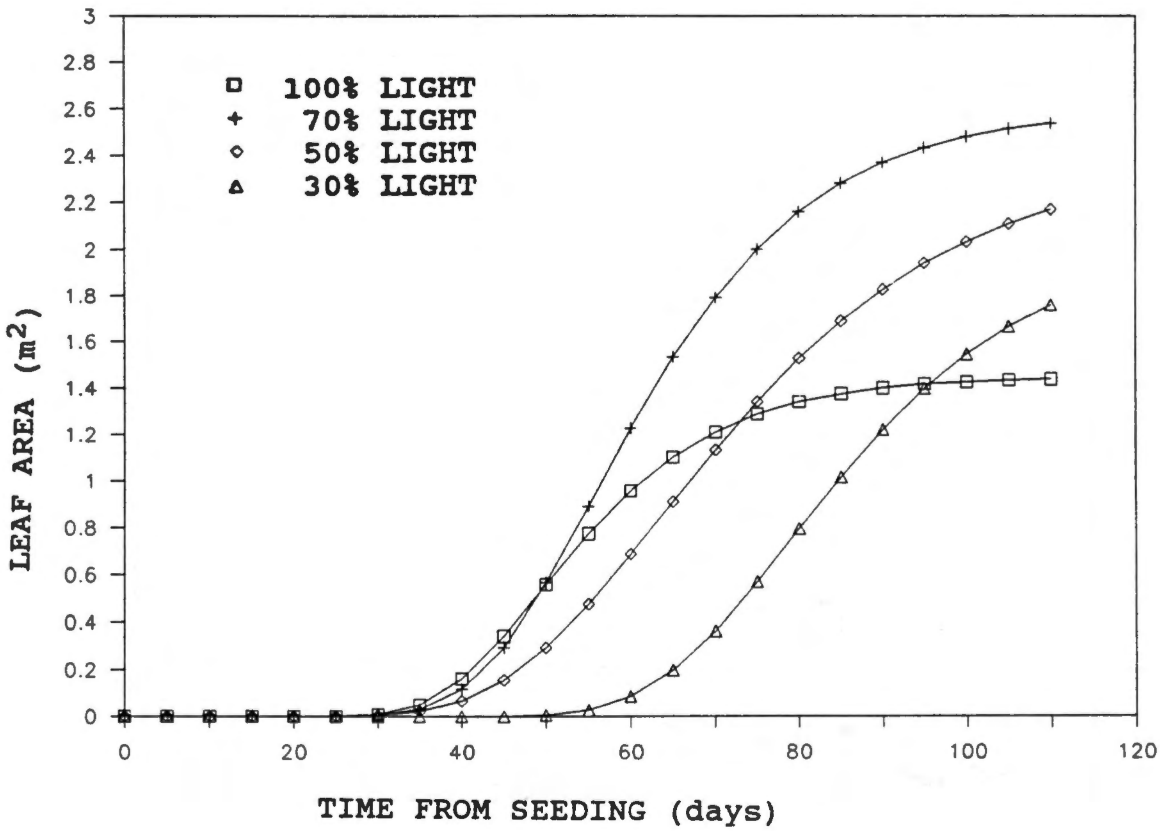

Figure IV-9. The predicted leaf area as a function of time for the spring crop calculated with Model 1 on Table IV-1 using the appropriate coefficients for each light level.

seasons in Table IV-1 was much less reliable as it did not explain the differences between the seasons as seen in the lower 'R^2 like' statistic.

Linear models were also developed for each of the seasons and for the seasons combined (Table IV-1). The first linear model has two factors, time and PPF, while the second linear model includes a heat unit (HU) factor along with time and PPF. All of the models were significant. The R^2 statistics were also very high which increased the reliability of the fit. However, in both the fall and spring crops, Model 3 did not significantly increase the accuracy of the prediction of the model. For both fall and spring crops the HU factor did not significantly contribute to the models. When the data from the two seasons were combined, the variation in the data explained by the model decreased. The HU factor was significant in the combined model. This would indicate that in predictive models for only one season, such as for fall or for spring, light and time are sufficient as factors, but when a comprehensive models is desired to predict fall and spring, temperature should be included as a factor.

Table IV-2 list the models developed from the data for the fall and spring crops to predict leaf number. Only linear models were used to predict leaf number. Again two linear models were considered; one with and one without the HU factor. All of the models were highly significant in

Table IV-2. Empirical models developed to predict leaf number (LNO) for the vegetative growth stage of broccoli depending on the variables time from seeding (TIME) in days, photosynthetic photon flux (PPF) in mol/m^2, and Heat Unit summation with a 10^o C base (DD50) in degree days.

Model	Equation	R^2
Fall		
1	LNO = -1.79 + .147 TIME + .047 PPF	0.97
2	LNO = -2.38 + .12 TIME + .045 PPF + .0044 DD50	0.97
Spring		
1	LNO = -4.07 + .200 TIME + .058 PPF	0.98
2	LNO = -4.49 + .252 TIME + .058 PPF - .0044 DD50	0.98
Combined		
1	LNO = -2.81 + .167 TIME + .0566 PPF	0.94
2	LNO = -3.11 + .078 TIME + .050 PPF + .0105 DD50	0.97

explaining the variation in leaf number. As with leaf area, no advantage was gained by including the HU factor in the model for each of the individual seasons but it did improve the model when the data from both seasons were combined.

There was no other data available to validate these models, therefore, these models should be taken as a guide for future modeling rather than as final models.

Time to Visible Bud:

In the first facet of growth considered, the time from seeding to visible bud, the rate of increase of leaf area of the plants in the fall and spring crops was different and the best models describing this stage of growth were season specific. For the second facet of growth considered, time to visible bud, the data from both seasons were complementary. In Figure IV-10 the relationship between PPF (mol/m^2) and the time to visible bud (days) is shown. The data from the plants in the fall experiment fills out the curve at lower PPF levels and the data from the plants in the spring experiment fills out the curve at the higher PPF levels. The mathematical model was developed through non-linear statistical methods and was significant. The model in Figure IV-10 had an 'R^2 like' value of 0.68 and is shown below.

$$TIME = 872.3 - 808.8 * EXP(-3.33/PPF)$$

TIME - time to visible bud (days)
PPF - total photosynthetic photon flux (mol/m^2)

