DYNAMIC SIMULATION OF SUPPLEMENTAL LIGHTING FOR GREENHOUSE HYDROPONIC LETTUCE PRODUCTION

Thesis · January 1995

DOI: 10.13140/RG.2.2.11209.29282

A.J. Both
Rutgers, The State University of New Jersey

DYNAMIC SIMULATION OF SUPPLEMENTAL LIGHTING FOR GREENHOUSE HYDROPONIC LETTUCE PRODUCTION

Photograph: Hydroponic lettuce experiment in one of the greenhouse sections of the Kenneth Post Laboratory Greenhouses at Cornell University.

This is a reformatted copy of my dissertation that was developed for the purpose of making it available in electronic format. The proper citation is:

Both, A.J. 1995. Dynamic simulation of supplemental lighting for greenhouse hydroponic lettuce production. Ph.D. Dissertation. Cornell University Libraries, Ithaca, NY 14853. 172 pp.

A.J. Both
July, 2019
both@sebs.rutgers.edu

DYNAMIC SIMULATION OF SUPPLEMENTAL LIGHTING FOR

GREENHOUSE HYDROPONIC LETTUCE PRODUCTION

A Dissertation

Presented to the Faculty of the Graduate School

of Cornell University

in Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy

by

Arend-Jan Both

January 1995

DYNAMIC SIMULATION OF SUPPLEMENTAL LIGHTING FOR GREENHOUSE HYDROPONIC LETTUCE PRODUCTION

Arend-Jan Both, Ph.D.

Cornell University 1995

During an eight-month period, hydroponic lettuce growth experiments, consisting of 35 different supplemental lighting treatments, were conducted in five identical greenhouse sections in order to: (1) determine how supplemental lighting can be used to ensure consistent and timely year-round greenhouse lettuce production in New York State, and (2) provide greenhouse growers and researchers with a computer simulation program to study the effects of different daily integrated light levels, indoor temperature, and plant spacing on the growth and development of lettuce.

The daily integrated photosynthetically active radiation (PAR) was kept constant during each of the treatments by supplementing the solar PAR with PAR from 400 Watt high pressure sodium (HPS) lamps. Among treatments, daily PAR varied between 4 and 22 mol m^{-2} d^{-1}. The indoor greenhouse environment was computer controlled and carbon dioxide enrichment (up to 1000 ppm) was used during the light period, but only when no ventilation was needed to maintain the temperature set point. The temperature was maintained at 24 and 18.8 °C during the light and dark periods respectively.

During the first 11 days, the lettuce seedlings were kept in a growth chamber under fluorescent lamps. After transplant, the plants remained 24 days in the greenhouse. Maintaining a daily PAR of 17 mol m^{-2} d^{-1} in the greenhouse resulted in a marketable lettuce head with a fresh weight of 150 grams (nearly 7 grams of dry weight) at 35 days after seeding. Lettuce tipburn was prevented using an overhead fan which blew ambient air downward onto the lettuce plants.

The computer simulation program predicts dry weight production based on environment conditions in the greenhouse and plant parameters extracted from the literature. The universal crop growth model SUCROS87 was adjusted and incorporated in the simulation program. Using long-term average daily solar radiation data collected for Ithaca, NY, the simulation model

successfully predicted dry weight production compared to plant dry weights measured during growth trials which were performed at Cornell University. The simulation program will be a helpful tool for commercial lettuce growers and future research.

BIOGRAPHICAL SKETCH

Arend-Jan Both (A.J. for his American friends and colleagues) was born in 1960 in Amsterdam, the Netherlands. He attended public schools in Leeuwarden (Friesland), graduating from the "Stedelijke Scholen Gemeenschap" (public high school) in May of 1980. He attended the only agricultural university in the country in Wageningen, studying agricultural engineering. While at the Agricultural University in Wageningen he majored in natural ventilation of livestock buildings and chose minors in computer science and business administration. In November 1988, he received a Master of Science degree in agricultural engineering. After graduation, he entered the Ph.D. program in the Department of Agricultural and Biological Engineering at Cornell University in Ithaca, NY. He continued to major in the field of agricultural structures and their environment, supplemented with minors in horticulture and meteorology.

ACKNOWLEDGEMENTS

From the start of my Ph.D. program at Cornell University I have received a lot of help and support from many different people. First, I would like to thank Dr. Louis D. Albright for believing in me and giving me an opportunity to learn many aspects of environment control for agricultural structures. His patience and wisdom will always be an inspiration to me. I thank Dr. Robert W. Langhans for teaching this Dutchman a thing or two about horticulture and for creating a very pleasant work environment which tolerated yet another agricultural engineer. Dr. Warren W. Knapp taught me a lot about the physical aspects of our weather and my six-year stay in Ithaca taught me to hope for the best and dress for the worst! All three professors were members of my special committee and without their advice and guidance this thesis would never have materialized.

I received a lot of help from the greenhouse crew at the Kenneth Post Lab: John Kumpf, Bob McBride, Barbara Stewart, Bill Thompson, Bob Spaulding, Martha Jensen, Peter Podaras, Andy

Leed, Bill Vinzant and Ramona Reiser. You all made my time at the greenhouses very enjoyable and your friendship is much appreciated.

Special thanks are due to Betty Czarniecki for correcting many of my manuscripts and for making time to chat which made yet another Dutchman feel more at home!

I would like to thank some of my fellow students for standing by me with advice and encouragement: Alain Rousseau, Norberto Adre, Eileen Fabian-Wheeler and Jan Boll.

Thanks are also due to Eiji Goto and Cheng Zou who joined our research group as visiting professors from Japan and China respectively. I would like to acknowledge Hanneke Pompe for a critical review of the Dutch summary.

During most of my studies I received financial support from the Department of Agricultural and Biological Engineering at Cornell University through a research assistantship. In 1991, I was stricken with thyroid disease which made it impossible to work for several months. Nevertheless, my funding was continued during this difficult period for which I am very grateful. Continued funding for my research was provided through the "Energy Efficiency in Controlled Environment Agriculture (CEA) Facilities" project. This project was funded by the New York State Energy Research and Development Authority (NYSERDA), the Empire State Electric Energy Research Corporation (ESEERCO), the New York State Electric and Gas Corporation (NYSEG) and Cornell University (NYSERDA agreement number 1548-EEED-IE-91). Additional funding for my studies was provided by the Fred C. Gloeckner Foundation and the "Boelstra-Olivier Stichting". The latter is a Dutch society and, in 1989, their support enabled me to buy a computer which I used throughout this study. During the final stages of this study I received funding from a NASA grant (NAG9-715) aimed at the study of growing plants in a Controlled Ecological Life Support System (CELSS) on the moon. Without any of the financial support the completion of my research would have been difficult at best.

Finally, I would like to thank my family: the one I grew up with in the Netherlands and my new family I found in the United States. You all are wonderful and your support means a lot to me!

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1

Introduction

Year-round greenhouse vegetable production has great potential in New York State. Today, many products are imported from California, Florida, Canada, Europe, Mexico and Israel. Relatively low fossil fuel prices have kept transportation cost down during the last decade. It remains a question, how long will these prices stay down? Higher oil prices will increase transportation costs, possibly making it too expensive to ship fresh vegetables over long distances. At that point, local vegetable production will be the only alternative for affordable quality produce. At the moment, local vegetable production is small and concentrates on outdoor summer production. For example, only 6.5% of the fresh lettuce sold in New York state is locally grown (New York Agricultural Statistics 1992-1993). Very little research regarding year-round greenhouse vegetable production has been reported, resulting in a lack of information ranging from economic analyses to growing techniques. Even fewer studies discuss the use of supplemental lighting in year-round greenhouse lettuce production, possibly due to perceived high costs of using supplemental lighting for a crop like lettuce. Interested growers have nowhere to turn for help or advice.

In the spring of 1991, a three-year research project was started to investigate the possibilities of year-round commercial greenhouse vegetable production in New York State. This project was funded by the New York State Energy Research and Development Authority (NYSERDA), a local electric utility (New York State Electric and Gas, NYSEG), the Empire State Electric Energy Research Corporation (ESEERCO), and Cornell University. It was decided to conduct the research in a Controlled Environment Agriculture (CEA) facility, since CEA is quickly becoming the most promising production technique for complying with the increasingly stricter environmental regulations. These regulations include, for example, no run-off of surplus irrigation water and a limited use of pesticides. In general, the latest regulations seek to prevent any environmental burdening by greenhouse operations.

In a CEA facility, environment parameters such as temperature, humidity, carbon dioxide concentration and nutrition can be accurately controlled with the help of computers to ensure optimum growing conditions throughout the entire life of a crop. High quality plants, disease and insect free, can be grown economically in a CEA facility without burdening the environment. Quality CEA products receive premium prices, offsetting the high investment for a CEA facility.

One of the most frequently used CEA systems for growing vegetables in greenhouses is the hydroponic system. In this system, the plant roots grow freely in a nutrient solution, which is recirculated while the nutrient concentration and the pH of the solution are maintained at an optimum level. Usually, the plants are started in a small amount of substrate (or growth medium, such as rockwool) for initial support. A hydroponic system was used in the research that formed the basis of this dissertation.

Lettuce was chosen as the first crop in the Cornell CEA research program, followed by spinach and vine crops such as tomato, pepper and cucumber. The work described in this dissertation will deal only with the results of the lettuce experiments. Lettuce was a logical first choice for various reasons: (1) an impressive amount of lettuce research has already been conducted all over the world, (2) lettuce is considered an easy crop to grow (except for a persistent tipburn problem), and (3) lettuce stays vegetative under most conditions, developing only leaves and roots, making it an ideal crop for plant growth modeling.

The amount of solar radiation received in New York state during the winter months is insufficient for consistent and timely greenhouse plant production. One solution is to keep the plants longer in the greenhouse compared to crops grown during the summer months. This, however, uses valuable greenhouse space during the potentially most profitable winter months. Another solution is to use supplemental lighting. Often, High Intensity Discharge (HID) lamps are used in greenhouses for their long lamp life, low light depreciation and relative efficiency. But these lamps need a bulky, energy consuming ballast, have a somewhat limited light spectrum, and produce a significant amount of infrared radiation (or heat).

Consistent timing of greenhouse vegetable production is very important. Most locally produced vegetables are sold directly to retailers (supermarkets) which prefer a steady (daily) availability of fresh produce. Consistent year-round vegetable production requires a constant amount of Photosynthetically Active Radiation (PAR) every day of the year. To supplement insufficient amounts of solar radiation, especially during the darker winter months, HID lamps were installed in the CEA research greenhouse. The use of HID lighting increases the electricity consumption of a greenhouse operation. With many electric utility companies trying to reduce their peak electricity demand, it is not surprising they are encouraging greenhouse operators to use supplemental lighting during off-peak periods (mainly at night, e.g., 10 pm - 6 am).

Consistent production of hydroponic greenhouse lettuce requires accurate control of environment parameters such as temperature, light level and carbon dioxide concentration. Marsh (1987) investigated the effect of daytime temperature on the growth of hydroponic lettuce. The current research extends her work and studies the effect of daily integrated light level (a combination of sunlight and supplemental light provided by HID lamps) and carbon dioxide concentration on hydroponic greenhouse lettuce production. Detailed knowledge of the effects of temperature, supplemental lighting and carbon dioxide enrichment on lettuce production will enable a grower to accurately predict a harvest day for each crop. Furthermore, crop scheduling and marketing can be optimized due to a predictable and reliable production. The more knowledge gathered about specific environment parameters important for hydroponic lettuce production, the more successful CEA facilities producing such lettuce will be.

Research Objectives

The objectives of this study were:

1. to determine how supplemental lighting can be used to ensure consistent (at least 150 grams of fresh weight) and timely (in 35 days from seed to harvest) year-round greenhouse lettuce production in New York State by investigating:
   (1) the optimum daily integrated light level (a combination of sunlight and supplemental light),
   (2) different supplemental light intensities, and
   (3) the timing of supplemental lighting (daytime compared with nighttime lighting).
2. to provide greenhouse growers and researchers with a tool (computer program) to analyze (simulate) the effects of different daily integrated light levels, plant spacing and temperature on the growth and development of greenhouse hydroponic lettuce.

The findings of this research will aid the development of a "blueprint" for successful production of hydroponic lettuce in a CEA facility located in New York State. The blueprint will include the entire sphere of such a facility, from building design to crop production and marketing. Such a blueprint is being planned by Cornell's CEA Program and will first be tested in a 10,000 square feet demonstration project before it will become available to interested growers. Hydroponic vegetable production in New York State using CEA techniques can become a successful and valuable addition to the state's agriculture industry.

Research Approach

A research greenhouse with five identical, but separate, sections was retrofitted to enable computer aided control of environment parameters such as temperature, supplemental light levels, and carbon dioxide concentration. Environment conditions were frequently monitored and stored on computer disk for further analyses. In each greenhouse section, supplemental lighting, carbon dioxide enrichment, evaporative cooling and a hydroponic growing system (troughs) on rolling benches were installed.

During an eight-month period, lettuce growth experiments consisting of 35 different supplemental lighting treatments were conducted in the five greenhouse sections in order to satisfy research objective 1. To satisfy research objective 2, a computer program was written based on research performed by Marsh (1987) and on the crop growth model SUCROS87 (Simple and Universal CROp growth Simulator, version 1987, Spitters et al., 1989). Results of the growth experiments were used to validate the calculations performed with the computer simulation model.

Some of the results of the supplemental lighting treatments and the design of the supplemental lighting system as described in this dissertation were previously submitted for publication (Both et al., 1994a and 1994b).

Chapter 2

Literature Review

As mentioned earlier, an impressive amount of lettuce research has been reported in the extant research literature. Comparing experimental results reported in the research literature to determine trends or contrasts is not easy, in the case of (hydroponic) lettuce due, to the wide range of environment conditions and different cultivars used for the many research interests. An attempt is made in this review to discuss and compare those references of particular interest to the current research. The review is divided into several sections, each describing a topic important to this research.

Canopy light absorption: The amount of light absorbed and the efficiency of converting absorbed light into photosynthesis determine canopy photosynthesis. However, the photosynthesis-light response of leaves is not described by a straight line but, instead, shows a convex and asymptotic response. This implies that canopy photosynthesis can be overestimated when light absorption by the entire canopy is averaged over a time period. Separating the total incoming radiation into direct and diffuse radiation enables a more accurate prediction of canopy photosynthesis. De Wit (1965) and van Keulen et al. (1982) assumed alternating periods during the day with clear or overcast conditions. Clouds were considered an on-off switch for the direct radiation. Spitters et al. (1986) showed the diffuse radiation predicted using this on-off switch is largely underestimated. Instead, Spitters et al. proposed to estimate the diffuse radiation from the ratio between the total (at the earth's surface) and the extra-terrestrial radiation (outside the atmosphere). Spitters (1986) divided the incoming direct radiation into direct and diffuse components. The diffuse component originates from the scattering of radiation by intercepting leaves. Spitters assumed a spherical leaf angle distribution and divided the canopy into successive leaf layers. Using a Gaussian integration (Goudriaan, 1986), Spitters approximated the daily canopy photosynthesis by calculating the assimilation rates at three selected canopy depths at three times of the day. The plant growth model SUCROS87 (Spitters et al., 1989) incorporates Spitters' calculations into a simple computer algorithm. However, SUCROS87 simulates dry matter production of an outdoor crop based on ambient solar radiation, temperature and carbon dioxide concentration. For the current research, supplemental lighting and carbon dioxide enrichment were used to grow hydroponic greenhouse lettuce. Therefore, adjustments to SUCROS87 were made to properly simulate the growth of lettuce under these controlled environment conditions. These adjustments are described in the following chapter. Most crop growth models, including SUCROS87, calculate the average diffuse radiation and add it to the appropriate amount of direct radiation. However, the transmission, and thus the light intensity, changes in the canopy from location to location. Critten (1989) argued the averaging of these variations can produce errors, especially during bright but partly cloudy skies, because of the non-linear photosynthesis-light response of leaves. Critten's solution, sub-dividing the sky into equal solid angle sectors, each with a radiation source at its center, works for a tomato crop, but proves a very time consuming calculation technique.

Supplemental lighting: In Japan, researchers investigating CEA have focused on factory-type plant production. The goal has been to produce plants successfully in completely controlled environment buildings, removed from outside weather conditions and using supplemental lighting as the only light source. Sase et al. (1988) compared High Pressure Sodium (HPS) and Metal Halide (MH) lamps for growing lettuce (***Lactuca sativa*** L., cv. Okayama Sarada) in separate but identical growth chambers. Similar PAR levels of 350 µmol m^{-2} s^{-1} were maintained in each chamber for 12 hours per day. The carbon dioxide concentration was kept at 800 ppm during the light period. The temperature during the light period was maintained at 24 °C and during the dark period at 22 °C. The pH of the nutrient solution was kept at 6.0 and the Electrical Conductivity (EC) at 0.21 S m^{-1}.

A fresh weight of 100 grams per head was reached after 27 days of growth using a plant spacing of 48 plants m^{-2}. Due to the different spectral output of the HPS and MH lamps, plants grown under these two light sources showed morphological differences. The lettuce grown under HPS lamps was of better quality and formed more compact heads. No differences in fresh and dry weights between the two treatments were observed. This result favors the use of HPS lamps as the preferred supplemental light source, especially because HPS lamps are more efficient in converting electric energy into light. The current research, using supplemental lighting (HPS) and carbon dioxide enrichment to grow lettuce in a greenhouse, confirmed it is possible to produce a fresh weight of 100 grams in 27 days.

Optimum daytime temperature: Marsh (1987) described a model calculating 24-hour optimum daytime air temperatures for hydroponic lettuce, such that the difference between the market value and the cost to provide the optimum daytime air temperature was maximized (i.e., maximize income minus expenses). Marsh concluded, using batch loading (i.e., all in - all out), daily temperature optimization could save up to 30% of the fuel cost compared to operating at the usually recommended 25 °C. Using continuous loading, savings were reduced to 10% because of the different optimum temperature requirements of the several age groups of plants simultaneously present in the greenhouse. Marsh did not investigate the effect of supplemental lighting nor carbon dioxide enrichment on growth and development of hydroponic lettuce. The current research is therefore a continuation of the study by Marsh and aims to show an increased benefit of using supplemental lighting and carbon dioxide enrichment on top of benefits from using optimum temperatures.