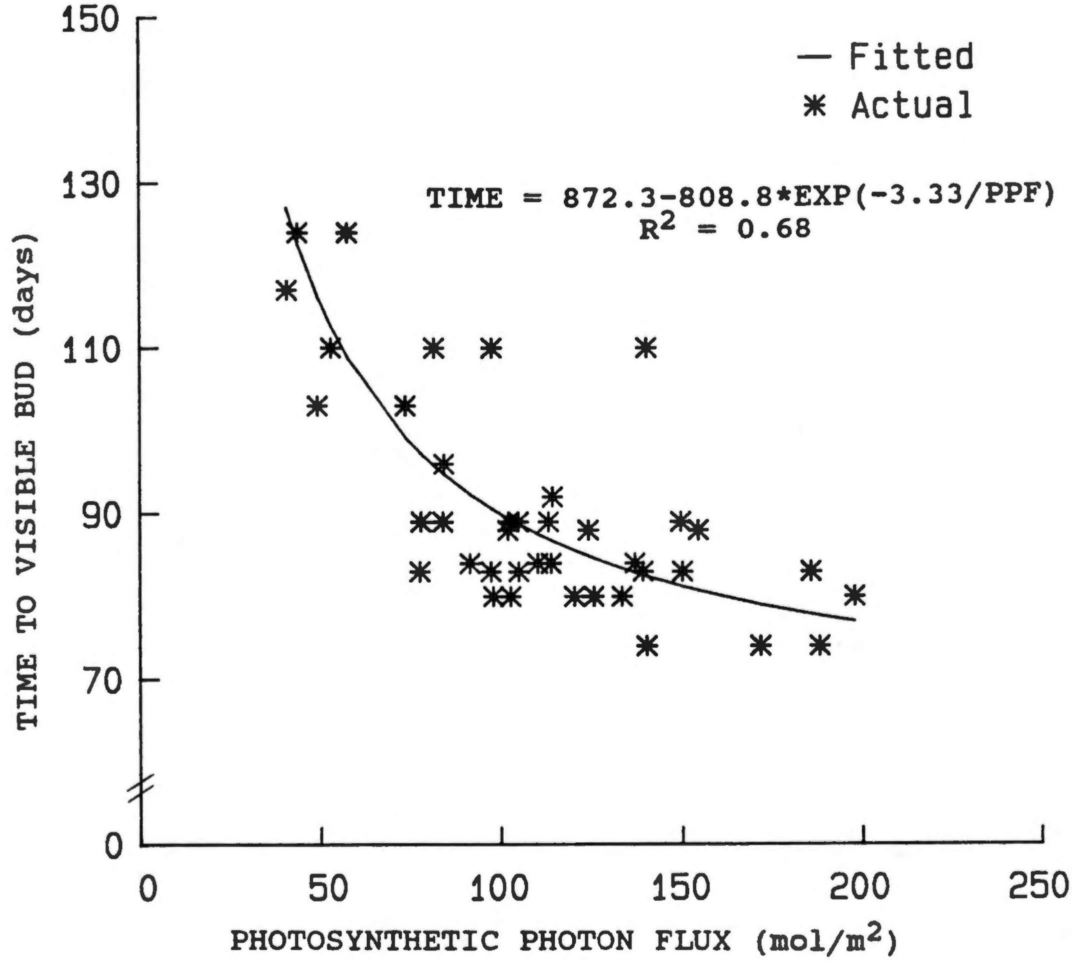

Figure IV-10. The non-linear model predicting the time from seeding to visible bud as a function of the total PPF derived using combined data from both fall and spring experiments.

The data seems to support two critical minimums required for plant growth. The relationship is asymptotic with one critical minimum being a minimum light requirement of around 40 to 50 mol/m^2. This indicates that the plant is unable to reach bud initiation if the total light received is lower than the minimum regardless of the time allowed for maturity. The second critical minimum supported in the relationship in figure IV-10 is a minimum amount of time that broccoli requires to reach a morphological stage such that the inflorescence is visible. The cultivar "Premium Crop" used in these greenhouse experiments seems to have an asymptotic minimum of around 75 days to reach visible bud, regardless of the amount of light received.

This model could possibly be used to predict visible bud occurrence if the accumulated PPF received could be projected from longterm data such that the accumulated PPF would be plotted against time from seeding. An overlay of this plot and the curve on Figure IV-10 should give an intersection which would correspond to the predicted time to visible inflorescence. The question is how accurate this predictive tool is as compared with other tools such as heat unit accumulation or just average time to visible bud. This problem is beyond the scope of this research.

<u>Inflorescence Development</u>:

The final stage of growth considered in this study was the inflorescence development. This stage was considered as the time from when the inflorescence was initiated to harvest maturity. The best linear model was selected using a statistical procedure which compared all possible models explaining the change in inflorescence diameter as a function of time from seeding (TIME), PPF, and HU summation at base 50^{o} F. The best model included TIME and PPF as variables and gave an R^2 of 0.37. To more closely investigate growth in this stage, the relationship between head development and temperature should be known. Since previous studies and observations indicate that this phase is highly correlated with temperature (Gauss, 1969; Coffey, 1987; Sams, 1987), it would be profitable to compare this model, a HU model, and a model with days to harvest to determine which one of these methods is superior.

V. SUMMARY

Two experiments were conducted in Knoxville, Tennessee in a greenhouse during 1987 and 1988 to develop a model describing vegetative growth in broccoli. Several linear and non-linear models were developed to describe growth in the vegetative phase. Season specific models for the fall and spring experiments gave better fits than did comprehensive models that predicted for both seasons. Models were developed to predict growth as the increase in leaf area and as the increase in leaf number. Light and time proved to be valuable factors in predicting growth. Including temperature as a factor improved the descriptive ability of the model if the model was used to describe growth in both the spring and the fall.

A model for the time to bud initiation was developed on the basis of the photosynthetic photon flux (PPF) received. The relationship between the time to bud initiation and PPF suggested that there is a critical light minimum required for bud initiation in this cultivar of broccoli. The relationship also indicated that there is a critical minimum time required for visible bud formation.

The database from which these models were developed was limited consisting of two greenhouse experiments in the fall and spring. To be very accurate, predictive models generally require a large database in their development. Other data is also necessary to validate a model before it should be accepted as a predictive tool. For this reason these models should not be relied on as a predictive model but rather used as a guide for future work. The relationships found in this study will be invaluable in setting up experiments for modeling growth of broccoli in the future, suggesting types of physiological and environmental data that are needed and in indicating the relationships between certain physiological and environmental factors.

LITERATURE CITED

LITERATURE CITED

__________. 1960. A critique of the heat unit approach to plant response studies. Ecology 41:785-790.

Armitage, A.M., W.H. Carlson, J.A. Flore. 1981. The effect of temperature and quantum flux density on the morphology, physiology and flowering of hybrid geraniums. J. Amer. Soc. Hort. Sci. 106:643-647.

Bender, D.A., R.L. Vanderlip, G.A. Smith, M.O. Bagby, R.M. Peart. 1983. Simulating the growth and development of sweet sorghum. ASAE paper 83-3022.

Chung, B. Prediction of maturity time for once-over harvest of broccoli. Unpublished.

Chung, B. 1982. Effects of plant density on the maturity and once-over harvest yields of broccoli. J. Hort. Sci. 57:365-372.

Chung, B., H.L. Strickland. 1986. Effect of Sowing time on the once-over harvest yield of broccoli cultivars in north-west Tasmania. Aust. J. Exp. Agric. 26:497-500.

Coffey, D.L. 1987. Personal communication.

Dale, J.L., J. McFerran, E.V. Wann. 1985. Yield and ear quality of sweet corn hybrids grown under virus disease conditions, 1985. Ark. Agric. Exp. Sta. Research Series 327, November, 1985.

Dufault, R.J. 1988. Nitrogen and phosphorus requirements for greenhouse broccoli production. Hortscience 23:576-578.

Fontes, M.R., J.L. Ozbun, S. Sadik. 1967. Influence of temperature on initiation of floral primordia in green sprouting broccoli. J. Amer. Soc. Hort. Sci. 91:315-320.

Gauss, J.F., G.A. Taylor. 1969. Environmental factors influencing reproductive differentiation and the subsequent formation of the inflorescence of <u>Brassica</u> <u>oleracia</u> L. var <u>italica</u>, Plenck cv 'Coastal'. J. Amer. Soc. Hort. Sci. 94:275-280.

Gbur, E.E., G.L. Thomas, F.R. Miller. 1978. Use of segmented regression in the determination of the base temperature in heat accumulation models. Agron. J. 71:949-953.

Hanks, R.J. 1974. Model for predicting plant yield as influenced by water use. Agron. J. 66:660-665.

Hulbert, S.H., T.J. Orton. 1984. Genetic and environmental effects on mean maturity date and uniformity in broccoli. J. Amer. Soc. Hort. Sci. 109:487-490.

Katz, Y.H. 1951. The relationship between heat unit accumulation and the planting and harvesting of canning peas. Agron. J. 43:74-78.

Kish, A.J., W.L. Ogle, C.B. Loadholt. 1971. A prediction technique for snap bean maturity, incorporating soil moisture with the heat unit system. Agr. Met. 10:203-209.

Lorber, M., D.A. Haith. 1981. A corn yield model for operational planning and management. TRANSACTIONS of the ASAE 24:1520-1525.

Lumpkin, T.A., D.P. Bartholomew. 1984. Predictive models for the growth response of eight azolla accessions to climatic variables. Crop Sci. 26:107-111.

Madariaga, F.J., J.E. Knott. 1951. Temperature summations in Relation to lettuce growth. J. Amer. Soc. Hort. Sci. 58:147-152.

Magnifico, V., V. Lattanzio, G. Sarli. 1979. Growth and nutrient removal by broccoli. J. Amer. Soc. Hort. Sci. 104:201-203.

Martin, E.C., J.T. Ritchie, T.L. Loudon. 1985. Advances in Evapotranspiration. Proceedings of the National Conference, Dec. 16-17, 1985. St. Joseph, Michigan: ASAE.

McMennamy, J.A., J.C., O'Toole. 1983. RICEMOD: A physiologically based rice growth and yield model. Research Paper Series 87. Los Banos, Philippines: IRRI.

Mills, W.T. 1964. A heat unit system for predicting optimum peanut harvesting time. TRANSACTIONS of the ASAE 7:307-312.

Perry, K.B., T.C. Wehner, G.L. Johnson. 1986. Comparison of 14 methods to determine heat unit requirements for cucumber harvest. Hortscience 21:419-423.

Salter, P.J., J.M. Jones. 1975. The effect of plant density on the initiation, growth and maturity of two cauliflower varieties. J. Hort. Sci. 50:239-248.

Salter, P.J., D.J. Andrews, J.M. Akehust. 1984. The effects of plant density, spatial arrangement and sowing date on yield and head characteristics of a new form of broccoli. J. Hort. Sci. 59:79-85.

Sams, C.E. 1987. Personal communication.

Scaife, A., E.F. Cox, G.E.L. Morris. 1986. The relationship between shoot weight, plant density, and time during the propagation of four vegetable species. Ann. Bot. 59:325-334.

Smith, E.M. O.J. Loewer Jr. 1981. A nonspecific crop growth model. ASAE paper 81-1013.

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

Ting, I.P. 1982. Plant Physiology. Addison-Wesley Publishing Co., Reading, Massachusetts.

Whisler, F.D., B. Acock, D.N. Baker, R.E. Fye, H.F. Hodges, J.R. Lambert, H.E. Lemmon, J.M. McKinion, V.R. Reddy. 1986. Crop simulation models in agronomic systems. Adv. in Agr. 40:141-208.

Wiebe, H.J. 1975. The morphological development of cauliflower and broccoli cultivars depending on temperature. Scientia Hort. 3:95-101.

Wilkerson, G.G., J.W. Jones, K.J. Boote, K.T. Ingram, J.W. Mishoe. 1983. Modeling soybean growth for crop management. TRANSACTIONS of the ASAE 26:63-73.

Zink, F.W., D.A. Akana. 1951. The effect of spacing on the growth of sprouting broccoli. J. Amer. Soc. Hort. Sci. 58:160-164.

Zink, F.W. 1962. Rate of growth and nutrient absorption of celery. J. Amer. Soc. Hort. Sci. 82:351-357.

Zink, F.W. 1965. Growth and nutrient absorption in spring spinach. J. Amer. Soc. Hort. Sci. 87:380-386.

APPENDIX

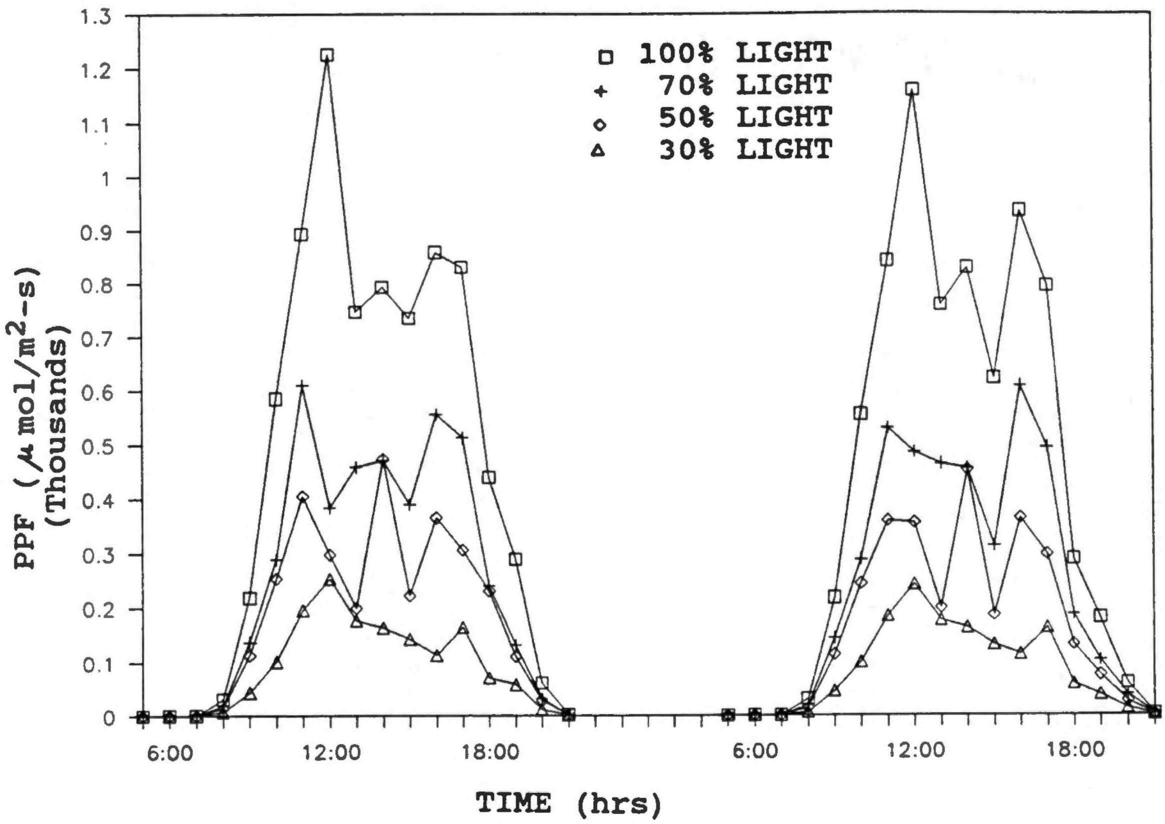

Figure A-1. Representative daily PPF received for each light treatment within replication 1 from two days in the spring.