Tipburn: Tipburn in young, fast growing lettuce leaves has long been a problem for researchers and commercial growers. The tips of the young leaves develop necrosis, making the lettuce unsalable. The generally accepted explanation for this physiological disorder is an insufficient transport of nutrients from roots to the rapidly growing leaf tips through the xylem cells, causing a calcium (Ca) deficiency in the young leaves. Relocation of Ca from mature to young leaf tissue through the phloem cells generally does not occur.

Growers have tried to prevent tipburn by reducing the growth rate of the lettuce plants through shading or lowering ambient temperatures, by using cultivars selected for tipburn resistance, by trying increased doses of Ca in the nutrient solution, and by applying foliar sprays with Ca salts. However, the results were not always successful. Besides, slowing down the growth rate in a year-round production facility will decrease the number of crops grown and thus the profitability.

Goto and Takakura (1992) hypothesized an increase in transpiration rate would increase the transport of Ca through the xylem cells, thus reducing or preventing tipburn. The lettuce (***Lactuca sativa*** L., cv. Okayama) was grown in a chamber and exposed to day-night cycles ranging from 6 to 72 hours. The temperature was maintained at 20 °C during the light period and

15 °C during the dark period. The supplemental light level (HPS) was maintained between 75 and 225 μmol m^{-2} s^{-1} and the carbon dioxide concentration was kept at 500 ppm during the first 30 days (Stage 1) and at 800 ppm during the final six days of growth (Stage 2). The pH of the nutrient solution was maintained between 6.4 - 6.8 during Stage 1 and between 6.0 and 6.8 during Stage 2. Compared to other research described in this review, this pH is relatively high. The EC of the nutrient solution was kept at 0.06 S m^{-1} during Stage 1 and at 0.12 S m^{-1} during Stage 2.

The transpiration rate of lettuce plants was increased by blowing air downward onto the lettuce heads through thin transparent tubes. A high growth rate was maintained while tipburn was prevented. The system, however, was not very practical for a commercial lettuce operation because many little tubes for air supply were needed to provide the center of each individual lettuce head with the right amount of airflow.

<u>Nutrient uptake:</u> Heinen et al. (1991) studied nutrient uptake by lettuce plants (***Lactuca sativa*** L., cv. Sitonia) grown in a Nutrient Film Technique (NFT) system, similar to the system used for this research. Growth curves were used to simulate dry weight production, nutrient uptake and transpiration rate of the lettuce plants. Although no supplemental lighting was used, high growth rates were reported caused by the high amount of solar radiation received by the summer crop. Only one crop of 144 plants was grown during the months of June and July without using carbon dioxide enrichment. The greenhouse temperature was maintained at 15 °C during the day and 10 °C during the night. These temperatures are considerably lower than the temperatures used in other research discussed in this review. The availability of nutrients in the supply system was manually controlled and kept at a constant level. The pH of the nutrient solution was kept at 6.0, and a relatively wide plant spacing of 15.7 plants m^{-2} was used.

On average, 3.1 grams of plant dry weight (roots and shoots) was produced per liter of transpiration. The relationship between total plant dry weight production and accumulated transpiration, as well as the relationship between the accumulated transpiration and accumulated daily radiation, could accurately be described by the logistic equation. An average of 126 ml of transpiration was observed per unit (mol m^{-2} d^{-1}) increase in radiation. Heinen et al. (1991) used three other

exponential growth curves to describe dry weight production and cumulative nutrient uptake: the Richards equation (general logistic), the Gompertz equation, and the second order exponential polynomial. These equations can be expressed as:
Logistic equation:

$$W_t = W_i * W_f/[W_i + (W_f - W_i) * \exp(-k_1 * t)], \qquad (2.1)$$

Gompertz equation:

$$W_t = W_f * \exp[-k_0 * \exp(-k_2 * t)/k_2], \qquad (2.2)$$

Richards equation:

$$W_t = W_i * W_f/[W_i^n + (W_f^n - W_i^n) * \exp(-k_3 * t)]^{1/n}, \qquad (2.3)$$

Second order exponential polynomial:

$$W_t = \exp(a + b * t + c * t^2), \qquad (2.4)$$

where:

W_t = weight at time t,
W_i = initial weight at t = 0,
W_f = weight at final harvest,
k_o, k_1, k_2, k_3 = proportionality factors,
n = determines the shape of the growth curve,
t = time,
a, b, c = coefficients.

The Richards and the logistic equations assume a growth rate (dW/dt, change in weight over time) proportional to plant weight and the difference between final and current plant weight. The Gompertz equation assumes the growth rate is proportional to plant weight, but less so as the plant ages (described by first order kinetics). The second order exponential polynomial is used as a pure mathematical tool, and is not derived from physiological relationships. Heinen et al. (1991) found little difference in accuracy of the fit among the four equations, but preferred to use the logistic equation.

Growth Modeling: Growth models are generally designed to predict the increase of a crop parameter (e.g., weight, leaf area, or stem length) over a certain growing period (Spitters et al., 1989, Van Henten, 1994, Bertin and Heuvelink, 1993, and Dayan et al., 1993a and 1993b). Many environment and plant parameters are needed to make accurate predictions. For example, parameters like temperature, light level, plant spacing, reflectivity of leaf surface, light use efficiency at low light levels, and carbon dioxide assimilation at light saturation are some of the parameters determining the outcome of various growth models (Spitters et al, 1989, and Van Henten, 1994). Many researchers use values of parameters reported by other researchers, simply because of the time and effort it took to determine some of these parameters (Spitters et al., 1989, Van Henten, 1994, Bertin and Heuvelink, 1993, and Dayan et al., 1993a and 1993b). It should be clear this practice can result in erroneous predictions, especially if the conditions the "borrowed" parameter is used under are different from the conditions the parameter value was derived from. Often statements like: "It seems reasonable to assume the value of parameter X (reported by researcher Y) can be used under the current conditions Z", are used. A critical investigation of the truth of such a statement is too frequently omitted.

Another potential problem with growth models can be the size of the time step used. In other words, is the crop parameter under investigation calculated every minute, every hour, or every day? In the plant, physiological processes occur continuously, making them very hard to measure accurately. Most models assume certain environment (e.g., daytime and nighttime temperature) and plant parameters (e.g., reflectivity of the leaf surface) are constant during their time steps to simplify the calculations or when their rates of change (especially for the plant parameters) are unknown. However, this assumption is not always justified. For example, canopy temperature is directly affected by incoming radiation and is often not the same as air temperature even though this assumption is frequently made. Again, this practice can cause errors when the calculated change in the crop parameter under investigation is compared with the actual measured change.

It should be clear from the above that growth models are nothing but a tool to predict plant growth and the results of model calculations should be evaluated in the context of the underlying assumptions. Nevertheless, growth models are great tools to study plant development; to make predictions of plant growth under different environment conditions and, in a commercial application, to predict the time to maturity (crop scheduling); and to alert the grower when measured plant production deviates from model predictions. Some models are already used to support or direct the environment control of the greenhouse, enabling a continuous evaluation of the trade-off between the cost of modifying the environment and the predicted increase in economic return (Van Henten and Bontsema, 1991, and Van Henten, 1994).

Chapter 3

Materials and Methods

The research described in this dissertation consisted of two parts. The first part dealt with supplemental lighting experiments concerning the growth of hydroponic leaf lettuce. Results of this first part were then used to complete the second part: construction and testing of a lettuce growth model. Therefore, this chapter is divided into two sections, each describing the materials and methods used to complete each research part.

Part 1. Supplemental Lighting Experiments

<u>Facilities:</u> Two walk-in growth chambers and one glass-clad greenhouse, divided into five identical sections, were used. The chambers measured 2.5 by 3.6 m, with a ceiling height of 2.1 m. The ceiling consisted of a clear Plexiglass barrier (3 mm thick) above which fluorescent lamps were mounted. Each of the five greenhouse sections measured 8.5 m (North and South face) by 10.7 m (East and West face), with an eave height of 2.2 m and roof slope of 25 degrees. The ridge of the greenhouse ran East-West. The East wall of the greenhouse (in section A) was directly connected to a building and was 75% brick wall, 25% glass. The West wall of the greenhouse (in section E) was free-standing and entirely glass.

The bench area in each section measured 4.5 by 3.7 m, and was divided into three rolling benches, 1.5 m wide and 3.7 m long. Each bench held 19 troughs at the initial spacing and 10 troughs at the final spacing. Each trough measured 72 mm wide by 38 mm deep and 3.7 m long, and held 20 lettuce plants, resulting in plant densities of 78 and 39 plants m^{-2} before and after spacing. Spacing between plants in troughs was 180 mm. The plant position in one trough was staggered from the position in its neighboring troughs to allow the plants more space. The troughs were covered and square holes in the covers allowed a square plastic cube, filled with growing medium and a lettuce plant, to be positioned in the troughs. A slit in the bottom of the cubes allowed the roots to grow into the troughs. In each greenhouse section, a nutrient solution was pumped from a supply tank (maintained at 150 liter, with an additional 25 liter in the plumbing) to the

South end of the troughs. At the North end, the excess solution was collected and drained back to the supply tank. The troughs had a slope of 1:148.

Experimental Design: From October 1992, to May 1993, eight supplemental lighting experiments were conducted at the Kenneth Post Laboratory greenhouses on the Cornell University campus. Bibb lettuce (***Lactuca sativa*** L., cv. Ostinata) was grown in a peat-vermiculite soilless mixture in a recirculating hydroponic (Nutrient Film Technique) system. A listing of the different lighting treatments can be found in Table 3.1. Control treatments received no supplemental lighting. Treatments in the first six experiments were assigned to the five greenhouse sections according to a Latin square. This prevented repeating a treatment in the same greenhouse section, avoiding a 'section effect'.

The October, November, and December experiments were designed to find the optimum daily integrated PAR (in mol m^{-2} d^{-1}) for growing hydroponic lettuce in our system. Due to severe tipburn during the October and November experiments, the integrated PAR in the December experiment were significantly reduced. The January, February, and March experiments were designed to compare daytime to nighttime lighting. Nighttime lighting could be more economical due to the use of off-peak electricity. The daily integrated PAR during these experiments was increased because supplemental air movement directed downward on the plants significantly reduced tipburn. The April experiment compared the effect of delayed supplemental lighting and the May experiment compared different instantaneous supplemental PAR, while maintaining a constant daily integrated PAR. The supplemental lighting for both the April and May experiments was provided at night. Between each experiment every greenhouse section was thoroughly cleaned and the nutrient supply system was rinsed with a weak bleach solution.

Table 3.1 Experimental design, indicating daily target integrated PAR in each of the five greenhouse sections (A trough E); expressed in mol m^{-2} d^{-1} PAR. The instantaneous PAR from the HPS lamps in all treatments was 230 µmol m^{-2} s^{-1}, except in May. D = daytime lighting, N = nighttime lighting.

	A	B	C	D	E
Oct	20	25	15	10	Control
Nov	15	Control	10	20	25
Dec	12.5	10	Control	15	7.5
Jan	Control	12.5 D	7.5 D	12.5 N	7.5 N
Feb	12.5 D	12.5 N	17.5 N	Control	17.5 D
Mar	22.5 N	17.5 N	22.5 D	17.5 D	Control
Apr	---	3 hours every night	6 hours every 2nd night	9 hours every 3rd night	---
May	---	4.5 hours at 230 µmol m^{-2} s^{-1}	6 hours at 196 µmol m^{-2} s^{-1}	9 hours at 123 µmol m^{-2} s^{-1}	---

<u>Crop Schedule:</u> At day 0, 4100 seeds were sown with a pneumatic seeder into plastic cubes filled with a peat-vermiculite soilless mixture. This mixture consisted of one volume part dolomitic limestone and 239 volume parts each of sphagnum peat moss and horticultural vermiculite. The individual cubes were cut from a Grodan number 150 square plug tray and had a volume of 11 ml. Thirty-two plug trays (number 128, square) were filled with the cubes and soilless mixture before seeding. After seeding, the seeds were misted and the trays placed on ebb and flow benches in the two growth chambers. The cubes were bottom irrigated for approximately half an hour twice daily. The ebb and flow benches were covered with translucent plastic for the first 48 hours to maintain high humidity.

At day 6, the plants were visually selected. Poorly germinated plants were removed (usually less than 5%). Then, each seedling was rated according to the size and expansion of the first true leaf. The seedlings were divided into three groups: small, medium, and large. The large and small seedlings (up to 20% of the total) were used as guard plants in the greenhouse sections. The guard plants were positioned around the perimeter of the growing area in positions 1 and 20 in each trough and in guard troughs 1 and 30.

At days 7 and 11 approximately 100 plants were harvested from each growth chamber and an average dry weight of the heads (leaves) was determined. The plants were dried in a drying oven for at least 72 hours at 70 °C. When the plants were exactly 11 days old, they were transplanted from the growth chambers into the greenhouse sections. Three thousand lettuce plants were transplanted, filling 30 troughs in each of the five greenhouse sections. Seedlings from the 32 plug trays were randomly distributed over the five greenhouse sections.

In the greenhouse, the lettuce was harvested on days 14, 18, 21, 25, 28, 32, and 35, for a total of seven harvests. For each harvest, 4 troughs were randomly selected in pairs of two adjacent troughs. Immediately after harvesting, the remaining troughs were repositioned to preserve the proper spacing. At day 21, the spacing was changed from 78 to 39 plants m^{-2}. Per harvest, a total of 72 plants per greenhouse section were dried in a drying oven for at least 72 hours at 70 °C and weighed. Only the leaves (heads) were used for measurement; the roots, with some remaining growing medium and the plastic cubes, were discarded. Guard plants and guard troughs were not used for dry weight measurements.

Environment Control: During the first 24 hours, temperature in the growth chambers was maintained at 20 °C and the PAR (cool white fluorescent) averaged 125 µmol m^{-2} s^{-1}. For the next 10 days, the temperature was 25 °C and the PAR averaged 255 µmol m^{-2} s^{-1}. The photoperiod during the first 11 days was 24 hours. No CO_2 enrichment was used in the growth chambers.

Each greenhouse section was controlled by an environment control computer. Two-minute averages of temperature, relative humidity, instantaneous PAR, CO_2 concentration, and heating and venting stages were stored in a data file. These data files were used to track the operation of heating, venting, carbon dioxide enrichment, and supplemental lighting and to calculate hourly averages of the parameters measured. Relative humidity was the only parameter measured but not controlled.

The greenhouse air temperature was maintained using steam heating and a staged ventilation system. The temperature set point was 24 °C between 07:15 and 17:15 hr and 18.8 °C thereafter. Both temperatures were believed to be the optimum temperatures for dry weight production. Forced ramping between day and night temperatures occurred in a time span of 35 minutes. Evaporative cooling pads, along the entire North wall of the greenhouse, were operated during the April and May experiments, as necessary, to maintain temperature. Usually, greenhouse temperatures were maintained within 0.5 °C of the set point temperatures.

High Pressure Sodium (HPS) lamps were used as the supplemental light source in the greenhouse, starting at day 12, to avoid further plant stress during the first day after transplant. The supplemental lighting system installed in each of the five greenhouse sections, was described in detail by Both et al. (1994b). An analysis of 400 Watt HPS luminaires, provided accurate PAR distribution data for the luminaire model (GTE Sylvania, model MGC, 400 Watt HPS) installed in the research greenhouse. The PAR distribution data were used to design a layout of 21 luminaires for each greenhouse section, providing several different, but uniform, PAR intensities ranging between 50 and 230 µmol m^{-2} s^{-1}.

From October 1992, until the end of March 1993, CO_2 was supplemented inside each of the five greenhouse sections. Liquid CO_2 from a bulk container was vaporized, piped into each greenhouse section, and released above the plants through syringe needles stuck in a thin polyethylene tube. The target CO_2 concentration during injection was 1000 ppm. CO_2 injection was stopped whenever venting took place or when no light (sun or supplemental) was available for the plants. After March 1993, CO_2 enrichment was not used due to the frequent venting needed to maintain temperature.

Nutrient Solution: During the first 24 hours in the growth chamber, the seeds were bottom-irrigated with Reverse Osmosis (RO) water. Thereafter, a half-strength nutrient solution (Table 3.2) was used with a pH of 5.8.

The pH and Electrical Conductivity (EC) of the nutrient solution in the greenhouse, were measured twice daily and adjusted manually until mid-March 1993. Thereafter, automatic pH controllers were installed in each of the five greenhouse sections. The nutrient solution pH was controlled at 5.8, the EC at 0.12 S m^{-1}. The pH was adjusted using 0.1 N HNO_3. Plant transpiration after transplant was recorded daily during each of the experiments by measuring the depletion of the nutrient solution volume in the supply tank.

Fresh Weight and Leaf Area: During the December and March experiments, fresh weight and leaf area were measured. In December, on each of the seven harvest days, and in March on five of the seven harvest days, five plants from each section in December and from three sections in March were randomly selected from the troughs that were to be harvested that day. After fresh weight and leaf area were determined, the plants were dried in a drying oven for at least 72 hours at 70 °C and dry weights recorded.

Integrated and Accumulated PAR: Instantaneous PAR readings were taken weekly in the growth chambers, enabling calculation

Table 3.2 Set points for the macro and micro-nutrients of the fertilizer solution, and the amount of salts added to the stock tanks. All set points are for a full strength nutrient solution (the full strength solution was diluted once to get a half strength solution).