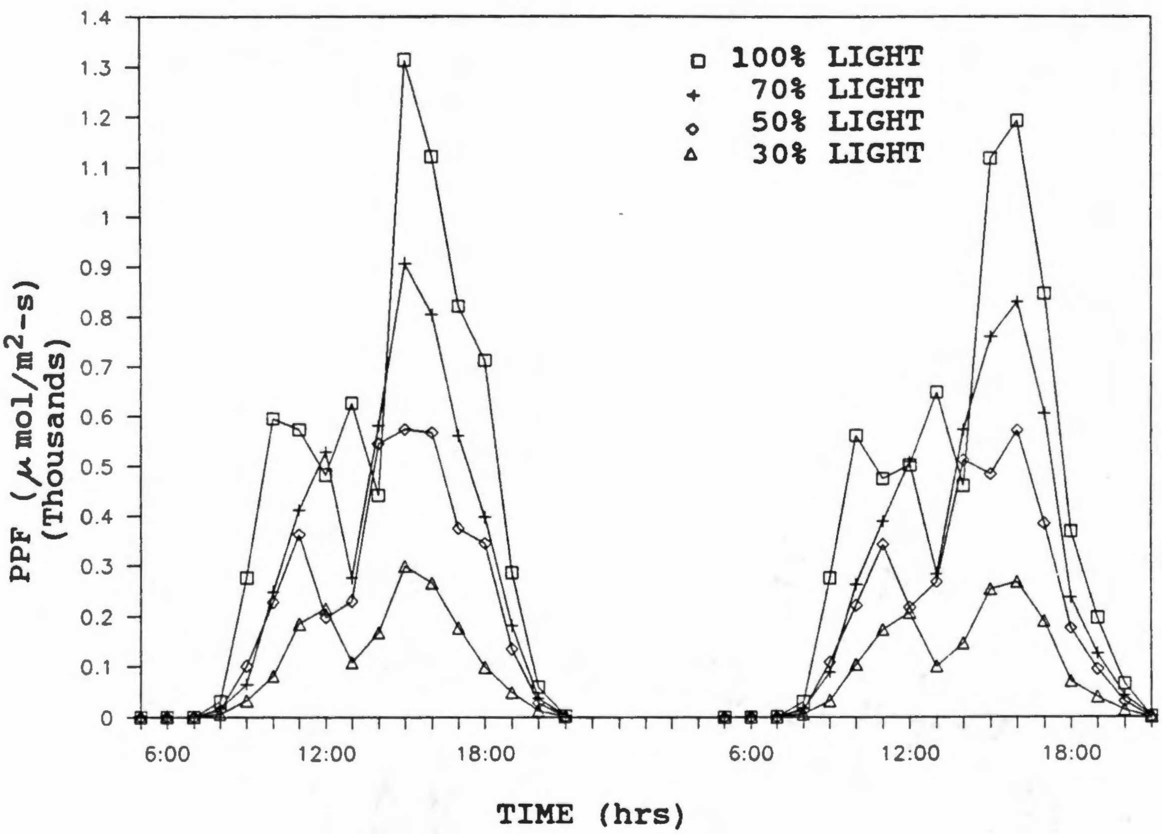

Figure A-2. Representative daily PPF received for each light treatment within replication 2 from two days in the spring.

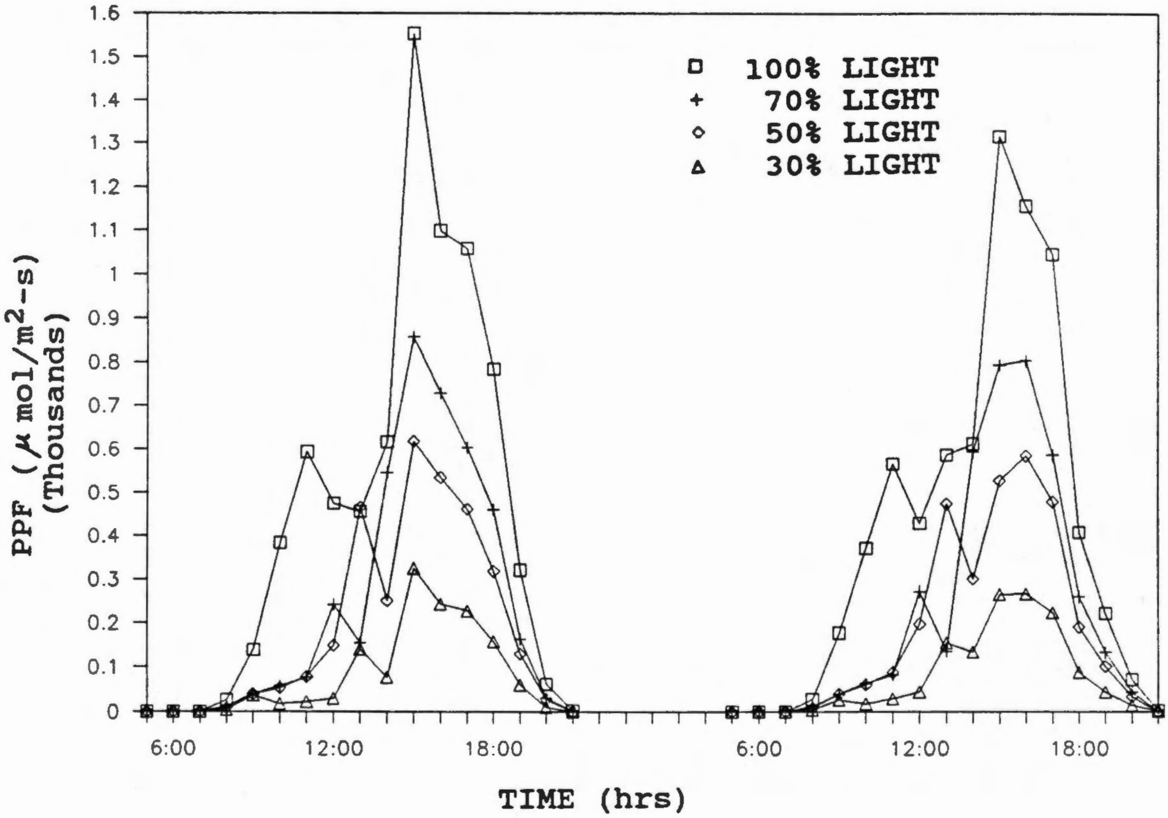

Figure A-3. Representative daily PPF received for each light treatment within replication 3 from two days in the spring.