Macro-nutrients:				Micro-nutrients:			
N	17.65	mmol l^{-1}	(247 ppm)	Fe	33.54	µmol l^{-1}	(1.87 ppm)
P	2.00	mmol l^{-1}	(62 ppm)	Mn	5.07	µmol l^{-1}	(0.28 ppm)
K	10.99	mmol l^{-1}	(430 ppm)	B	3.00	µmol l^{-1}	(0.03 ppm)
Ca	4.12	mmol l^{-1}	(165 ppm)	Cu	0.75	µmol l^{-1}	(0.05 ppm)
Mg	2.04	mmol l^{-1}	(50 ppm)	Zn	3.83	µmol l^{-1}	(0.25 ppm)
S	2.17	mmol l^{-1}	(70 ppm)	Mo	4.92	µmol l^{-1}	(0.47 ppm)

This system utilized two stock tanks to reduce the possibility of precipitation. The concentrated stock tank solutions were mixed in equal volume parts and diluted 100 times with RO water before being delivered to the plants. The following quantities of soluble fertilizers were incorporated into 30 liters of RO water in each stock tank:

Stock Tank A:			Stock Tank B:		
2916.0	g	$Ca(NO_3)_2$	2037.8	g	KNO_3
613.2	g	KNO_3	816.0	g	KH_2PO_4
84.0	g	NH_4NO_3	738.0	g	$MgSO_4$
56.2	g	Fe-DTPA (10% Fe)	65.5	g	K_2SO_4
			5.580	g	H_3BO_3 (17.5% B)
			3.345	g	$MnSO_4*4H_2O$ (25% Mn)
			2.148	g	$ZnSO_4*H_2O$ (35% Zn)
			0.562	g	$CuSO_4*5H_2O$ (25% Cu)
			0.363	g	$Na_2MoO_4*2H_2O$ (39% Mo)

of daily integrated PAR. In the greenhouse, the PAR was integrated continuously by the control computer in 24 hour cycles (PAR_i), starting at 06:00 hr daily. At the end of each experiment, the daily PAR accumulations were summed to a total PAR accumulation for the treatment (PAR_a). Starting with the March experiment, shading was used in the greenhouse to reduce the amount of solar radiation entering the greenhouse. The shading was needed to enable sufficient use of the supplemental lighting for the various lighting experiments. In March, a shade cloth, shading the South wall and ceiling, was installed in each greenhouse section. During the April and May experiments, layers of white wash were sprayed on the entire outside glass surface of the greenhouse to further reduce the solar radiation.

Tipburn: During the first two experiments (October and November), severe tipburn developed in all treatments except the control; the higher the daily integrated PAR, the more severe the tipburn. The reduced integrated PAR in the December experiment reduced both the dry weight production and the occurrence of tipburn. The work reported by Goto and Takakura (1992), preventing tipburn by blowing air through a thin transparent tube onto the lettuce head, was adapted for this study by hanging a thin and clear polyethylene tube (180 mm diameter) directly over two troughs with lettuce plants. Precisely above the center of each lettuce head in the two troughs, a small hole (10 mm diameter) was punctured in the poly tube. The poly tube was inflated using ambient air supplied by a small fan. The air would exit the poly tube through the holes above the lettuce plants. The maximum air velocity in a jet measured around 5 m s^{-1}. The plants underneath the poly tube did not develop tipburn, while neighboring plants, not receiving any additional air flow, did. This promising result, using the poly tube to prevent tipburn, supported the claims by Goto and Takakura (1992), but a system of poly tubes over an entire crop in a commercial operation was not considered practical. In addition, the poly tube would prevent some of the incoming radiation from reaching the leaves through absorption and reflection, especially after the tube became dirty.

To simplify the adequate air supply to young lettuce leaves, an overhead fan was installed above the benches in each of the five greenhouse sections. The fans, similar to residential ceiling fans, blew ambient air vertically downward onto the lettuce plants. Only one fan per section was installed, making the air distribution over the benches somewhat non-uniform with air velocities over the canopy ranging between 1 and 5 m s^{-1}. Tipburn, however, did not occur, except on most of the guard row plants. Dry weight production was found not to suffer from the additional air movement. Starting with the January experiment, the overhead fans were operational in each greenhouse section. From day 18 onward, the fans were operating 24 hours a day in all but the control section.

Part 2. Growth Modeling

<u>Adjustments to SUCROS87:</u> Adjustments to SUCROS87 were necessary to incorporate the use supplemental lighting in a greenhouse environment. SUCROS87 was written for outdoor crops receiving only solar radiation (i.e., short wave radiation, 280 - 2800 nm). In SUCROS87, straightforward equations are used to determine the position of the sun in the sky for any location on earth and for any time of the day. The amount of daily solar radiation reaching the earth's surface is determined by estimating the amount of cloud cover a location would on average encounter for the day under investigation. From the daily total solar PAR (400 - 700 nm; SUCROS87 assumes 50% of the daily total short wave radiation is PAR), SUCROS87 calculates the instantaneous direct and diffuse radiation at the top of the canopy and at successive leaf layers going down into the canopy. This radiation profile in the canopy enables SUCROS87 to calculate the daily amount of crop photosynthesis (assimilation) and plant dry weight production.

The daily amount of PAR received at the top of the canopy was maintained at a target daily integrated PAR during the experiments by supplementing the available sunlight with supplemental light from HPS luminaires. The amount of supplemental light needed to reach the daily target PAR could be calculated by subtracting the amount of daily solar radiation received from the daily target PAR. The following assumptions were needed to incorporate supplemental lighting in the simulation model:

1. Plant response to supplemental lighting is assumed identical to the response to sunlight (i.e., the plant does not distinguish between supplemental and sunlight),
2. All the light received from HPS luminaires can be considered diffuse light (the luminaires above the canopy act as a large diffuse light source),

3. The supplemental light is only provided to the plants during regular daylight hours,
4. The daily amount of supplemental light needed to reach the target daily integrated PAR (PAR_i) is evenly distributed over the daylight hours, making the instantaneous intensity of the supplemental light dependent of the daylength and the daily amount of supplemental light needed to reach the target PAR_i.

These assumptions will be further discussed in Chapter 5.

SUCROS87 applied a three point Gaussian integration method (Goudriaan, 1986 and Lanczos, 1988) to estimate the daily amount of photosynthesis from the available direct and diffuse radiation and the amount of leaf area present. This method requires the calculation of instantaneous rates of photosynthesis at three specific times during the sunlight hours and at three specific depths in the canopy (from the top of the canopy going downward). However, testing this three-point integration method revealed it was not sufficiently accurate in all possible circumstances. Therefore, in the simulation model LETSGROW.PAS, the three point Gaussian integration method was replaced with a five-point integration method (Goudriaan, personal communication, 1994). Implementation of this change was simple after the proper distance and weighing factors were calculated (Lanczos, 1988).

Table 3.3 illustrates the improved accuracy of the five point Gaussian integration method. The effect of light saturation on the amount of daily assimilation can be bypassed in SUCROS87 by using a large value (1E6) for A_{max} (CO_2 assimilation rate of individual leaves at light saturation). Comparing crops grown in winter and summer time with the same daily integrated PAR (PAR_i), using supplemental lighting in the winter time, reveals the five points integration method calculates a higher daily total gross assimilation (DTGA) on a winter day. On a winter day the solar elevation is low, increasing the extinction coefficient (Kbl) for light penetrating the canopy. The increased extinction coefficient causes light to be absorbed more rapidly in the canopy and the three-point integration method lacks sufficient resolution to accurately calculate the DTGA. An A_{max} of 1E6 on January 15 and July 15 causes the model to calculate different DTGA for both days due to the different transmission of light through the canopy caused by the different solar elevation.

Table 3.3 Daily total gross assimilation (DTGA, in kg CO_2 ha^{-1} d^{-1}) for an A_{max} (CO_2 assimilation rate of individual leaves at light saturation, in kg CO_2 ha^{-1} h^{-1}) of 40 and 1E6 for a winter and a summer day while using the three-point and five-point Gaussian integration method in the original SUCROS87 model.

	January 15		July 15	
A_{max} ----->	40	1E6	40	1E6
3 point	373.1	915.3	661.1	928.3
5 point	379.5	950.1	661.3	929.8

Note: Latitude = 42.3 degrees (Ithaca, NY),
EFF = 0.45 kg CO_2 ha^{-1} h^{-1} per W m^{-2},
LAI = 5 ha ha^{-1},
Kdf = 0.72 ha ha^{-1},
PAR_i = 34 mol m^{-2} d^{-1} (= 8.171505 MJ PAR m^{-2} d^{-1}).

Parameters in SUCROS87: Several parameters are required by SUCROS87 to properly describe the growth of plants. Some of these parameters for lettuce could be estimated based on data reported in the literature. Other parameters were defined using the results from the growth trials conducted for this research. A third group of parameters was described by Spitters et al. (1989) and van Keulen et al. (1982). Each of these important parameters will be discussed in the following paragraphs.

The maximum carbon dioxide assimilation rate of a light saturated leaf (A_{max}) depends on temperature, CO_2 concentration and plant species (Versteeg and van Keulen, 1986). The day and night temperature were kept constant during all experiments (24 °C and 18.8 °C respectively). CO_2 enrichment with a target concentration of 1000 ppm occurred only during the October through March experiments. However, measurements of the actual CO_2 concentration in each of the five greenhouse sections were not very accurate due to infrequent calibration of the equipment. In order to estimate the CO_2 concentration in each greenhouse section during the experiments, the following assumptions were made:

1. At low daily integrated PAR (7 mol m^{-2} d^{-1}), little supplemental lighting was needed and thus little extra heat from the supplemental lighting system (a total of twenty 400 Watt HPS luminaires releasing 5.8 kW in radiant energy in each section, Both et al., 1994b) was released in the greenhouse, limiting the amount of venting needed to maintain the temperature set point. The low ventilation rate enabled a sustained maximum CO_2 concentration of 1000 ppm during the light period.
2. At high daily integrated PAR (22 mol m^{-2} d^{-1}), supplemental lighting was needed for a large number of hours. This resulted in a relatively large amount of heat from the supplemental lighting system being released into the greenhouse sections. Thus, more frequent venting was needed to maintain the temperature set point. This higher ventilation rate caused the CO_2 concentration to drop to an ambient level of 350 ppm during the light period.
3. For daily integrated PAR between 7 and 22 mol m^{-2} d^{-1}, a linear interpolation can be used to find the CO_2 concentration maintained in the greenhouse during the light period.

According to Goudriaan (personal communication, 1994) the value of A_{max} at a CO_2 concentration of 1000 ppm can be set at 50 kg CO_2 ha^{-1} h^{-1}. For an ambient CO_2 concentration (350 ppm) the value of A_{max} drops to 40 kg CO_2 ha^{-1} h^{-1}. Therefore, in the simulation model LETSGROW.PAS, the value of A_{max} is dependent upon the daily integrated PAR (PAR_i) received by the plants. For PAR_i = 7 mol m^{-2} d^{-1} A_{max} is set at 50 kg CO_2 ha^{-1} h^{-1} and for PAR_i = 22 mol m^{-2} d^{-1} A_{max} is set at 40 kg CO_2 ha^{-1} h^{-1}. For PAR_i between 7 and 22 mol m^{-2} d^{-1} A_{max} is calculated through linear interpolation.

A similar approach was followed for the light use efficiency of absorbed visible radiation for carbon dioxide assimilation at low light levels (or the initial slope of the photosynthesis-light response curve), EFF. For an ambient CO_2 concentration, a value of 0.45 kg ha^{-1} h^{-1} per W m^{-2} for EFF was used by Spitters et al., 1989. For a CO_2 concentration of 1000 ppm the value of

EFF can be calculated through the following equation (Goudriaan, personal communication, 1994):

$$EFF = 0.6 * (C - \Gamma)/(C + 2*\Gamma) \qquad (3.1)$$

where:

EFF = the light use efficiency of absorbed visible radiation for carbon dioxide assimilation at low light levels in kg ha^{-1} h^{-1} per W m^{-2},
C = CO_2 concentration in ppm,
Γ = CO_2 compensation point (around 50 ppm).

For a CO_2 concentration of 1000 ppm, EFF becomes 0.52 kg ha^{-1} h^{-1} per W m^{-2} (equation 3.1). Following the same assumptions used for the determination of A_{max}, EFF was assumed to be a function of PAR_i for the current experiments. A linear interpolation was used to determine the value of EFF for treatments with a PAR_i between 7 and 22 mol m^{-2} d^{-1}.

The percentage of daily solar total irradiance (short wave, 280 - 2800 nm) in the PAR waveband (400 - 700 nm) fluctuates with the amount of cloud cover in the sky (Goudriaan, personal communication, 1994). For sunny days this percentage can be estimated at 50%, but for very cloudy days this value can increase to 60%. In the simulation model LETSGROW.PAS, this percentage is assumed to be dependent upon PAR_i: a very cloudy day was assumed to receive 7 mol m^{-2} d^{-1} and a clear day 22 mol m^{-2} d^{-1}. The percentage of the daily total irradiance in the PAR waveband was calculated for any PAR_i between 7 and 22 mol m^{-2} d^{-1} through a linear interpolation.

The following calculation of ATMTR (atmospheric transmission coefficient for sunlight) and FRDF (fraction of sunlight reaching the earth's surface as diffuse light) is different from the calculation found in SUCROS87. This new calculation method was provided by J. Goudriaan (personal communication, 1994) and is an update of the method used in SUCROS87. The new calculation method (in Pascal statements) is:

```
ATMTR:=DTR*SINB*(1+0.4*SINB)/(SC*SINB);
IF (ATMTR <= 0.22) THEN
     FRDF:=1.0
```

```
ELSE
BEGIN
    IF (ATMTR > 0.22) AND (ATMTR <= 0.35) THEN
      FRDF:=1-6.4*(ATMTR-0.22)*(ATMTR-0.22)
    ELSE
      FRDF:=1.47-1.66*ATMTR
END;
FRDF:=MAXIMUM(FRDF,0.15+0.85*(1-EXP(-0.1/SINB));
```

where:

DTR = daily total solar radiation (short wave, 280-2800 nm) in J m^{-2} d^{-1},

SINB = sine of the solar elevation [-],

SC = solar constant at the top of the atmosphere and corrected for the varying earth-sun distance in W m^{-2},

MAXIMUM = function determining the maximum of two values.

The ratio of accumulated leaf area to shoot dry weight, LAR in ha of leaf per kg dry weight, was derived from measurements conducted during the December and March experiments. These measurements are described in more detail in Chapter 4. The measurements included fresh and dry weight of lettuce heads and total leaf area. Regression analysis of the relationship between fresh and dry weight and between fresh weight and leaf area resulted in two equations (equations 4.6 and 4.7) describing these relationships. Combining these two equations into one gives the following equation for the leaf area ratio (LAR):

$$LAR = 1E-5 * (23.9/DW + 615.4 - 24.1*DW) \qquad (3.2)$$

where:

LAR = leaf area ratio [ha kg^{-1}],

DW = shoot dry weight in grams per head.

The fraction of total plant dry weight allocated to the roots (FRT, root dry weight divided by total plant dry weight) for hydroponic lettuce plants was estimated from data reported in the literature (Wheeler et al., 1994) because no root dry weight measurements were performed. The values of FRT used in the simulation model are listed in Table 3.4. A linear interpolation was used to calculate FRT for days falling between the days listed in Table 3.4.

Table 3.4 The fraction of total plant dry weight allocated to the roots (FRT) used in the simulation model.

Days since seeding	FRT [kg/kg]
11	0.31
14	0.21
21	0.14
28	0.06
35	0.05

The assimilate requirement for dry matter conversion, ASRQ in kg CH_2O per kg dry matter, or the inverse of the conversion efficiency for dry matter from carbohydrates, was defined and adjusted for lettuce as (Spitters et al., 1989):

$$ASRQ = 1.46 * (1 - FRT) + 1.44 * FRT, \qquad (3.3)$$

where:

FRT = fraction of the total plant dry weight allocated to the roots.

Typical values for the maintenance requirements of root and shoot tissues are 3% and 1.5% of the root and shoot dry weights respectively as derived by Penning de Vries and van Laar (1982) and used by Spitters et al. in SUCROS87. As reported by Penning de Vries and van Laar, the maintenance requirement increases with every 10 °C temperature rise above a reference temperature of 25 °C (for plant species from temperate climates) according to the equation:

$$Q_{10} = 2^{(0.1 * T - 2.5)}, \qquad (3.4)$$

where:

T = weighted average of day and night temperature [°C].

Two parameters were kept constant during the calculations with the model. The canopy scattering coefficient for PAR (SCP) was set at 0.2 and the extinction coefficient for diffuse PAR (k_{df}) was set at 0.72 (Spitters et al., 1989).

In this study, the daily total radiation (a combination of sun and supplemental light) received by the canopy was measured in the unit mol m^{-2} d^{-1} (PAR_i). However, in the simulation program LETSGROW.PAS (as in SUCROS87) the unit MJ m^{-2} d^{-1} is used. To convert the measurements from mol m^{-2} d^{-1} (PAR, 400 - 700 nm) to MJ m^{-2} d^{-1} (short wave radiation, 280 - 2800 nm) a conversion factor of 1/2.0804 was reported by Ting and Giacomelli (1987). This conversion factor was calculated from two sets of measurements of solar radiation, one in each unit. However, in LETSGROW.PAS daily total radiation is expressed in PAR and not in short wave radiation. In this study, the assumption was made half of the energy in the short wave radiation falls in the PAR waveband for a combination of sun and supplemental light. Therefore, to convert the daily PAR_i measured in mol m^{-2} d^{-1} to MJ m^{-2} d^{-1} of PAR, a conversion factor of 0.5*(1/2.0804) = 0.2403 was used in this study.

<u>Overview of the simulation model:</u> The computer simulation program LETSGROW.PAS consists of three parts:

A. Initialization (prepare for the simulation)
B. Simulation calculations (based on SUCROS87)
C. Output (screen graphics)

Each part consists of various procedures and calls to procedures. The three parts and the procedures they contain are listed below and a short description of the function of each procedure is given. The complete computer code of the simulation program LETSGROW.PAS is listed in Appendix C.

<u>A. Initialization:</u>

1. procedure Initialize
   Assigns values to constants and initial values to parameters.
2. procedure Read_weather_data
   Reads hourly average solar radiation data for a whole year for Ithaca, NY from the input file SolRad.DAT.
3. procedure Cal_daily_sol_rad
   Calculates solar radiation outside the greenhouse for each day of the year for Ithaca, NY.

4. procedure Cal_daily_FRT
   Calculates the fraction of the total plant dry weight allocated to the roots for each of the 24 days the plants remain in the greenhouse.
5. procedure Respace
   Calculates the new plant weight per unit growing area immediately after respacing took place.
6. procedure Cal_daily_solar_radiation_parameters
   Calculates the daylength, solar constant and the daily integral of the sine of the solar elevation.
7. procedure Cal_daily_PAR_and_fractions_solar_and_supplemental_PAR
   Calculates the daily PAR received from sunlight and supplemental light from the total daily PAR received in the greenhouse.
8. procedure Cal_above_canopy_radiation
   Calculates the instantaneous direct and diffuse PAR from sunlight and supplemental light just above the canopy at a specified time of the day.
9. procedure Cal_canopy_radiation_profile
   Calculates the instantaneous absorbed radiation at a specific depth in the canopy and at a specified time of the day.
10. procedure Cal_daily_assimilation
    Calculates the potential daily assimilation from sunlight using the Gaussian integration method. This procedure calls procedures 6, 7, 8 and 9.
11. procedure Input_crop_and_temperature_data
    Shows a sub-menu to the user when the user requests to change one or more of seven crop and temperature data.
12. procedure Prepare_output
    Prepares the output file LETSGROW.DAT which will be filled with the simulated dry weight data.
13. procedure Output_data
    Writes the simulated dry weight data to the output file LETSGROW.DAT and to an array used for presenting the dry weight data in a graph on the screen.
14. procedure Main_menu
    Shows the main menu to the user and, if requested by the user, calls procedure 13.
15. procedure Fill_array

Fills an array with the dry weight data calculated with the reference equation (general curve fit) representing the dry weight accumulation.

16. procedure Draw_grid
    Draws the axes, tic marks and horizontal grid lines for the graph on the computer screen.
17. procedure Axes_scales
    Determines the minimum and maximum value along the x and y axes.
18. procedure Label_axes
    Labels the axes of the graph on the computer screen.
19. procedure Plot_curve
    Draws the simulated and the reference growth curves in the graph on the computer screen.

REPEAT (start of the loop)

B. Simulation Calculations:

20. Call procedures 1, 2, 3, 4, 12 and 14 (preparation for the simulation).
21. Calculate the dry weight accumulation from transplant day to the day of respacing:
    21.1 Call procedure 10 (simulate daily dry weight production),
    21.2 Call procedure 13 (write results to output file).
22. Respace: call procedure 5.
23. Calculate the dry weight accumulation from the day of respacing to the day of final harvest:
    23.1 Call procedure 10 (simulate daily dry weight production),
    23.2 Call procedure 13 (write results to output file).

C. Output:

24. Call procedure 15 (calculate reference growth curve).
25. Call procedures 16, 17, 18 and 19 (screen output).

UNTIL the users stops the program (end of the loop).

Chapter 4

Results

Similar to the previous chapter, this chapter is divided into two parts, one part describing the results of supplemental lighting experiments and the other describing the testing of and modeling with a growth model.

Part 1. Supplemental Lighting Experiments

Dry Weight Measurements: The growth chamber dry weight measurements and transplant dates for each of the eight experiments are shown in Table 4.1. Table 4.2 contains average dry weight data on each of the harvest days for each of the 35 treatments. Some dry weight data are missing from Table 4.2, due to various technical problems. During harvest six of the November experiment, a computer malfunction occurred while weighing, destroying some data. The treatment in section B of the December experiment was canceled because an accidental low pH destroyed most of the plant roots. Harvest four of the March experiment could not be performed because a major blizzard ("The Storm of the Century!") prevented the harvest crew from reaching the greenhouse.

The dry weight measurements of each of the 35 treatments were fitted with a second order exponential polynomial of the form:

$$DW = \exp(a + b * DAY + c * DAY^2), \qquad (4.1)$$

where:

DW = shoot dry weight in grams per head,
DAY = number of days after seeding,
a, b, c = coefficients.

For each treatment, the coefficients a, b and c were determined and are listed in Table 4.3. Plotting the dry weight data and the fitted curves in the same graph for each treatment, revealed a near perfect fit with r^2 values of at least 0.99.

Table 4.1 Average dry weight data in grams per head from the growth chambers at 7 and 11 days after seeding, and the transplant date which occurred 11 days after seeding.

	Day 7	Day 11	Transplant Date
Oct	0.0073	0.0347	9/28/1992
Nov	0.0062	0.0322	10/26/1992
Dec	0.0076	0.0371	11/23/1992
Jan	0.0088	0.0396	1/4/1993
Feb	0.0065	0.0308	2/1/1993
Mar	0.0088	0.0402	3/1/1993
Apr	0.0080	0.0388	3/29/1993
May	0.0093	0.0453	4/26/1993

Table 4.2 Average dry weight data for each experiment in grams per head. The days after seeding are listed horizontally, and the treatments (sections A through E) are listed in the first column.

	Day 14	Day 18	Day 21	Day 25	Day 28	Day 32	Day 35
Oct A	0.131	0.658	1.32	2.76	3.97	6.04	6.95
Oct B	0.135	0.703	1.48	3.36	4.78	7.08	7.84
Oct C	0.115	0.427	1.02	2.21	3.39	5.02	5.93
Oct D	0.103	0.325	0.91	1.65	2.54	3.88	4.80
Oct E	0.096	0.329	0.76	1.46	2.32	3.09	3.43
Nov A	0.061	0.169	0.48	1.54	2.52	-	5.12
Nov B	0.064	0.153	0.30	0.76	1.01	-	2.46
Nov C	0.061	0.193	0.38	1.11	1.85	-	4.30
Nov D	0.064	0.213	0.55	1.97	3.20	5.04	6.35
Nov E	0.065	0.263	0.67	2.11	3.22	5.53	6.79
Dec A	0.095	0.385	0.80	1.92	3.05	4.38	5.33
Dec B	-	-	-	-	-	-	-
Dec C	0.060	0.131	0.22	0.46	0.82	1.25	1.72
Dec D	0.132	0.495	1.02	2.34	3.58	5.29	5.96
Dec E	0.076	0.264	0.50	1.24	2.38	3.51	4.61
Jan A	0.063	0.141	0.20	0.44	0.84	1.20	1.87
Jan B	0.117	0.407	0.88	1.81	3.09	4.56	5.04
Jan C	0.095	0.258	0.50	1.10	1.91	2.82	3.50
Jan D	0.069	0.342	0.75	1.88	2.83	4.36	5.03
Jan E	0.074	0.250	0.50	1.20	2.04	2.83	3.60
Feb A	0.074	0.251	0.51	1.29	2.22	3.63	5.09
Feb B	0.089	0.342	0.73	1.84	3.12	4.44	6.24
Feb C	0.099	0.408	0.87	2.24	3.77	5.15	7.26
Feb D	0.085	0.288	0.53	1.21	1.98	3.15	4.81
Feb E	0.089	0.345	0.77	2.16	3.50	5.61	7.04
Mar A	0.135	0.681	1.44	-	4.97	6.58	7.81
Mar B	0.130	0.663	1.34	-	4.63	6.16	7.67
Mar C	0.131	0.677	1.39	-	5.31	7.33	8.60
Mar D	0.106	0.511	1.12	-	4.34	5.94	7.27
Mar E	0.102	0.273	0.50	-	2.08	3.16	4.22
Apr B	0.088	0.267	0.67	1.31	2.00	3.08	3.59
Apr C	0.086	0.256	0.61	1.27	1.98	3.02	3.80
Apr D	0.089	0.318	0.72	1.37	2.15	3.10	3.76
May B	0.121	0.503	0.92	2.18	3.23	4.66	5.57
May C	0.128	0.562	1.01	2.39	3.56	4.84	5.71
May D	0.135	0.594	1.12	2.57	3.93	5.05	6.83

Table 4.3 Coefficients a, b and c for the second order exponential polynomial (Equation 4.1) predicting the dry weight accumulation of leaf lettuce from 7 to 35 days after seeding, and the time at which the maximum growth rate (DAY_{max}) occurred in days after seeding. The treatments (sections A through E) are listed in the first column.

	a	b	c	DAY_{max}
Oct A	-6.9549	0.4766	-0.00635	28.7
Oct B	-7.5668	0.5355	-0.00744	27.8
Oct C	-7.6727	0.5081	-0.00680	28.8
Oct D	-6.8700	0.4299	-0.00540	30.2
Oct E	-8.1543	0.5294	-0.00747	27.3
Nov A	-10.6296	0.6647	-0.00898	29.5
Nov B	-6.7032	0.3392	-0.00349	36.6
Nov C	-9.1915	0.5356	-0.00661	31.8
Nov D	-9.6021	0.6115	-0.00813	29.8
Nov E	-9.4412	0.6030	-0.00796	30.0
Dec A	-7.9206	0.5132	-0.00684	29.0
Dec B	-	-	-	-
Dec C	-7.3024	0.3617	-0.00393	34.7
Dec D	-8.2149	0.5532	-0.00764	28.1
Dec E	-8.7099	0.5276	-0.00672	30.6
Jan A	-6.0356	0.2631	-0.00209	47.5
Jan B	-9.1130	0.6005	-0.00839	28.1
Jan C	-8.2583	0.4966	-0.00643	29.8
Jan D	-8.7127	0.5647	-0.00770	28.6
Jan E	-8.1022	0.4920	-0.00641	29.5
Feb A	-7.4882	0.4317	-0.00490	33.9
Feb B	-6.7908	0.4177	-0.00491	32.4
Feb C	-6.5823	0.4191	-0.00500	31.9
Feb D	-5.6181	0.2944	-0.00255	43.7
Feb E	-8.6394	0.5556	-0.00723	30.1
Mar A	-7.2356	0.5104	-0.00701	28.0
Mar B	-6.7461	0.4664	-0.00617	28.8
Mar C	-7.8469	0.5518	-0.00761	28.1
Mar D	-7.7237	0.5245	-0.00707	28.7
Mar E	-7.4974	0.4408	-0.00531	31.8
Apr B	-7.8799	0.4872	-0.00644	29.0
Apr C	-7.3768	0.4425	-0.00554	30.4
Apr D	-7.1902	0.4449	-0.00576	29.3
May B	-7.2814	0.4807	-0.00639	28.8
May C	-7.2896	0.4934	-0.00673	28.0
May D	-5.9007	0.3937	-0.00488	30.2

Table 4.4 Grouping of the experimental treatments according to the amount of average daily integrated PAR received by the plants (in parenthesis).

Group $mol\ m^{-2}\ d^{-1}$	Interval $mol\ m^{-2}\ d^{-1}$	Treatment ($mol\ m^{-2}\ d^{-1}$)
4	3.6 - 4.5	Dec C (3.8)
5	4.6 - 5.5	Jan A (4.7)
6	5.6 - 6.5	Nov B (6.2)
7	6.6 - 7.5	Dec E (7.2), Jan E (7.3)
8	7.6 - 8.5	Jan C (8.2), Apr B (8.5)
9	8.6 - 9.5	Apr D (8.8), Apr C (9.2)
10	9.6 - 10.5	Mar E (9.6), Nov C (9.6), Oct E (10.1), Feb D (10.5)
11	10.6 - 11.5	Oct D (11.4), Jan D (11.3)
12	11.6 - 12.5	Dec A (11.9), Feb B (12.5)
13	12.6 - 13.5	Nov A (12.6), Jan B (12.8)
14	13.6 - 14.5	May B (13.8), Feb A (14.1)
15	14.6 - 15.5	Oct C (15.2), Dec D (15.1), Mar B (15.5)
16	15.6 - 16.5	May C (15.6), May D (15.9), Nov D (16.4)
17	16.6 - 17.5	Feb C (17.1), Mar D (17.3)
18	17.6 - 18.5	Feb E (17.7)
19	18.6 - 19.5	Oct A (18.9)
20	19.6 - 20.5	Nov E (19.8), Mar A (20.4)
21	20.6 - 21.5	-
22	21.6 - 22.5	Mar C (21.6), Oct B (22.4)

Next, supplemental lighting treatments with comparable daily integrated PAR were grouped, as if the entire group received the same daily integrated PAR (the rounded numbers in the first column of Table 4.4). For each group an average growth curve was determined by averaging the dry weights of the treatments within a group and calculating a curve fit for the averaged data. Plant (shoot) growth rate (dW/dt), or the change in dry weight over time, was found from the first derivative of equation 4.1:

$$dW/dt = \exp(a + b*DAY + c*DAY^2) * (b + 2*c*DAY), \quad (4.2)$$

where:

dW/dt = plant (shoot) growth rate in grams day^{-1},
DAY = number of days after seeding,
a, b, c = coefficients.

The time at which the maximum growth rate occurred during the 35 day growing period (DAY_{max}), was found by setting the second derivative of equation 4.1 to zero. This resulted in the equation:

$$DAY_{max} = [-b + \sqrt{(-2 * c)}]/(2 * c), \qquad (4.3)$$

where:
DAY_{max} = day at which the maximum growth rate occurred,
b, c = coefficients.

DAY_{max} was calculated for each treatment and the values are listed in Table 4.3. For all but two treatments (February A and B treatments), the maximum growth rate (dW/dt_{max}) occurred at 30 ± 2 days after seeding, except for most control treatments where the plants were still growing exponentially at the final harvest day. The correlation between the maximum growth rate in grams day^{-1} (dW/dt_{max}) and the daily integrated PAR in mol m^{-2} d^{-1} (PAR_i) can be described by the equation (Figure 4.1):

$$dW/dt_{max} = 0.111 + 0.0231 * PAR_i, \quad r^2 = 0.85, \qquad (4.4)$$

where,
dW/dt_{max} = maximum growth rate in grams day^{-1},
PAR_i = daily integrated PAR in mol m^{-2} d^{-1}.

The values of coefficients a, b and c (Table 4.3 and equation 4.1) were studied for trends indicating a relationship between the values of the coefficients and the daily integrated PAR (PAR_i) used in different treatments. The values of the coefficients b and c for PAR_i treatments between 7 and 22 mol m^{-2} d^{-1} were averaged and their average values were 0.4822 and -0.006225 respectively. The value of coefficient a was (arbitrarily) assumed dependent on PAR_i. A linear equation was found to describe this relationship:

$$a = -8.426 + 0.0593 * PAR_i, \quad r^2 = 0.99, \qquad (4.5)$$

where:
a = coefficient,
PAR_i = average daily integrated PAR in mol m^{-2} d^{-1}.

Following this procedure, it was possible to calculate the growth curve for any supplemental lighting experiment, based on:

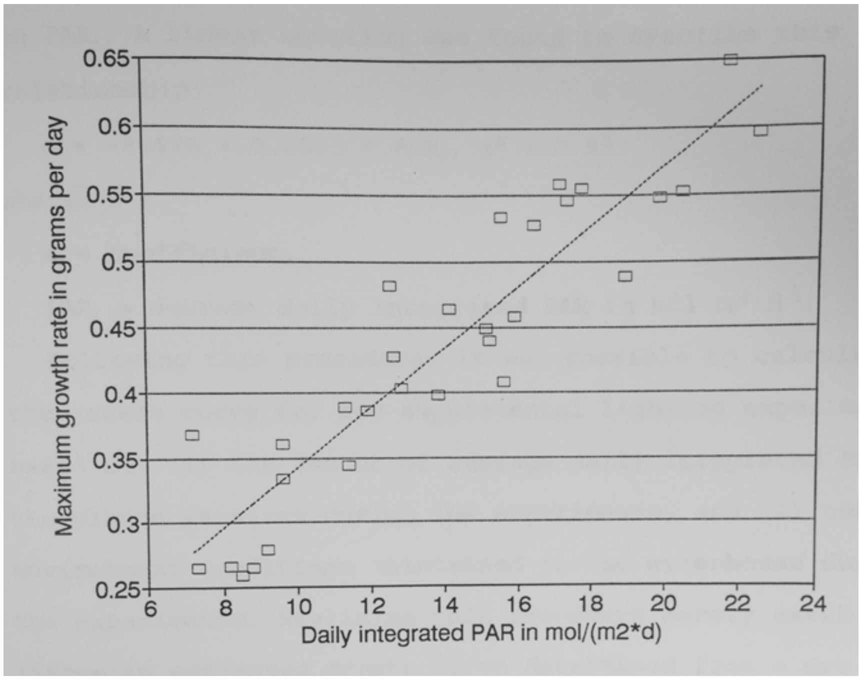

Figure 4.1 Maximum growth rate (dW/dt_{max}) versus daily integrated PAR (PAR_i).

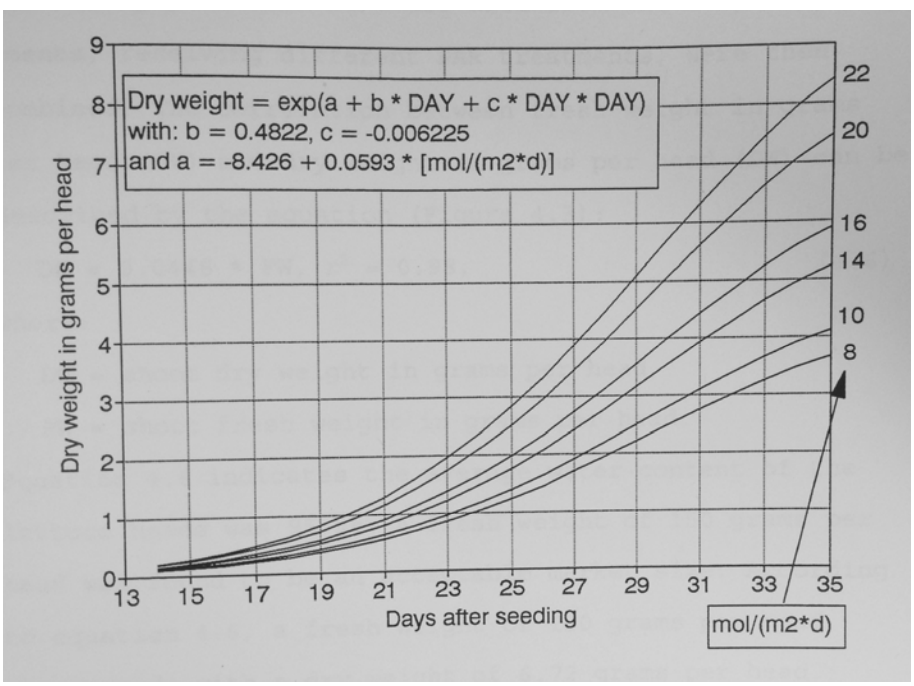

Figure 4.2 Fitted growth curves for different values of the daily integrated PAR (PAR_i).