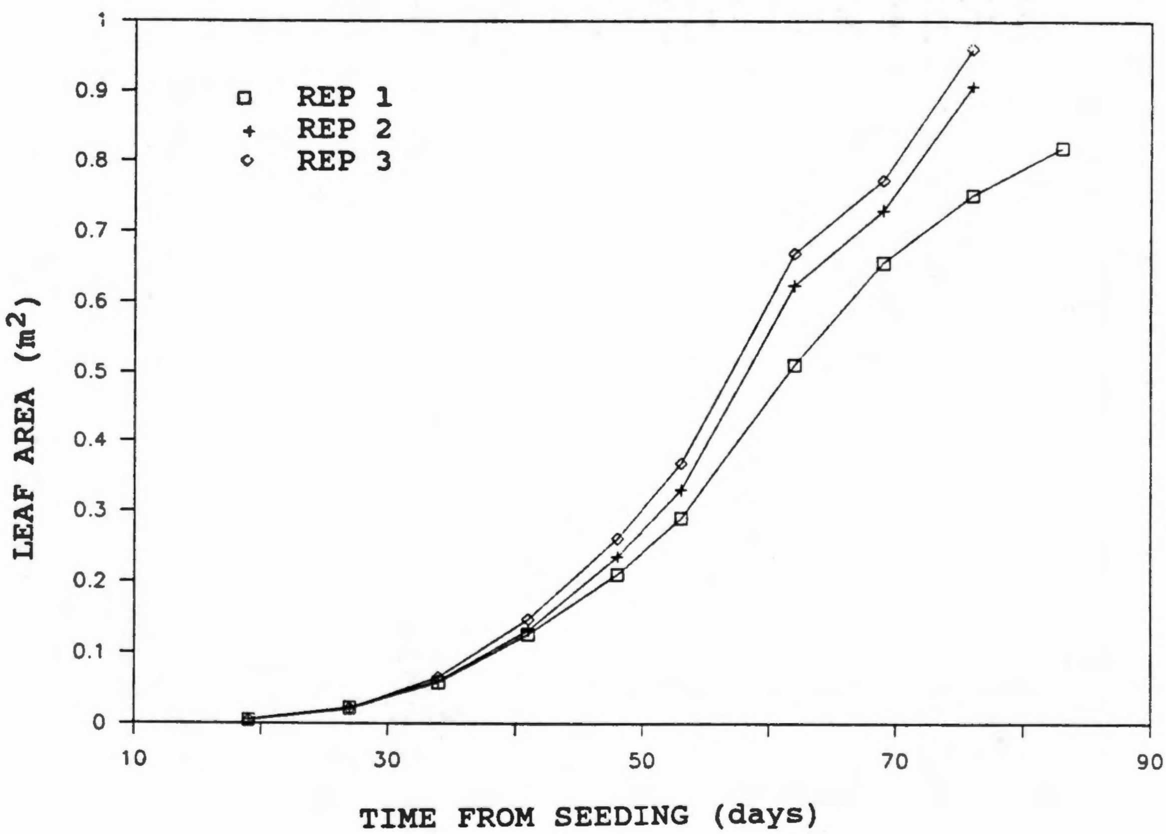

Figure A-4. A comparison of growth differences in the 3 replications of fall broccoli plants grown under treatment 1.

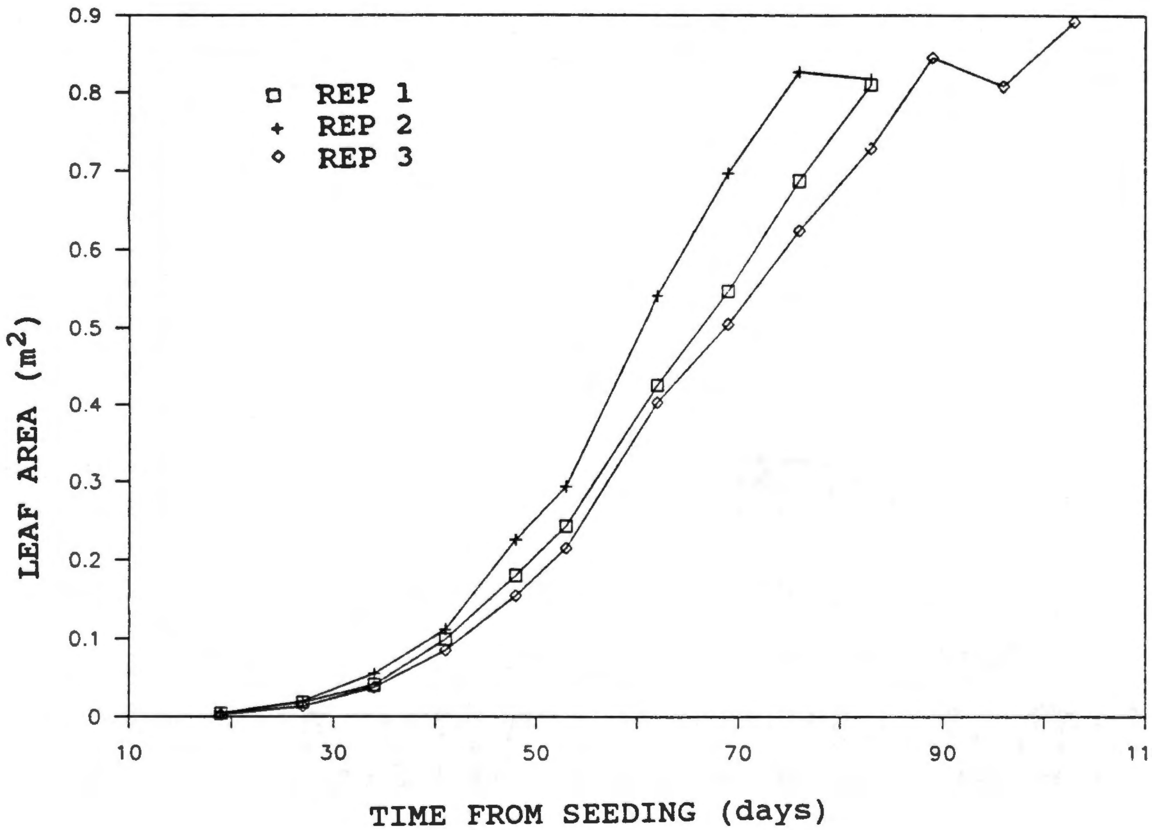

Figure A-5. A comparison of growth differences in the 3 replications of fall broccoli plants grown under treatment 2.

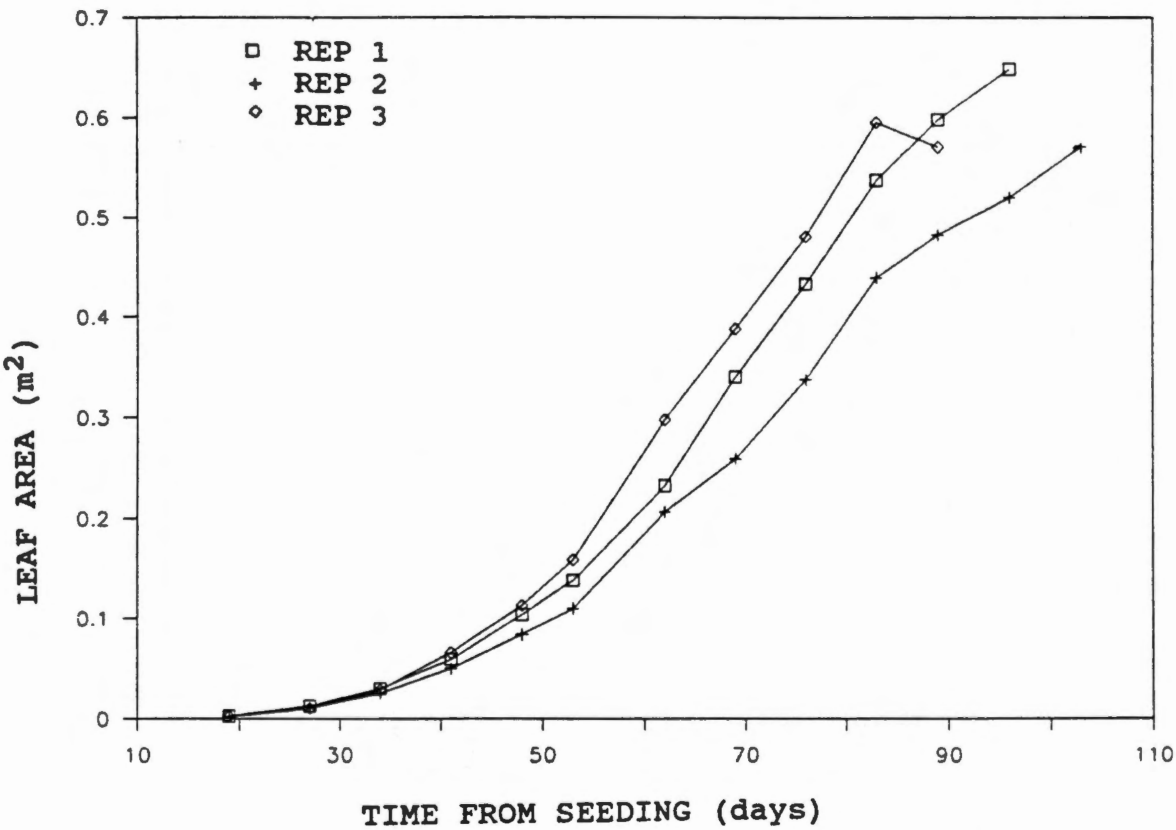

Figure A-6. A comparison of growth differences in the 3 replications of fall broccoli plants grown under treatment 3.