(1) the amount of average daily integrated PAR the plants received during the experiments, and (2) the environment conditions maintained in the greenhouse during the experiments. Realizing this procedure merely establishes an ***estimated*** growth curve determined from a projected amount of PAR_i, these growth curves, showing a steady pattern, are summarized in Figure 4.2.

It was the general equation for the average growth curve, the curve with only the average daily integrated PAR as unknown, which was used in the program LETSGROW.PAS to determine the accuracy of the algorithm used in that program. In other words, it was used as the reference growth curve.

Fresh Weight and Leaf Area Measurements: Fresh weight, leaf area and dry weight data were only collected during the December and March experiments. During each harvest, measurements were performed on five plants and the data was averaged (Table 4.5). All data from these two experiments, receiving different PAR treatments, were then combined. The correlation between fresh weight in grams per head (FW) and dry weight in grams per head (DW) can be described by the equation (Figure 4.3):

$$DW = 0.0448 * FW, \quad r^2 = 0.98, \qquad (4.6)$$

where:
DW = shoot dry weight in grams per head,
FW = shoot fresh weight in grams per head.

Equation 4.6 indicates the average water content of the lettuce heads was 95.5%. A fresh weight of 150 grams per head was found to be an acceptable market size. According to equation 4.6, a fresh weight of 150 grams per head corresponds with a dry weight of 6.72 grams per head. Therefore, production of acceptable size lettuce heads in the experimental setup used for this research, required a dry weight production of 6.72 grams in 35 days.

The correlation between fresh weight in grams per head (FW) and leaf area in cm^2 per head (LA) can be described by the equation (Figure 4.4):

$$LA = 23.89 + 27.57*FW - 0.04834*FW^2, \quad r^2 = 0.98, \qquad (4.7)$$

where:

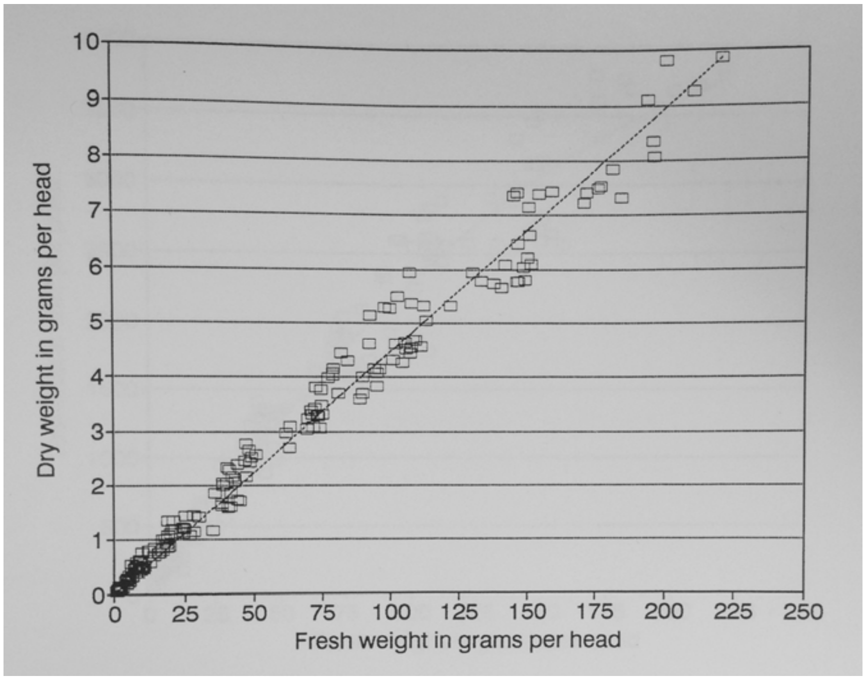

Figure 4.3 Leaf dry weight (DW) versus leaf fresh weight (FW).

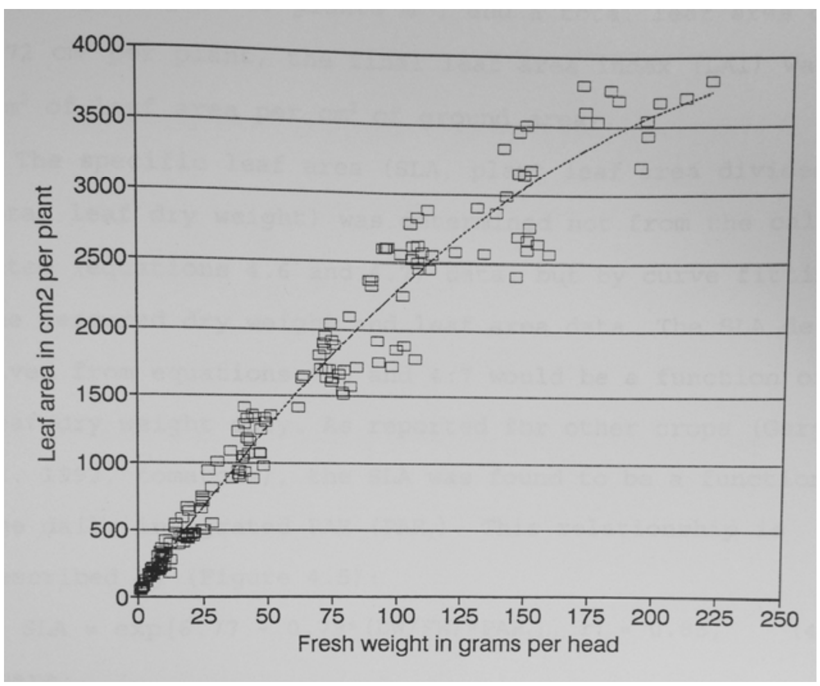

Figure 4.4 Leaf area (LA) versus leaf fresh weight (FW).

Table 4.5 Fresh weight (FW, in grams per head), leaf area (LA, in cm^2), and dry weight (DW, in grams per head) for several treatments during the December and March experiments. Each value is the average of measurements on five plants. The harvest days are listed at the top of the table.

	Day 14	Day 18	Day 21	Day 25	Day 28	Day 32	Day 35
Dec A							
FW	1.60	6.46	17.22	39.40	68.12	106.18	134.56
LA	56.7	196.3	449.4	952.4	1637.4	2460.4	3036.6
DW	0.10	0.41	0.83	2.07	3.20	4.64	5.54
Dec C							
FW	1.34	3.10	5.00	9.00	16.72	30.74	42.12
LA	50.8	111.1	192.7	355.5	595.9	1010.2	1347.5
DW	0.06	0.13	0.21	0.43	0.66	1.30	1.64
Dec D							
FW	2.08	8.08	19.30	43.50	75.52	116.80	157.24
LA	74.8	212.4	462.4	959.7	1616.4	2624.1	3501.0
DW	0.13	0.51	1.08	2.40	3.82	5.40	6.45
Dec E							
FW	1.42	5.30	10.48	24.98	46.20	75.50	97.34
LA	51.9	171.2	334.6	729.5	1246.0	2023.8	2539.8
DW	0.07	0.28	0.50	1.24	2.39	3.41	4.15
Mar C							
FW	-	10.72	23.40	-	99.78	150.84	201.93
LA	-	228.1	491.5	-	1801.2	2570.7	3563.8
DW	-	0.72	1.28	-	5.44	7.35	9.70
Mar D							
FW	-	7.64	19.58	-	83.24	146.28	189.26
LA	-	197.1	448.8	-	1685.3	2759.4	3627.1
DW	-	0.53	1.10	-	4.19	6.23	8.00
Mar E							
FW	-	4.80	8.80	-	42.52	72.62	98.64
LA	-	155.2	282.7	-	1142.7	1867.9	2648.1
DW	-	0.27	0.43	-	2.05	3.16	4.09

LA = plant leaf area in cm^2 per plant,
FW = shoot fresh weight in grams per head.

Producing 150 grams (FW) lettuce heads in 35 days would result in a total leaf area of 3072 cm^2 per plant. At the final spacing of 39 plants m^{-2}, and a total leaf area of 3072 cm^2 per plant, the final leaf area index (LAI) was 12 (cm^2 of leaf area per cm^2 of ground area).

The specific leaf area (SLA, plant leaf area divided by total leaf dry weight) was determined not from the calculated (equations 4.6 and 4.7) data, but by curve fitting the measured dry weight and leaf area data. The SLA derived from equations 4.6 and 4.7 would be a function of leaf dry weight only. As reported for other crops (Gary et al. 1993, tomatoes), the SLA was found to be a function of the daily integrated PAR (PAR_i). This relationship is described by (Figure 4.5):

$$SLA = \exp[6.77 - 0.79*(DW/FW)*PAR_i], \quad r^2 = 0.85, \qquad (4.8)$$

where:

SLA = plant leaf area divided by shoot dry weight in cm^2 $gram^{-1}$,
DW = shoot dry weight in grams per head,
FW = shoot fresh weight in grams per head,
PAR_i = daily integrated PAR in mol m^{-2} d^{-1}.

PAR Measurements: Before transplant, the seedlings received, on average, 231 mol m^{-2} PAR in the growth chamber over 11 days. Daily integrated PAR measurements were collected inside and outside the greenhouse. Table 4.6 shows the monthly averages of daily outside PAR measurements during the experiments and compares them to historical, nine-year average, data. From the inside and outside PAR measurements, it was possible to calculate the greenhouse cover transmission loss. Additional transmission loss during the March through May experiments, due to the use of the shading cloth and additional layers of white wash, is also reported in Table 4.6.

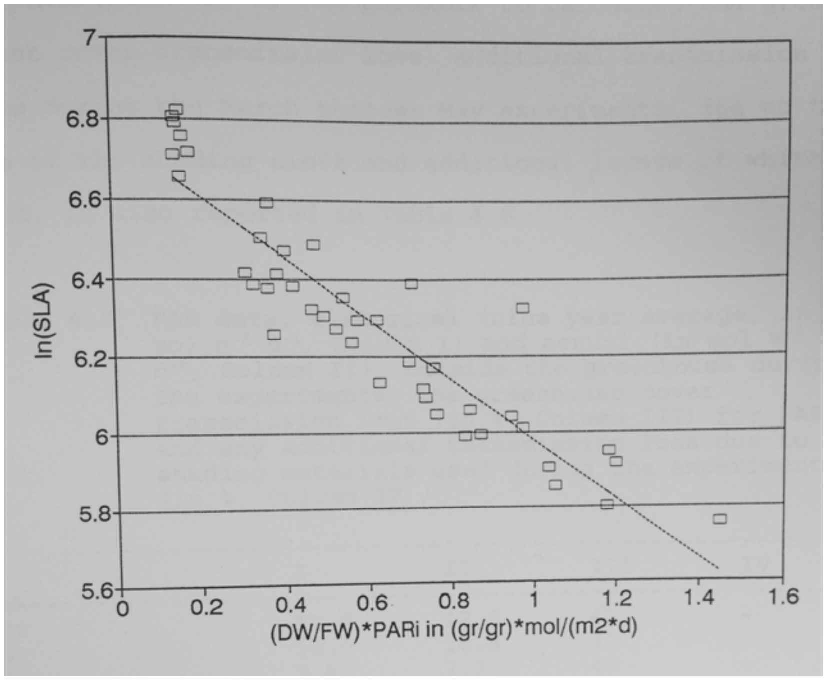

Figure 4.5 Correlation graph to determine the specific leaf area (SLA).

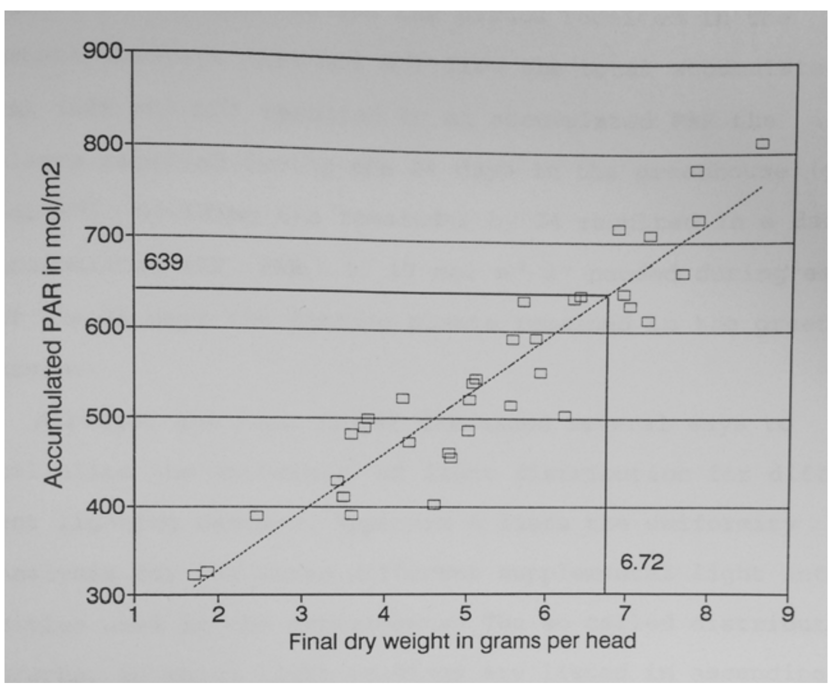

Figure 4.6 Total accumulated PAR(PAR_a) versus final dry weight at day 35 (DW_f).

Table 4.6 PAR data, historical (nine-year average, in mol m^{-2} d^{-1}, Column I) and actual (in mol m^{-2} d^{-1}, Column II), outside the greenhouse during the experiments, the greenhouse cover transmission loss (in %, Column III) for PAR, and any additional transmission loss due to shading materials used during the experiments (in %, Column IV).

	I	II	III	IV
Oct	18.0	17.6	43	-
Nov	10.0	10.5	41	-
Dec	7.8	7.5	49	-
Jan	10.4	8.1	43	-
Feb	15.6	19.2	40	-
Mar	24.3	23.2	42	10
Apr	29.3	24.6	42	30
May	36.2	39.8	44	28

Table 4.7 lists start times for all supplemental lighting treatments and the measured amounts of average daily integrated PAR. The correlation between total accumulated PAR level in mol m^{-2} (Table 4.7; PAR_a) and final dry weight in grams per head (at day 35; DW_f) for all treatments can be described by the equation (Figure 4.6):

$$PAR_a = 195.88 + 65.92 * DW_f,\ r^2 = 0.87, \qquad (4.9)$$

where:

PARa = total accumulated PAR over 35 days in mol m^{-2},

DWf = final shoot dry weight at day 35 in grams per head.

Table 4.7 Start time for the supplemental lighting (military time, in hour, Row I), average daily actual integrated PAR (PAR_i, for day 11 to day 35, in mol m^{-2} d^{-1}, Row II), and the total accumulated PAR from day 0 to day 35 (PAR_a in mol m^{-2}, Row III).

	A	B	C	D	E
Oct I	09:00	06:00	12:00	18:00	Control
Oct II	18.9	22.4	15.2	11.4	10.1
Oct III	641.6	726.0	552.1	460.8	428.8
Nov I	12:00	Control	18:00	09:00	06:00
Nov II	12.6	6.2	9.6	16.4	19.8
Nov III	544.4	389.6	472.7	636.0	715.9
Dec I	14:00	16:00	Control	12:00	18:00
Dec II	11.9	canceled	3.8	15.1	7.2
Dec III	514.8	-	321.9	592.1	402.4
Jan I	Control	07:00	12:00	18:00	22:00
Jan II	4.7	12.8	8.2	11.3	7.3
Jan III	325.5	521.3	411.1	486.2	389.7
Feb I	10:00	18:00	15:00	Control	06:00
Feb II	14.1	12.5	17.1	10.5	17.7
Feb III	540.5	502.9	613.1	454.8	628.9
Mar I	12:00	18:00	06:00	09:00	Control
Mar II	20.4	15.5	21.6	17.3	9.6
Mar III	781.3	665.7	811.7	708.3	522.4
Apr I	---	21:00	00:00	21:00	---
Apr II		8.5	9.2	8.8	
Apr III		481.6	498.6	489.4	
May I	---	20:00	21:00	21:00	---
May II		13.8	15.6	15.9	
May III		591.0	633.7	640.0	

According to equations 4.3 and 4.5, the total accumulated PAR (PAR_a) required to grow 150 grams (FW) lettuce heads in 35 days was 639 mol m^{-2} (using the environment conditions maintained during this study). Subtracting the amount of accumulated PAR the plants received in the growth chambers (231 mol m^{-2}) from the total accumulated PAR (639 mol m^{-2}) resulted in an accumulated PAR the plants received during the 24 days in the greenhouse (408 mol m^{-2}). Dividing the remainder by 24 resulted in a daily accumulated PAR (PAR_i) of 17 mol m^{-2} d^{-1} needed during each of the 24 days the lettuce plants remained in the greenhouse.

Albright and Both (1994) discussed several ways to calculate the uniformity of light distribution for different lighting designs. Appendix A lists the uniformity analysis for the three different supplemental light intensities used in the experiments. The so-called distribution graphs, in which light readings are listed in ascending order, are shown in Figures A.1, A.2 and A.3. The described uniformity coefficients together with distribution graphs give an accurate assessment of the uniformity of a light distribution over a growing area. Despite high Uniformity Coefficients for all three supplemental light intensities (around 0.90), the fraction of the PAR intensities over the growing area within ± 15% of the average PAR intensity varied between 0.73 and 0.79 during different PAR intensity treatments. Ideally the value of this fraction should be close to 1 according to newly proposed guidelines for the design of lighting systems in research greenhouses (International Lighting for Plants in Controlled Environments Workshop. University of Wisconsin, Madison, WI. March 27-30, 1994).

Transpiration: Table 4.8 shows the accumulated water loss data on each of the harvest days for each of the 35 treatments. No water loss data were recorded on the transplant (day 11) and the final harvest day (day 35). The total accumulated water loss is therefore calculated as the water loss at day 34.

The use of an overhead fan to reduce tipburn by increasing the transpiration, made it necessary to separate the treatments in two groups. One group received no additional air supply from an overhead fan (W/O FAN treatments, October through December, 1992). The other group was exposed to additional air supply from an overhead fan (W/ FAN treatments, January through May, 1993). In addition, all treatments remained grouped according to the amount of daily integrated light (PAR_i) the plants received as shown in Table 4.4.

The daily plant water loss (ml) per gram of dry weight accumulated between transplant day and day 34 is shown in Figures 4.7 and 4.8 for selected W/O FAN and W/ Fan treatments. The curves in Figures 4.7 and 4.8 were fitted to measured data with a power function, generally expressed as:

$$\text{Daily plant water loss per gram DW} = a * DAY^{b}, \quad (4.10)$$

where:

units of the left hand side = ml day^{-1} $(gram\ DW)^{-1}$,

DAY = number of days after seeding,

a, b = coefficients.

Table 4.8 Accumulated water loss data for each treatment in ml per plant. The days after seeding are listed at the top of the table, and the treatments (sections A through E) are listed in the first column.

	Day 14	Day 18	Day 21	Day 25	Day 28	Day 32	Day 34
Oct A	83	276	617	1158	1640	2040	2332
Oct B	83	295	659	1353	1799	2174	2466
Oct C	75	200	439	800	1121	1396	1646
Oct D	108	253	434	782	1067	1392	1684
Oct E	83	199	335	571	839	1139	1347
Nov A	67	124	227	574	913	1288	1496
Nov B	83	131	188	341	466	641	724
Nov C	83	141	209	362	576	801	1051
Nov D	108	176	289	581	920	1295	1504
Nov E	83	141	243	591	966	1366	1532
Dec A	67	182	318	624	892	1292	1542
Dec B	-	-	-	-	-	-	-
Dec C	58	106	175	313	438	573	698
Dec D	50	223	462	864	1239	1939	2189
Dec E	83	199	324	546	796	1096	1346
Jan A	75	152	266	432	718	1068	1318
Jan B	67	201	383	703	1095	1645	1937
Jan C	100	187	334	626	947	1497	1706
Jan D	75	171	364	725	1172	1697	1947
Jan E	67	144	314	620	959	1409	1617
Feb A	50	152	345	706	1081	1731	2023
Feb B	92	217	398	829	1240	1915	2248
Feb C	75	219	458	944	1390	2090	2424
Feb D	50	156	281	545	777	1377	1627
Feb E	83	218	468	982	1446	2371	2871
Mar A	92	265	481	758	1187	2112	2404
Mar B	67	201	440	732	1107	1957	2332
Mar C	67	249	533	825	1147	2022	2480
Mar D	67	221	471	721	1060	1835	2126
Mar E	100	235	348	529	761	1461	1753
Apr B	125	313	555	840	1195	1502	1643
Apr C	125	356	628	990	1365	1830	2121
Apr D	150	352	636	1067	1620	2110	2402
May B	106	287	529	1029	1456	2006	2256
May C	125	317	579	1051	1533	2183	2516
May D	117	351	624	1082	1600	2350	2767

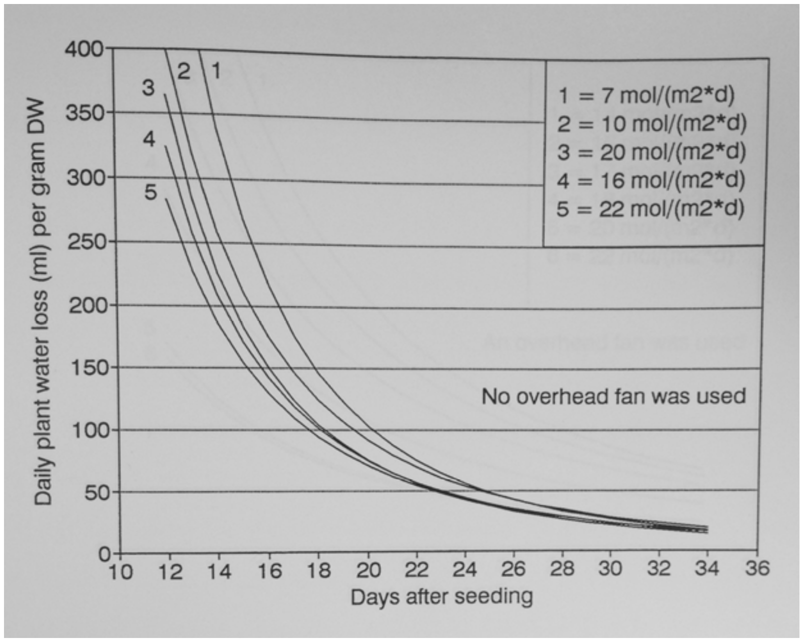

Figure 4.7 Daily plant water loss (ml) per gram dry weight accumulated versus days after seeding for several 'without FAN' treatments.

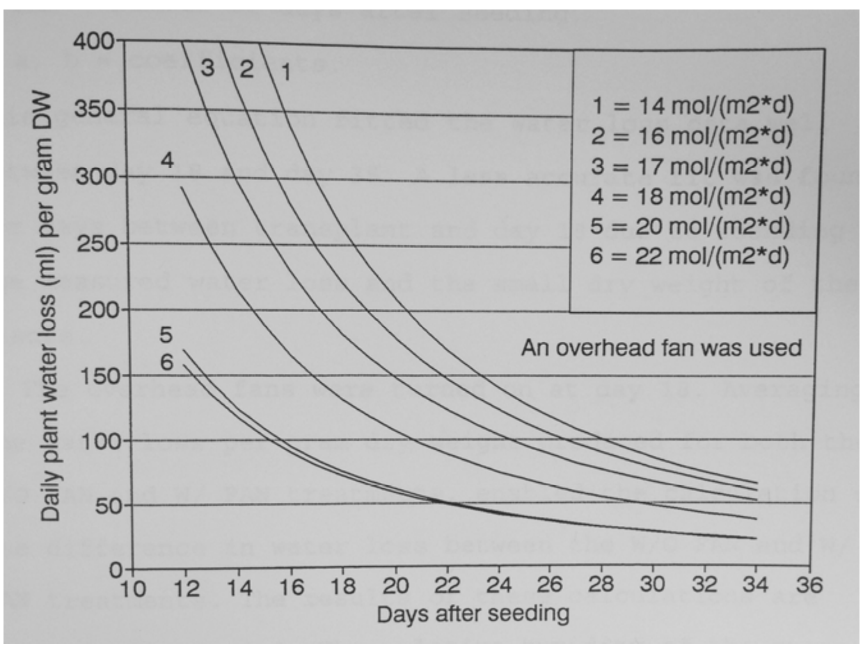

Figure 4.8 Daily plant water loss (ml) per gram dry weight accumulated versus days after seeding for several 'with FAN' treatments.

This general equation fitted the water loss data well between day 18 and day 35. A less accurate fit was found for days between transplant and day 18 due to rounding of the measured water loss and the small dry weight of the plants.

The overhead fans were turned on at day 18. Averaging the water loss per gram dry weight produced for both the W/O FAN and W/ FAN treatments, enabled the calculation of the difference in water loss between the W/O FAN and W/ FAN treatments. The results of these calculations are shown in Figure 4.9. The relative humidity of the greenhouse air, and, thus, the vapor pressure deficit between a stomatal cavity and the ambient greenhouse air, fluctuated little among all experimental treatments and did not shown a seasonal trend. Therefore, it was concluded the air blown vertically downward onto the lettuce plants with an overhead fan increased the transpiration from the lettuce plants. Figure 4.9 shows this result.

The accumulated water loss in 23 days was found to be correlated with the daily integrated PAR (PAR_i) used in the treatments (Figure 4.10). Figure 4.10 shows the difference in accumulated water loss over 23 days between W/O FAN and W/ FAN treatments decreases from 0.75 to 0.5 liter as the PAR_i increases from 4 to 22 mol m^{-2} d^{-1}.

The accumulated water loss in 23 days was also found to correlate with the final dry weight (Figure 4.11). Figure 4.11 shows the difference in accumulated water loss over 23 days between W/O FAN and W/ FAN treatments decreases from 0.8 to 0.3 liter as the final dry weight of the plants increases from 2 to 8 grams.

Figure 4.10 shows on average 69 ml of nutrient solution was transpired per plant per unit (mol m^{-2} d^{-1}) increase in PAR for the W/ FAN treatments. For the W/O FAN treatments, this quantity was 82 ml. In addition, Figure 4.11 shows 3.8 grams of shoot dry weight was on average produced per liter of nutrient solution transpired for the W/ FAN treatments. For the W/O treatments this quantity was 5.8 grams.

Figure 4.12 shows the accumulated water loss per plant versus the accumulated dry weight for several W/ FAN treatments. Figure 4.12 reveals the minimum required slope of the water loss line is 400 ml water per plant per gram dry weight accumulated for treatments showing no signs of tipburn. All treatments with a

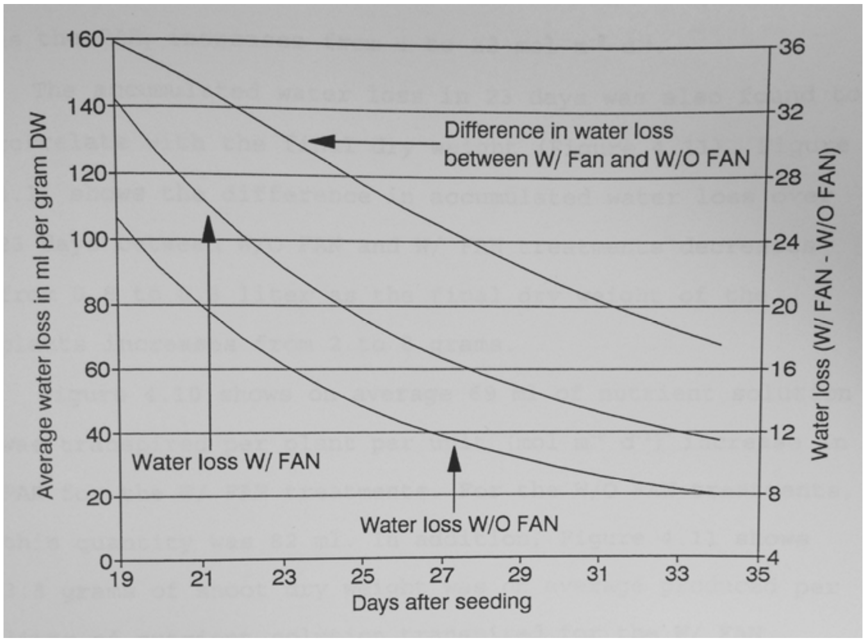

Figure 4.9 Average plant water loss (ml) per gram dry weight accumulated for 'without FAN' and 'with FAN' treatments and their difference versus days after seeding.

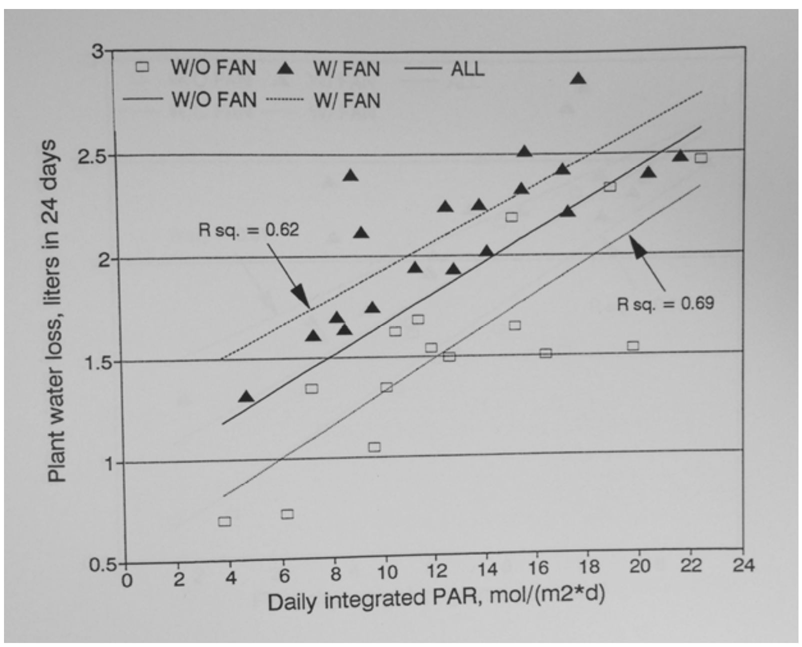

Figure 4.10 Accumulated water loss (liter) for 'without FAN' and 'with FAN' treatments versus the daily integrated PAR (PAR_i).

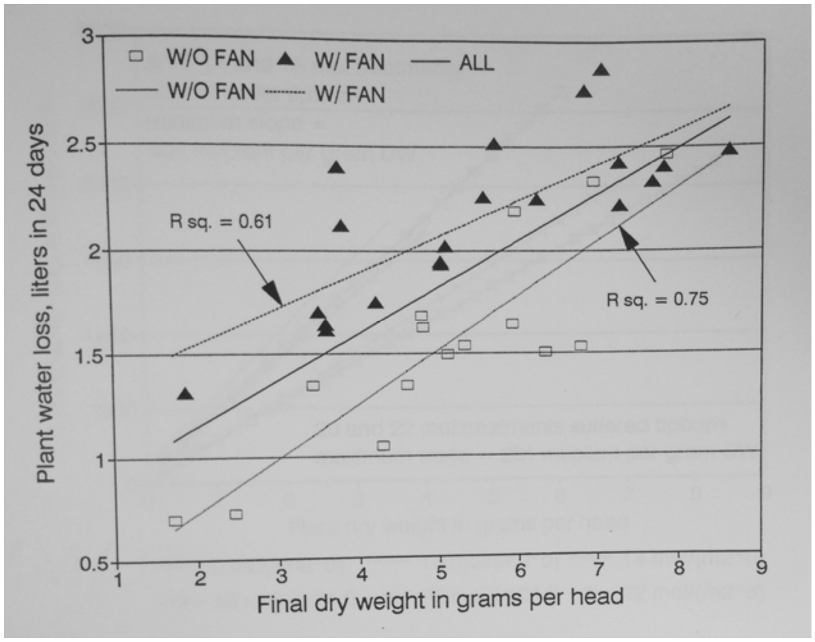

Figure 4.11 Accumulated water loss (liter) for 'without FAN' and 'with FAN' treatments versus final dry weight (DW_f).

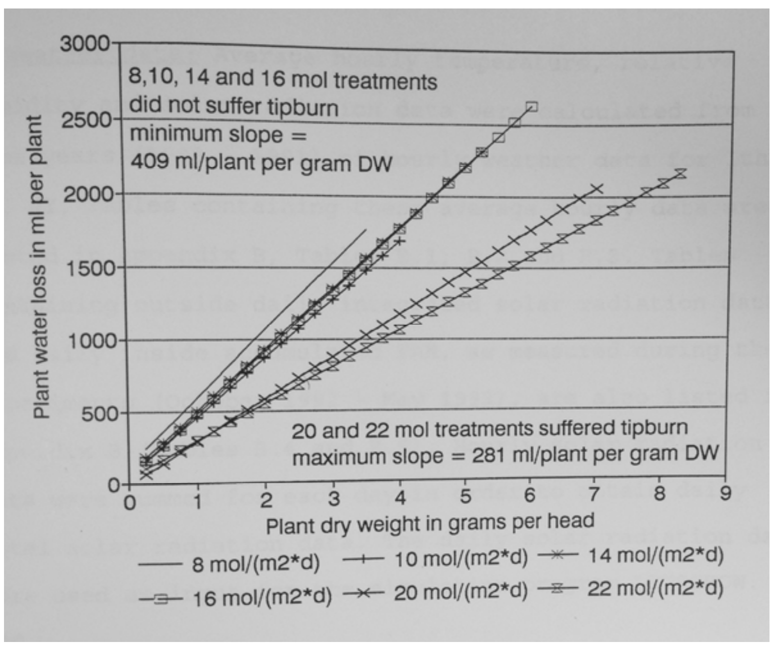

Figure 4.12 Accumulated water loss (ml) for 'with FAN' treatments versus accumulated dry weight.

maximum slope of 300 ml water per plant per gram dry weight accumulated, whether W/O FAN or W/ FAN, showed signs of tipburn.

Part 2. Growth Modeling

Weather data: Average hourly temperature, relative humidity and solar radiation data were calculated from nine years (1983 - 1991) of hourly weather data for Ithaca, NY. Tables containing these average hourly data are listed in Appendix B, Tables B.1, B.2 and B.3. Tables containing outside daily integrated solar radiation data and daily inside accumulated PAR, as measured during the experiments (October 1992 - May 1993), are also listed in Appendix B (Tables B.4 and B.5). Hourly solar radiation data were summed for each day in order to obtain daily total solar radiation data. The daily solar radiation data were used as input for the simulation program LETSGROW.
PAS.

Simulation runs: The computer code of the simulation program LETSGROW.PAS is listed in Appendix C. Two slightly different versions of the model were used for the simulation runs. The first version, Model1, is the one listed in Appendix C and uses the average historical solar radiation data for Ithaca, NY, to determine the amount of solar radiation a particular day of the year receives outside the greenhouse. The second version, Model2, uses the measured solar radiation during the experiments (Appendix B, Table B.4) to determine the amount of solar radiation a particular day during the experiments received outside the greenhouse. Model2 also uses the actual daily integrated PAR (Appendix B, Table B.5) as measured inside the greenhouse during the treatments to determine the daily PAR received by the plants. Thus, Model1 relies on the more general average solar radiation for the location under investigation and Model2 needs the actual measured solar radiation and inside PAR_i to perform the simulation calculations.

The results of the simulation runs with both models are summarized in Table 4.9. The 35 treatments are sorted in Table 4.9 according to the average daily integrated PAR the plants received during the treatment. This table compares the experimental measurements with the results of the simulation runs at final harvest (i.e., harvest 7, or 35 days after seeding). The performance of Model1 and Model2, compared to the experimental results, was evaluated after an analysis of the experimental results. Table 4.9 shows the spread of the measurements at final harvest through the values of the minimum and maximum measurement and the standard deviation of the entire measurement (72 plants).