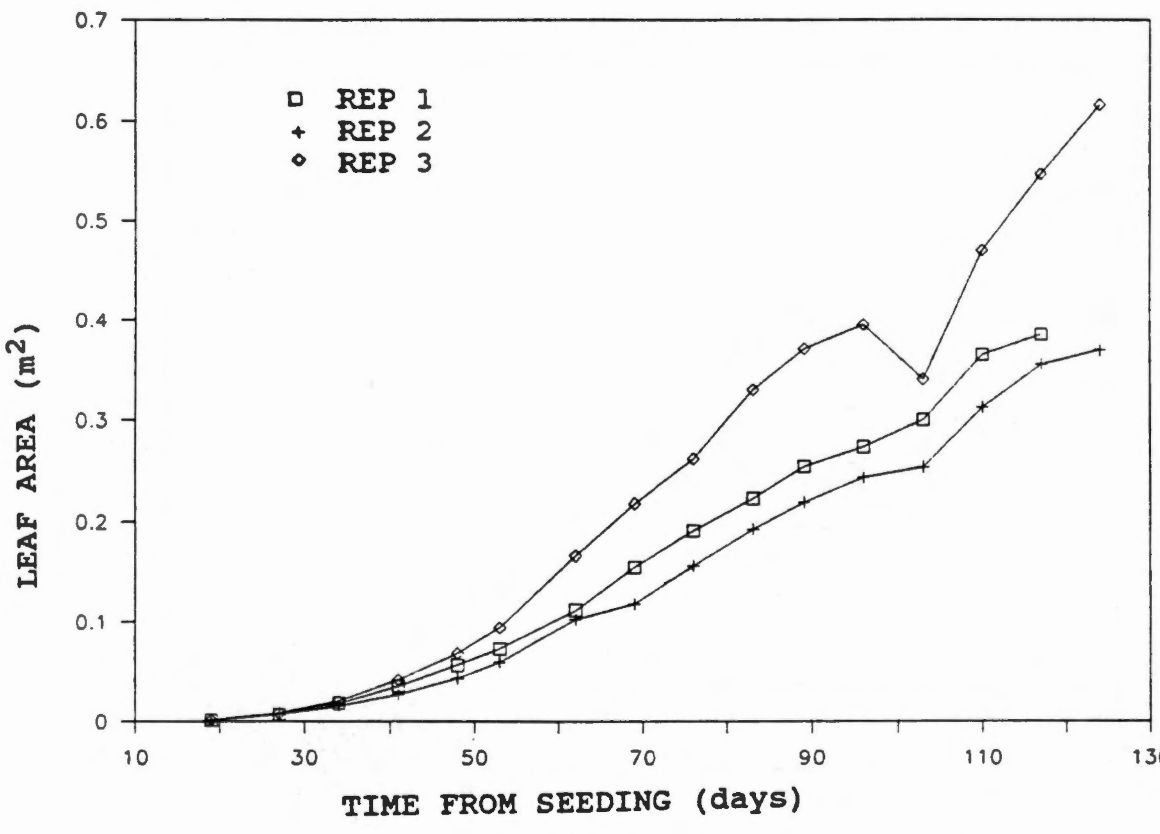

Figure A-7. A comparison of growth differences in the 3 replications of fall broccoli plants grown under treatment 4.

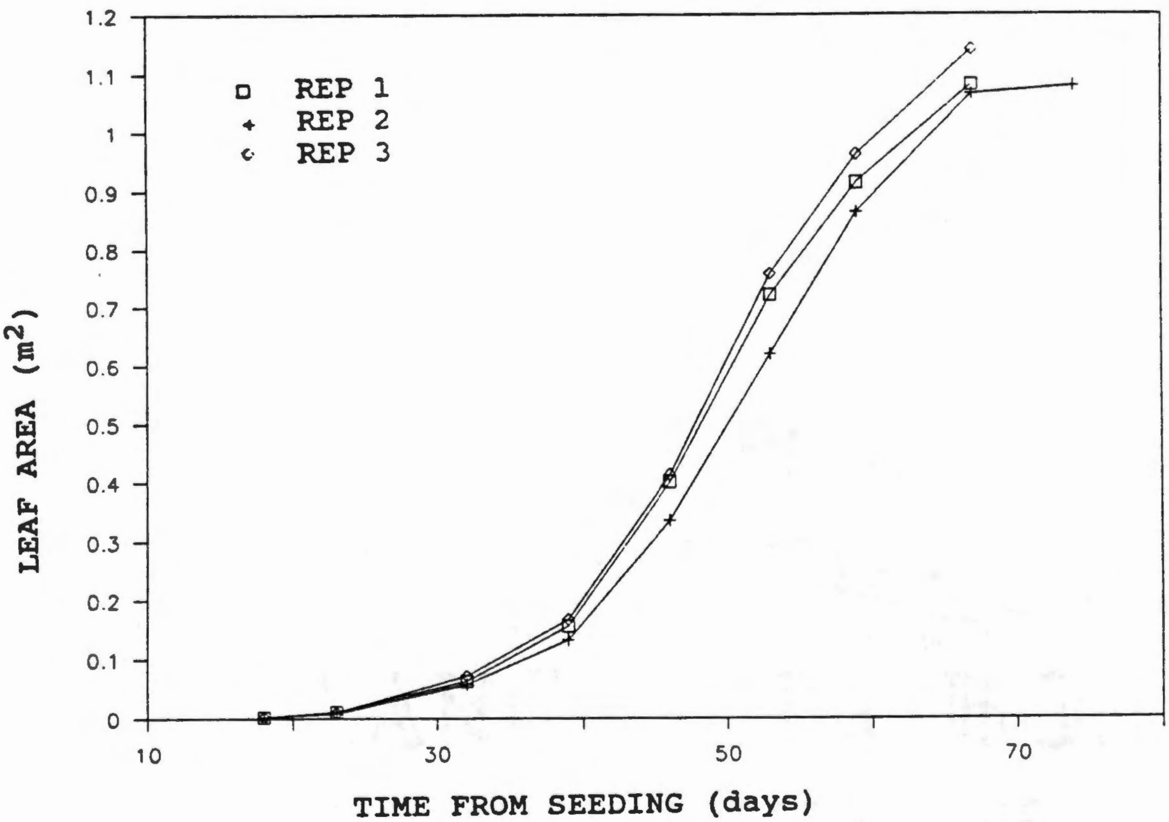

Figure A-8. A comparison of growth differences in the 3 replications of spring broccoli plants grown under treatment 1.

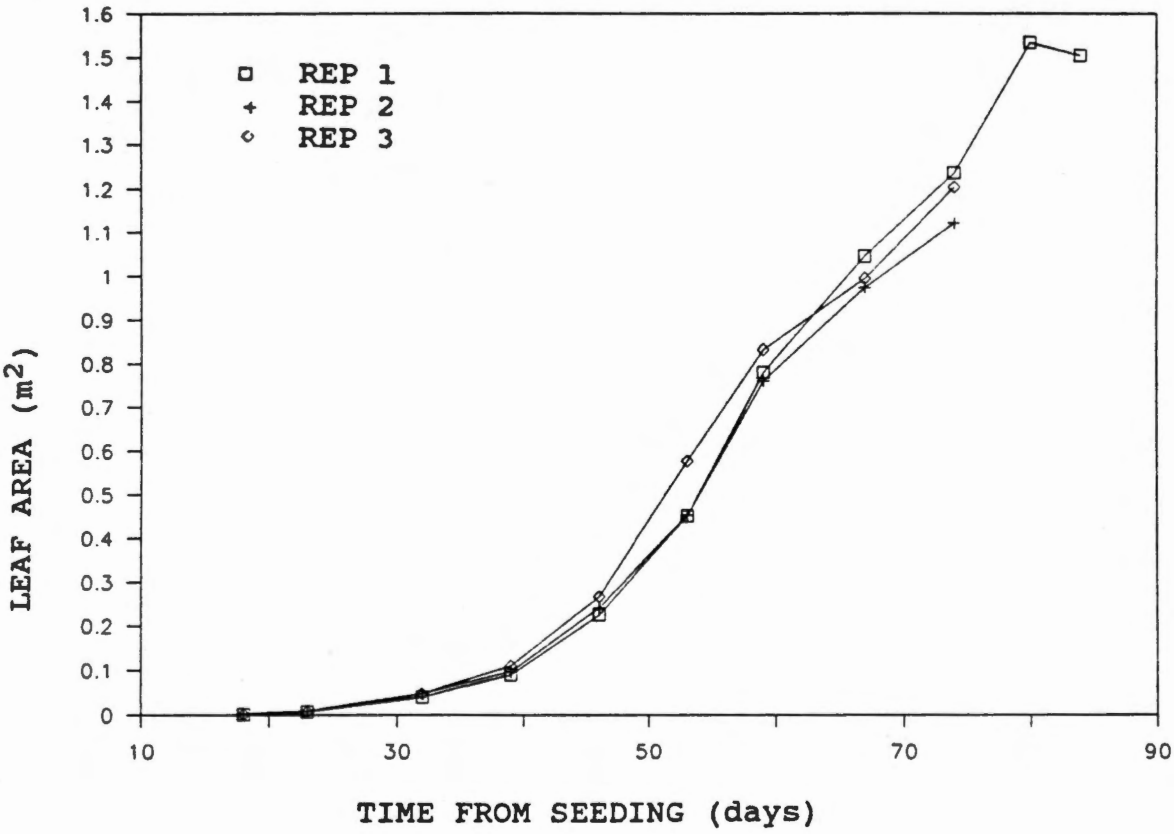

Figure A-9. A comparison of growth differences in the 3 replications of spring broccoli plants grown under treatment 2.

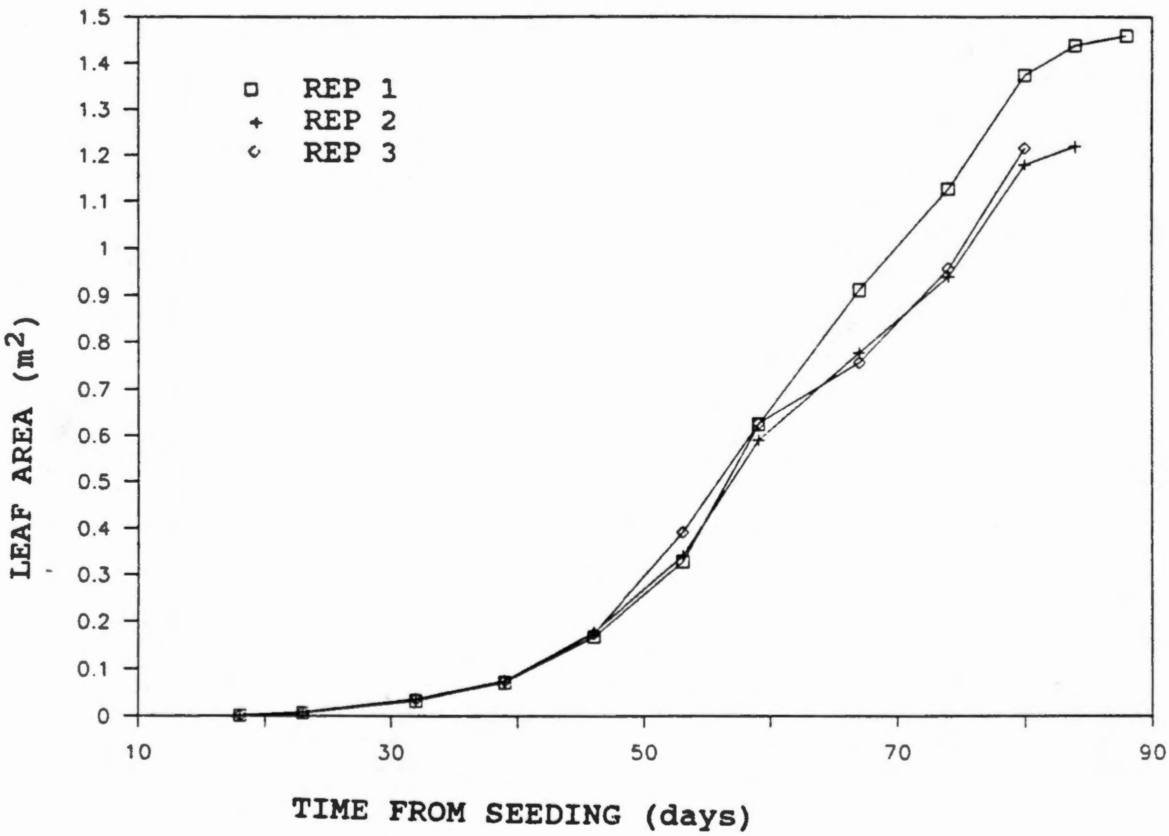

Figure A-10. A comparison of growth differences in the 3 replications of spring broccoli plants grown under treatment 3.