Figure 4.13 shows the increase in measured minimum, average and maximum dry weight at harvest 7 with an in crease in PAR_i. Linear regression lines were calculated to describe the relationship between PAR_i and the minimum, maximum and average dry weights at harvest 7. The straight line trends with high correlation coefficients indicate light saturation did not occur for the amounts of PAR_i used in the 35 treatments.

Figures 4.14 and 4.15 show the increase in the value of the standard deviation of the dry weight measurement at harvest 7 as the PAR_i or the average dry weight at harvest 7 increases respectively. Regression lines were calculated to enable an estimate of the standard deviation of the dry weight measurement for different amounts of PAR_i or different final dry weights.

Figure 4.16 shows the difference between the measured final dry weights and the predicted final dry weights for different amounts of PAR_i using Model1. The region between the two sloping lines (the regression lines of plus and minus one standard deviation from the average dry weight) indicates a satisfactory performance by the simulation model. For four treatments (all controls, i.e., without the use of supplemental lighting) Model1 predicted a final dry weight larger than one standard deviation from the measured average dry weight at harvest 7. Three simulation calculations resulted in a final dry weight more than one standard deviation smaller than the measured average dry weight at harvest 7 for those treatments. It is not clear why these seven simulation treatments resulted in a final dry weight falling outside the region of plus or minus one standard deviation from the measured average dry weight at harvest 7. However, for the remaining 28 treatments Model1 performed satisfactory.

Table 4.9 Average daily integrated PAR (PAR_i), dry weight data at harvest 7 (35 days after seeding) and predicted dry weights at harvest 7 using nine-year average Ithaca, NY solar radiation data (Model1) and actual measured solar radiation and inside PAR data (Model2).

	PAR_i mol m^{-2} d^{-1}	Ave DW grams $head^{-1}$	Max DW grams $head^{-1}$	Min DW grams $head^{-1}$	Stand Dev grams $head^{-1}$	Model1 DW grams $head^{-1}$	Model2 DW grams $head^{-1}$
Dec C	3.8	1.72	2.07	1.19	0.188	2.49	1.36
Jan A	4.7	1.87	2.55	1.42	0.186	3.43	1.83
Nov B	6.2	2.46	3.20	1.69	0.301	3.38	2.23
Dec E	7.2	4.61	5.83	3.67	0.427	3.03	3.09
Jan E	7.3	3.60	4.70	2.71	0.350	3.29	3.23
Jan C	8.2	3.50	4.50	2.78	0.368	3.49	3.60
Apr B	8.5	3.59	4.62	2.78	0.397	3.55	3.04
Apr D	8.8	3.76	4.97	3.16	0.391	3.53	3.12
Apr C	9.2	3.80	4.84	2.57	0.451	3.54	3.31
Mar E	9.6	4.22	5.32	3.59	0.389	4.20	4.09
Nov C	9.6	4.30	5.19	3.26	0.396	4.09	4.09
Oct E	10.1	3.43	4.05	2.76	0.310	5.19	3.66
Feb D	10.5	4.81	6.07	3.29	0.643	4.61	4.40
Jan D	11.3	5.03	6.89	3.90	0.551	4.75	4.88
Oct D	11.4	4.80	6.12	3.79	0.537	5.12	4.74
Dec A	11.9	5.33	6.32	3.25	0.562	4.98	5.04
Feb B	12.5	6.24	8.15	4.09	0.704	5.15	5.30
Nov A	12.6	5.12	6.05	3.99	0.453	5.25	5.34
Jan B	12.8	5.04	5.99	3.76	0.442	5.29	5.41
May B	13.8	5.57	6.92	4.43	0.546	5.38	5.27
Feb A	14.1	5.09	6.06	4.18	0.647	5.71	5.71
Dec D	15.1	5.96	7.47	4.49	0.623	6.02	6.01
Oct C	15.2	5.93	7.25	4.97	0.576	6.11	6.17
Mar B	15.5	7.67	8.80	5.41	0.726	6.43	6.38
May C	15.6	5.71	7.12	4.22	0.613	6.12	5.93
May D	15.9	6.83	7.96	5.34	0.669	6.23	5.97
Nov D	16.4	6.35	7.71	3.38	0.687	6.46	6.52
Feb C	17.1	7.26	9.31	5.95	0.690	6.64	6.74
Mar D	17.3	7.27	9.25	5.97	0.777	6.98	6.97
Feb E	17.7	7.04	8.35	4.60	0.597	6.80	6.95
Oct A	18.9	6.95	8.41	5.30	0.678	7.20	7.16
Nov E	19.8	6.79	8.56	5.50	0.599	7.32	7.16
Mar A	20.4	7.81	9.62	5.59	0.836	7.81	7.76
Mar C	21.6	8.60	10.76	6.49	0.903	8.09	8.01
Oct B	22.4	7.84	9.89	6.24	0.764	8.02	7.83

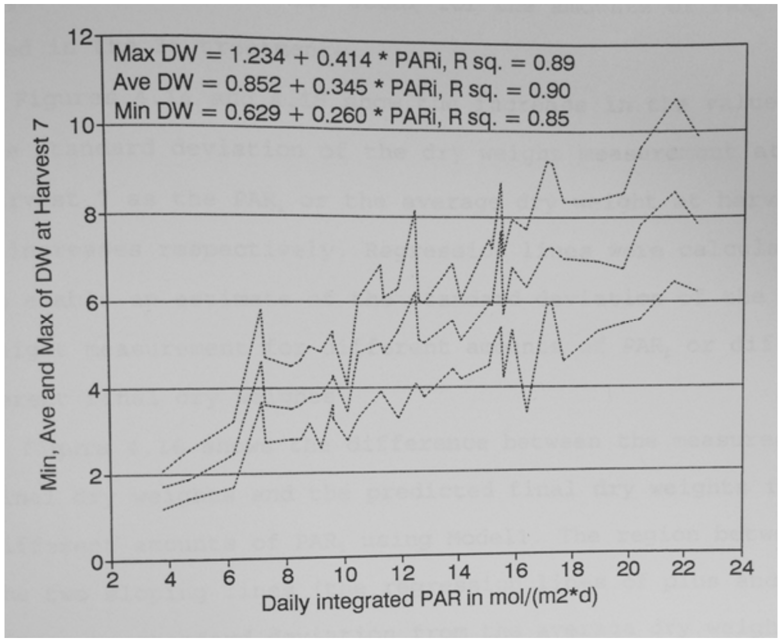

Figure 4.13 Measured minimum, average and maximum dry weight at harvest 7 versus daily integrated PAR (PAR_i).

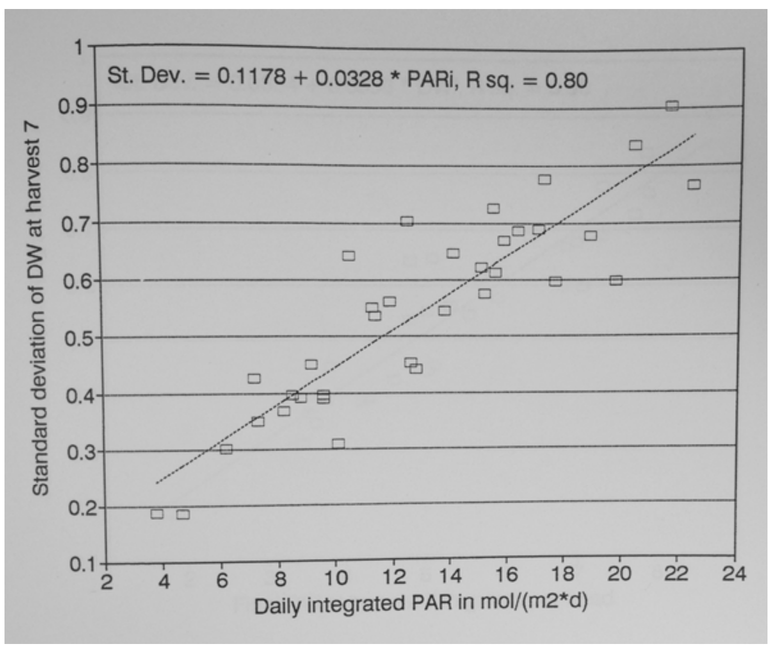

Figure 4.14 Calculated standard deviation of measured average dry weight at harvest 7 versus daily integrated PAR (PAR_i).

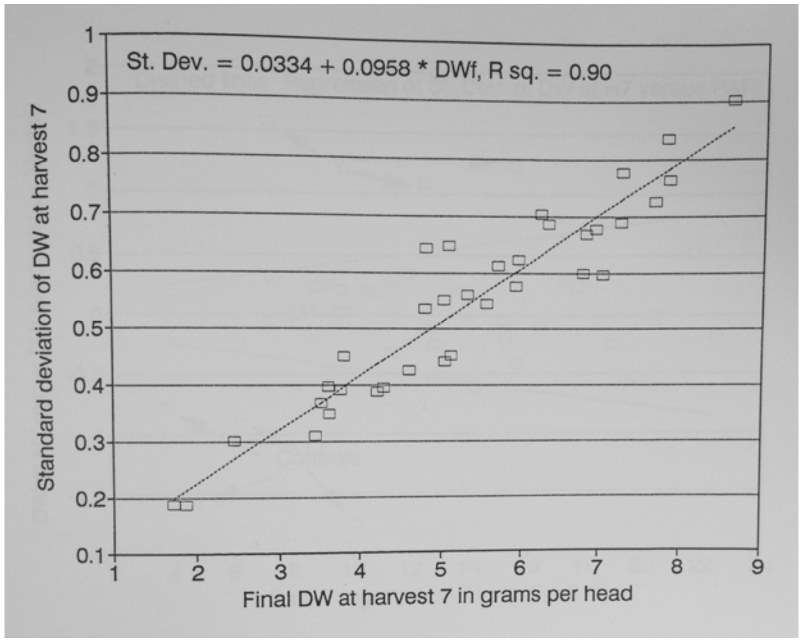

Figure 4.15 Calculated standard deviation of measured average dry weight at harvest 7 versus measured average dry weight at harvest 7 (DW_f).

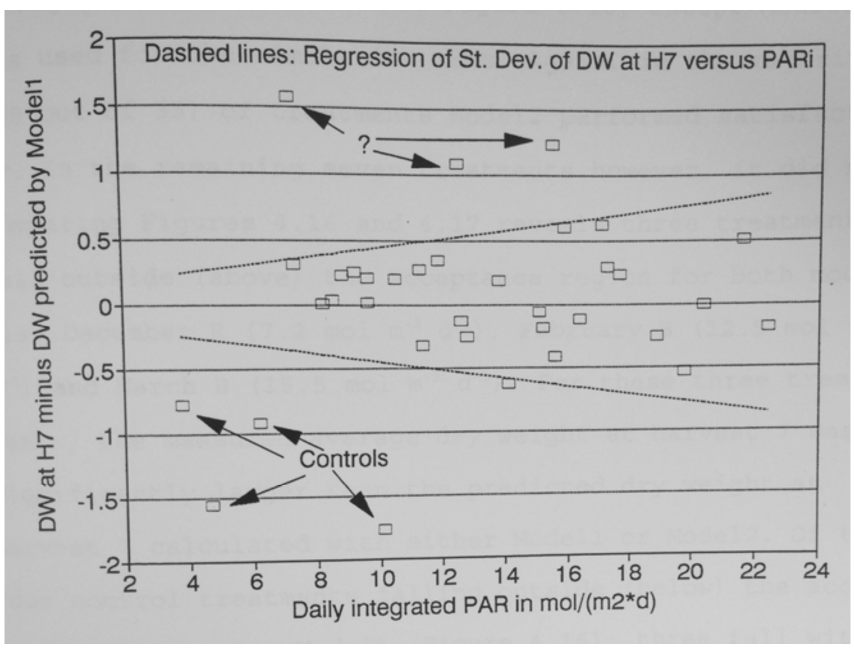

Figure 4.16 Difference of measured average dry weight at harvest 7 and dry weight at harvest 7 predicted by simulation Model1 versus daily integrated PAR(PAR_i).

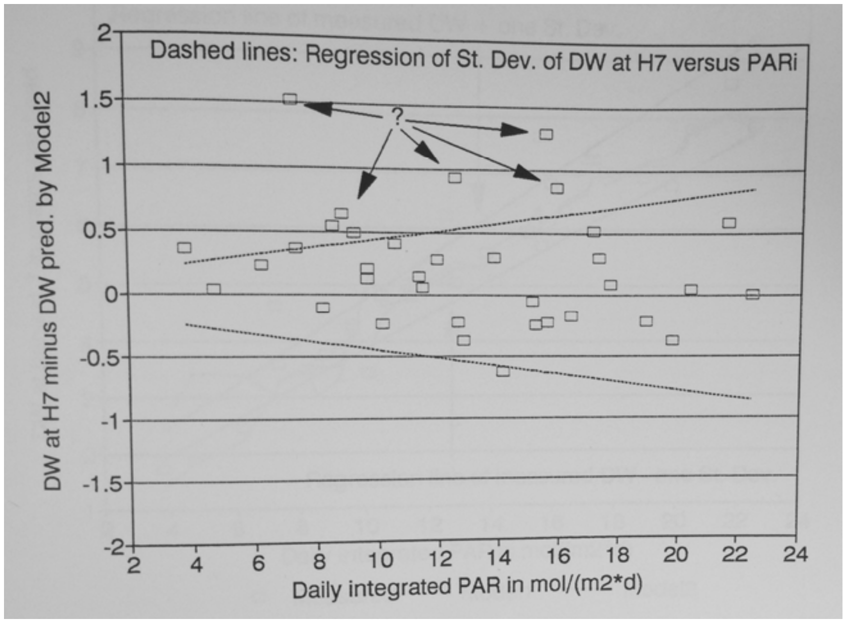

Figure 4.17 Difference of measured average dry weight at harvest 7 and dry weight at harvest 7 predicted by simulation Model2 versus daily integrated PAR(PAR_i).

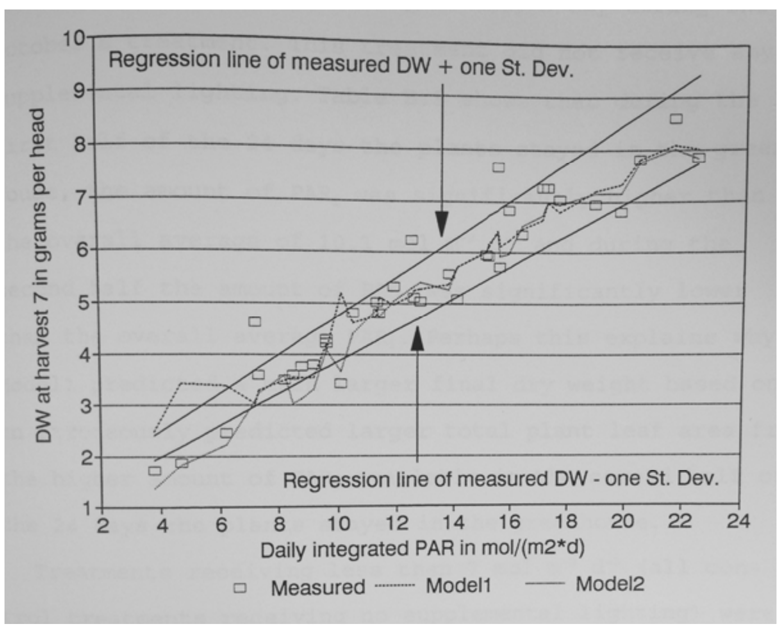

Figure 4.18 Measured average dry weight at harvest 7 and predicted dry weight at harvest 7 using simulation Model1 and simulation Model2 versus daily integrated PAR(PAR_i). The regression lines of plus and minus one standard deviation from the measured average dry weight (Figure 4.14) are included.

Figure 4.17 is similar to Figure 4.16, except Model2 was used for the simulation runs. Again, in the majority (28 out of 35) of treatments Model2 performed satisfactory. In the remaining seven treatments however, it did not. Comparing Figures 4.16 and 4.17 reveals three treatments fall outside (above) the acceptance region for both models: December E (7.2 mol m^{-2} d^{-1}), February B (12.5 mol m^{-2} d^{-1}) and March B (15.5 mol m^{-2} d^{-1}). For these three treatments, the measured average dry weight at harvest 7 was significantly larger than the predicted dry weight at harvest 7 calculated with either Model1 or Model2. Of the four control treatments falling outside (below) the acceptance region using Model1 (Figure 4.16), three fall within this region using Model2 and one falls very close to the acceptance region (December C, 3.8 mol m^{-2} d^{-1}).

Figure 4.18 combines the information found in Figures 4.16 and 4.17. Figure 4.18 shows that between 7 and 22 mol m^{-2} d^{-1} most predicted final dry weights, using either Model1 or Model2, fall within the acceptance region bounded between the lines of plus and minus one standard deviation from the measured final dry weight at harvest 7.

The largest disagreement between the two models was found for one of the control treatments (October E, 10.1 mol m^{-2} d^{-1}). Model2 predicted much better for this particular treatment than Model1. Table B.5 (Appendix B) shows the daily integrated PAR (PAR_i) for each day during the October E treatment. This treatment did not receive any supplemental lighting. Table B.5 shows that during the first half of the 24 days the plants stayed in the greenhouse, the amount of PAR_i was significantly higher than the overall average of 10.1 mol m^{-2} d^{-1} and during the second half the amount of PAR_i was significantly lower than the overall average PAR_i. Perhaps this explains why Model1 predicted a much larger final dry weight based on an erroneously predicted larger total plant leaf area from the higher amount of PAR_i available in the second half of the 24 days the plants stayed in the greenhouse.

Treatments receiving less than 7 mol m^{-2} d^{-1} (all control treatments receiving no supplemental lighting) were much better simulated using Model2. However, in a commercial hydroponic lettuce operation using supplemental lighting, such low amounts of daily integrated PAR will not be economical and therefore will not be used.

From Figure 4.18 it was concluded Model1 and Model2 performed overall equally well for the PAR_i between 7 and 22 mol m^{-2} d^{-1}. This result shows that it is possible to use average solar radiation data for a location under investigation and still adequately predict the dry weight production of hydroponic lettuce grown using supplemental lighting.