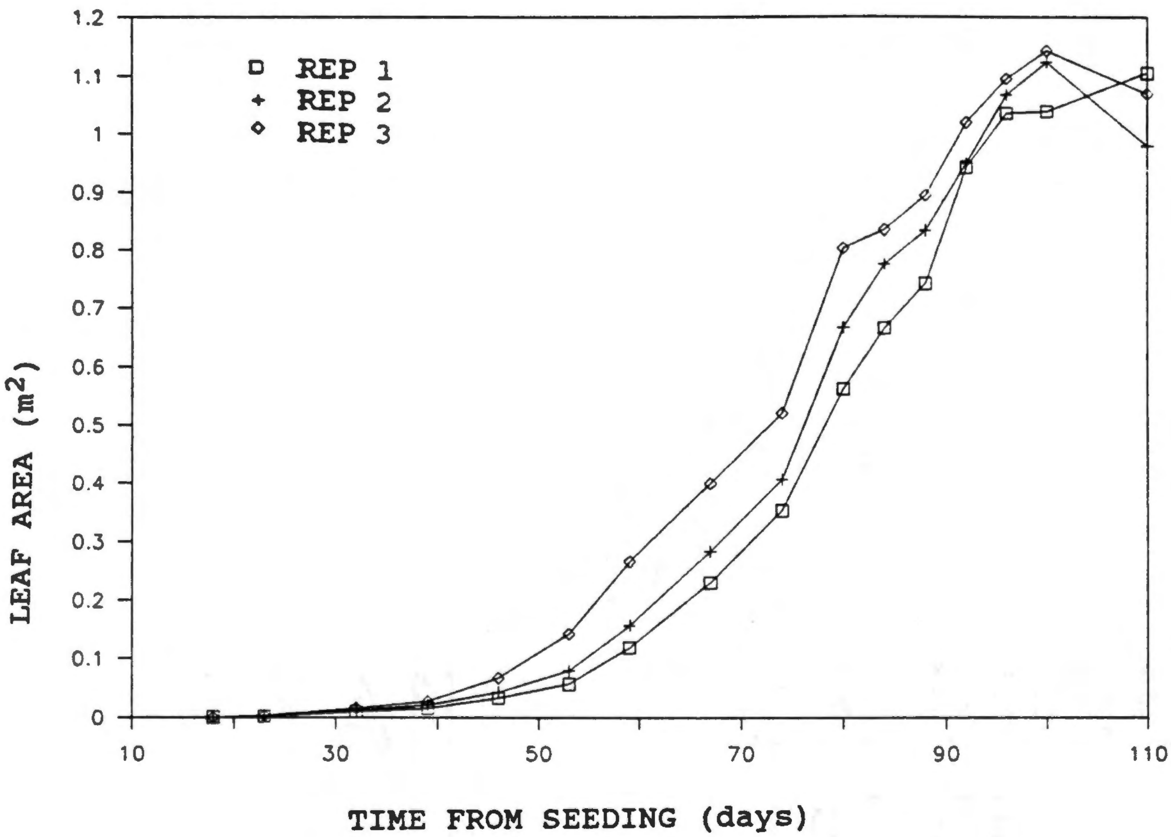

Figure A-11. A comparison of growth differences in the 3 replications of spring broccoli plants grown under treatment 4.

Table A-1. The coefficients for each individual plant for the non-linear model of the same form as Model 1 in Table IV-1, experiment 1.

tmt	rep	plt	a	k	u
1	1	1	0.998	0.056	20.279
1	1	2	1.002	0.054	18.406
1	1	3	1.012	0.045	13.946
1	1	4	1.239	0.020	6.116
1	2	1	1.052	0.035	10.088
1	2	2	1.033	0.045	14.655
1	2	3	1.022	0.045	14.993
1	2	4	1.040	0.042	12.360
1	3	1	1.030	0.049	13.882
1	3	2	1.021	0.050	15.943
1	3	3	1.023	0.048	18.102
1	3	4	1.071	0.033	10.399
2	1	1	1.059	0.031	8.648
2	1	2	1.066	0.032	8.259
2	1	3	1.059	0.030	9.006
2	1	4	1.073	0.027	7.716
2	2	1	1.046	0.041	12.607
2	2	2	1.031	0.047	14.705
2	2	3	1.040	0.034	10.526
2	2	4	1.091	0.027	7.630
2	3	1	1.033	0.035	11.102
2	3	2	1.004	0.046	14.475
2	3	3	0.999	0.046	15.403
2	3	4	1.007	0.043	18.673
3	1	1	0.998	0.034	10.229
3	1	2	1.001	0.034	12.027
3	1	3	1.002	0.034	9.886
3	1	4	1.007	0.032	10.028
3	2	1	0.977	0.040	13.959
3	2	2	0.990	0.033	10.369
3	2	3	0.970	0.034	9.639
3	2	4	0.990	0.027	7.977
3	3	1	1.071	0.026	7.717
3	3	2	1.034	0.026	7.691
3	3	3	1.016	0.036	10.336
3	3	4	1.051	0.024	7.977
4	1	1	1.016	0.012	3.662
4	1	2	1.002	0.012	3.648
4	1	3	0.963	0.017	3.965
4	1	4	0.919	0.019	4.732
4	2	1	1.152	0.010	3.500
4	2	2	2.022	0.003	2.522
4	2	3	0.868	0.016	4.584
4	2	4	0.909	0.023	5.423
4	3	1	1.246	0.009	3.358
4	3	2	0.932	0.035	10.094
4	3	3	0.996	0.031	8.220
4	3	4	0.933	0.043	15.174

Table A-2. The coefficients for each individual plant for the non-linear model of the same form as Model 1 in Table IV-1, experiment 2.

tmt	rep	plt	a	k	u
1	1	1	1.004	0.090	70.925
1	1	2	1.005	0.084	52.067
1	1	3	1.007	0.082	52.226
1	1	4	1.003	0.091	69.435
1	2	1	1.004	0.085	55.398
1	2	2	1.010	0.080	52.952
1	2	3	1.006	0.076	56.913
1	2	4	1.011	0.061	23.685
1	3	1	1.003	0.099	120.655
1	3	2	1.003	0.091	60.880
1	3	3	1.006	0.089	72.550
1	3	4	1.013	0.067	25.714
2	1	1	1.004	0.086	87.146
2	1	2	1.007	0.082	69.579
2	1	3	1.039	0.047	21.629
2	1	4	1.133	0.032	11.460
2	2	1	1.011	0.071	49.299
2	2	2	1.005	0.077	60.732
2	2	3	0.998	0.066	27.994
2	2	4	1.009	0.073	53.270
2	3	1	1.005	0.080	62.833
2	3	2	1.012	0.070	43.944
2	3	3	1.005	0.082	70.636
2	3	4	1.006	0.071	33.373
3	1	1	1.012	0.066	47.898
3	1	2	1.058	0.039	17.352
3	1	3	1.015	0.061	36.012
3	1	4	1.036	0.050	22.858
3	2	1	1.016	0.057	30.752
3	2	2	1.029	0.048	21.578
3	2	3	1.006	0.069	43.077
3	2	4	1.051	0.038	10.705
3	3	1	1.046	0.043	15.754
3	3	2	1.014	0.058	27.940
3	3	3	1.104	0.033	9.231
3	3	4	1.046	0.040	12.786
4	1	1	1.008	0.052	56.826
4	1	2	1.002	0.063	126.569
4	1	3	1.001	0.077	320.060
4	1	4	1.013	0.041	29.415
4	2	1	1.001	0.073	163.357
4	2	2	1.001	0.076	250.759
4	2	3	1.002	0.065	105.776
4	2	4	1.001	0.068	152.017
4	3	1	1.027	0.040	19.308
4	3	2	1.008	0.049	37.196
4	3	3	1.003	0.063	66.269
4	3	4	1.010	0.050	29.946

Table A-3. The treatment means of the coefficients from Tables A-1 and A-2 for the non-linear model of the same form as Model 1 in Table IV-1. This is an alternative method to the one used in this study for deriving coefficients for use with Model 1 as a predictive model.

exp	tmt	a	k	u
1	1	1.045	0.044	14.097
1	2	1.042	0.037	11.562
1	3	1.009	0.032	9.820
1	4	1.080	0.019	5.740
2	1	1.006	0.083	59.450
2	2	1.020	0.070	49.325
2	3	1.036	0.050	24.662
2	4	1.006	0.060	113.125

VITA

Brian D. Pennell was born in Toccoa, Georgia, in 1961. He received a Bachelor of Science degree in Agriculture with a major in Agricultural Engineering graduating with honors from The University of Tennessee, Knoxville, in 1984. After graduating, he was employed as a volunteer hunger relief technical representative for a year and a half. Upon completion of his assignments in Haiti, Mexico, and China, he returned to work as a laboratory assistant in the Agricultural Engineering Department of The University of Tennessee.

The author started his graduate program in 1986 at The University of Tennessee, Knoxville. During his graduate program he was employed as a research assistant with the Plant and Soil Science Department. He completed the requirements for a Master of Science degree with a major in Plant and Soil Science in December of 1988.