To show the result of the simulations with Model1, eight treatments were selected to be shown in a graph. Each graph shows the average dry weight at each of the seven harvests and the interval bounded by plus and minus one standard deviation from the mean. The curve fitted line through the average dry weights at each harvest is represented by a solid line and open rectangles. The predicted dry weight accumulation (using Model1) is represented by a dashed line and stars. Four amounts of PAR_i were selected to be shown in the graphs: 7, 12, 17 and 22 mol m^{-2} d^{-1}. Table 4.4 shows two treatments fell in each of these four PAR_i groups. Both treatments of each group are shown in Figures 4.19 through 4.26. In six of the eight treatments Model1 performed satisfactory. Two of the eight treatments (December E, 7.2 mol m^{-2} d^{-1} and February B, 12.5 mol m^{-2} d^{-1}) were previously identified as treatments whose measured dry weights at harvest 7 were significantly larger than the predicted dry weights at harvest 7 using either Model1 or Model2. An explanation for this result has not been found.

<u>Sensitivity analysis:</u> The sensitivity of a simulation model to changes in its parameters can be evaluated using the sensitivity function described by France and Thornley (1984) and applied by Van Henten (1994). This sensitivity function can be used to investigate the effect of parameter variation on the performance of the model This relative sensitivity was investigated using the equation:

$$S_i = [(DW_{new} - DW_{old})/DW_{old}] * [P_{old}/(P_{new} - P_{old})] \qquad (4.11)$$

where:

S_i = relative sensitivity for a variation of parameter i,
DW_{new} = dry weight at harvest 7 (or any other time) using the new parameter value P_{new},
DW_{old} = dry weight at harvest 7 (or any other time) using the original parameter value P_{old},
P_{new} = new parameter value,
P_{old} = original parameter value.

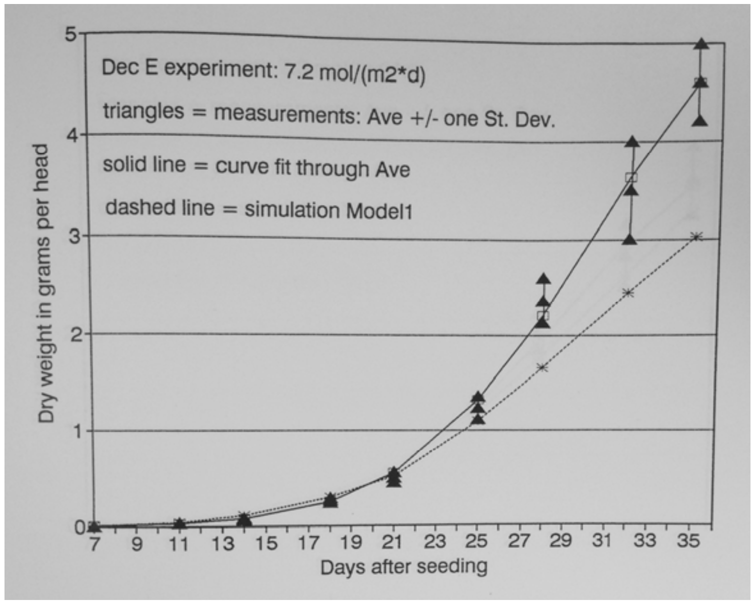

Figure 4.19 Measured average dry weight and calculated standard deviation at harvest 7 for the December E experiment showing the curve fit through the measured average dry weights and the predicted dry weights using simulation Model1.

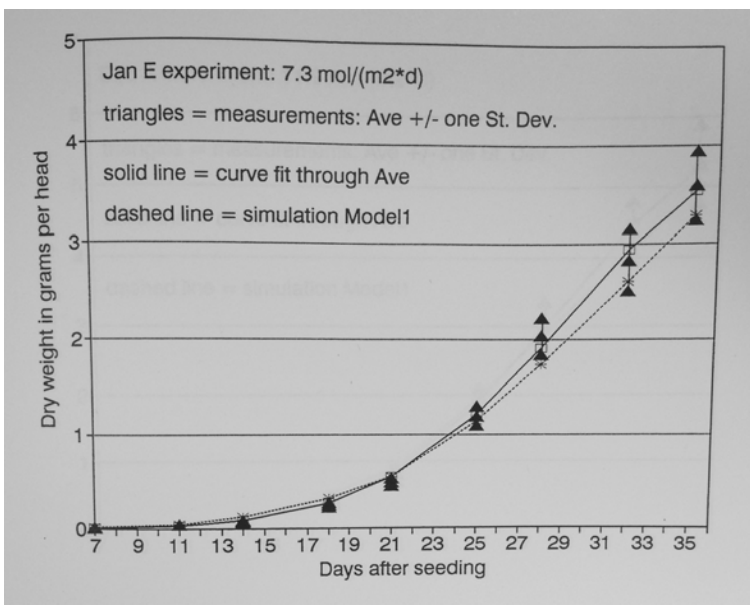

Figure 4.20 Measured average dry weight and calculated standard deviation at harvest 7 for the January E experiment showing the curve fit through the measured average dry weights and the predicted dry weights using simulation Model1.

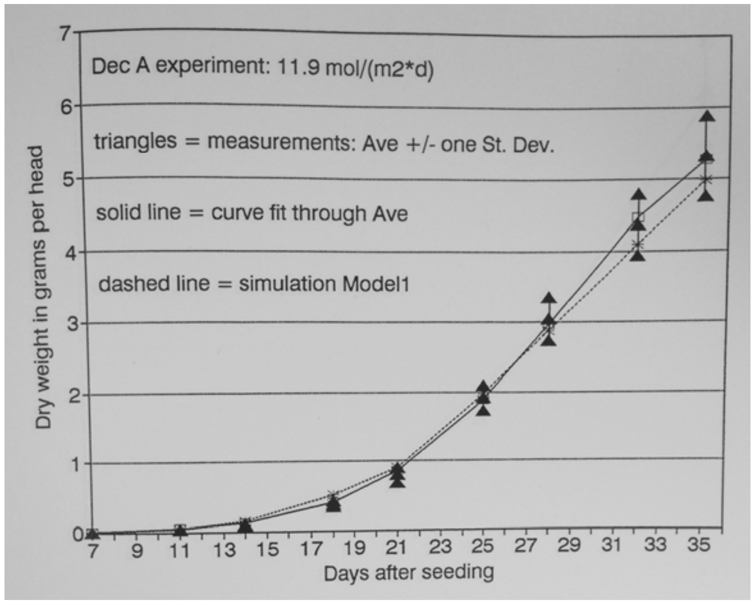

Figure 4.21 Measured average dry weight and calculated standard deviation at harvest 7 for the December A experiment showing the curve fit through the measured average dry weights and the predicted dry weights using simulation Model1.

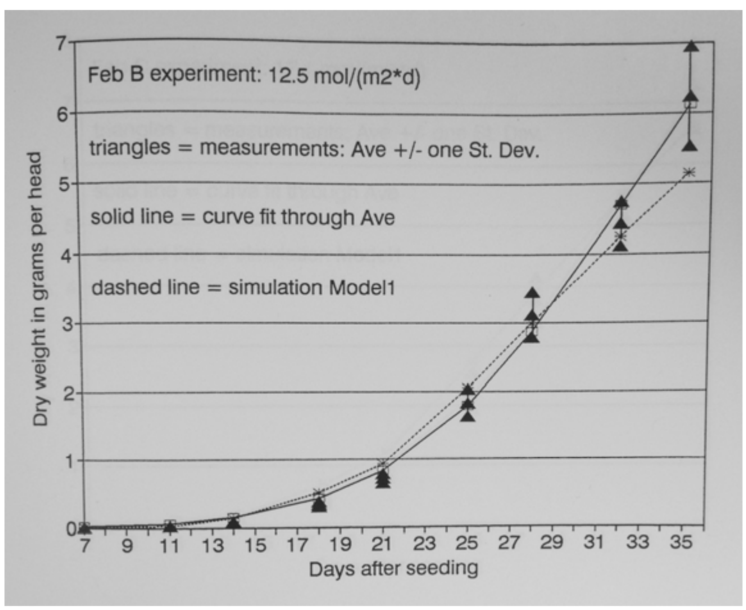

Figure 4.22 Measured average dry weight and calculated standard deviation at harvest 7 for the February B experiment showing the curve fit through the measured average dry weights and the predicted dry weights using simulation Model1.

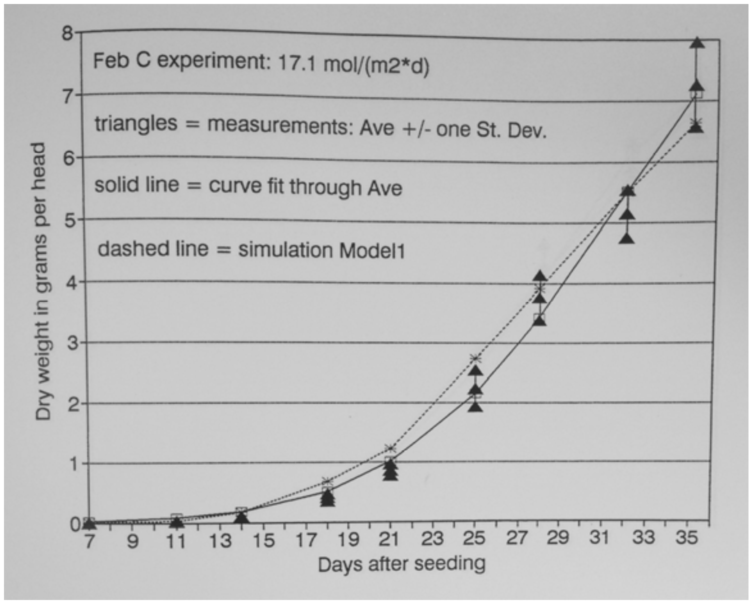

Figure 4.23 Measured average dry weight and calculated standard deviation at harvest 7 for the February C experiment showing the curve fit through the measured average dry weights and the predicted dry weights using simulation Model1.

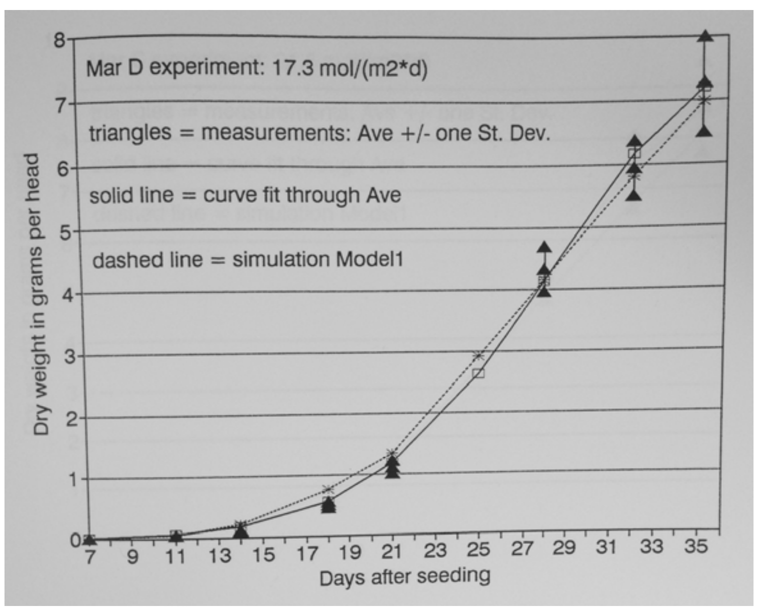

Figure 4.24 Measured average dry weight and calculated standard deviation at harvest 7 for the March D experiment showing the curve fit through the measured average dry weights and the predicted dry weights using simulation Model1.

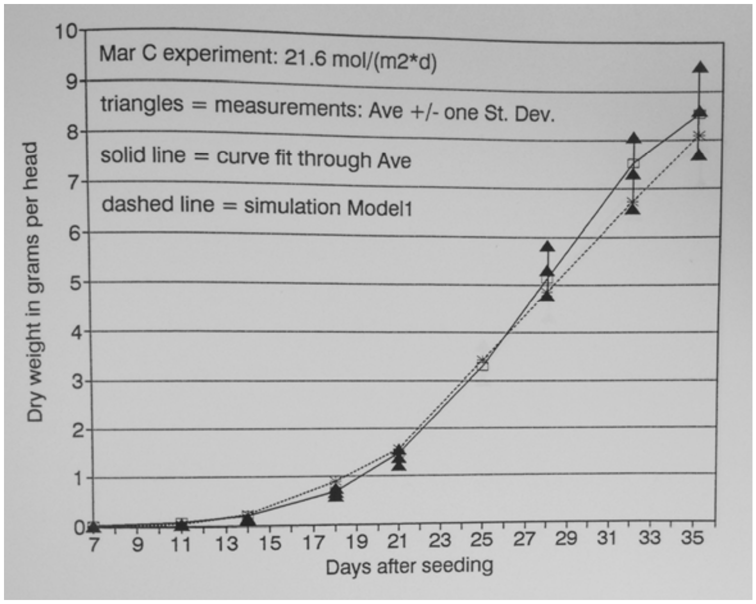

Figure 4.25 Measured average dry weight and calculated standard deviation at harvest 7 for the March C experiment showing the curve fit through the measured average dry weights and the predicted dry weights using simulation Model1.

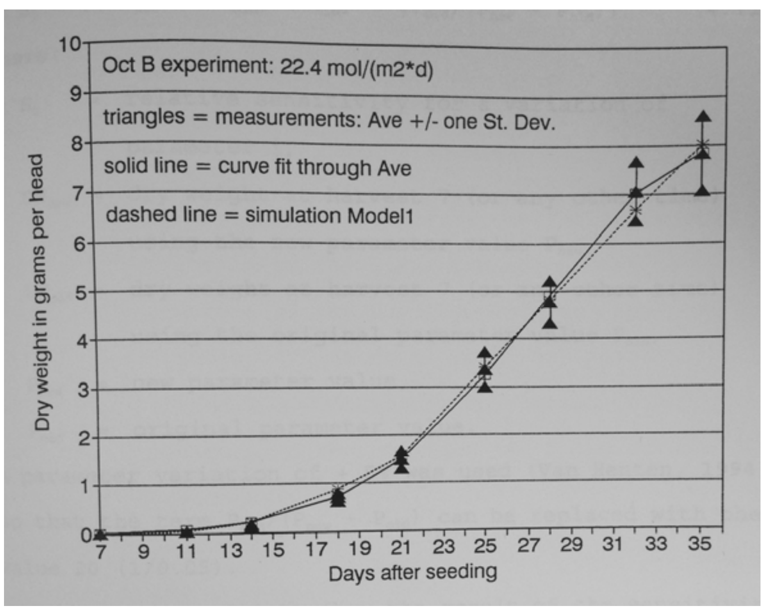

Figure 4.26 Measured average dry weight and calculated standard deviation at harvest 7 for the October B experiment showing the curve fit through the measured average dry weights and the predicted dry weights using simulation Model1.

A parameter variation of + 5% was used (Van Henten, 1994) so that the term $P_{old}/(P_{new} - P_{old})$ can be replaced with the value 20 (1/0.05).

Tables 4.10 and 4.11 show the result of the sensitivity analysis using Model1 and different amounts of daily integrated PAR for crops starting on two different days of the year: January 15 and July 15. Note the parameter variation can result in positive or negative values of S_i depending on their positive or negative influence on the dry weight production. Furthermore, $|S_i|$ can be larger than 1 depending on the extend of the parameter influence on the final dry weight at harvest 7.

Instead of a + 5% increase, the parameters Nday and Spaceday (Table 4.10 explains the names of the parameters) were increased by one day and the parameters Rampup and Rampdown were increased by one hour.

Several parameters listed in Tables 4.10 and 4.11 are dependent parameters (i.e., their values change when the value of an independent parameter upon which they depend is changed). When the latitude of the location under investigation (LAT) is changed, the daily total solar radiation received (DTR[i]) changes, which in turn determines the atmospheric transmission coefficient (ATMTR) which determines the fraction of the total radiation which is diffuse (FRDF). Similarly, when the daily incoming PAR (DPAR, a value entered by the user) is changed, the model parameters AMAX (actual CO_2 assimilation rate at light saturation for individual leaves), EFF (initial light use efficiency for individual leaves), and pcPAR (percentage of the solar radiation in the PAR waveband) change. Finally, the calculated leaf area ratio (LAR) depends on the plant density. Therefore, a parameter increase of + 5% of LAT, DTR[i], ATMTR, DPAR, or Density[i] not only increases its own value but also changes the value of the above mentioned dependent parameters. This dependency and its effect on the sensitivity analysis should be carefully considered when Tables 4.10 and 4.11 are interpreted.

Table 4.10 Relative sensitivity of Model1 to a + 5% variation in selected parameters (ranked from the largest negative sensitivity to the largest positive sensitivity) for a crop started on January 15 and grown under three different amounts of daily integrated PAR.

Parameter	Explanation
AMAX	actual CO_2 assimilation rate at light saturation for individual leaves
ATMTR	atmospheric transmission coefficient
Density[1]	plant density before spacing
Density[2]	plant density after spacing
DPAR	incoming daily PAR
DTR[i]	daily total solar radiation
EFF	initial light use efficiency for individual leaves
FRDF	fraction of the total radiation that is diffuse
FRDFHPS	fraction of the supplemental lighting that is diffuse
FRT[i]	fraction of the total plant dry weight allocated to the roots
KDF	extinction coefficient for diffuse PAR
LAR	leaf area ratio
LAT	latitude of the location (42.3 for Ithaca, NY)
Nday	number of days the plants stay in the greenhouse
pcPAR	percentage of the solar radiation in the PAR waveband
Q10	increase in the rate of maintenance processes per 10 degrees Celsius
Rampdown	hour of the day when the temperature is ramped up to the daytime set point
Rampup	hour of the day when the temperature is ramped down to the nighttime set point
SC	solar constant
SCP	scattering coefficient of leaves for PAR
Spaceday	number of days after transplant when spacing took place
tau	transmissivity of the greenhouse cover
Tiday	daytime temperature set point
Tinight	nighttime temperature set point
wshoot[11]	shoot (leaves) dry weight at transplant (11 days after seeding)
S_i	relative sensitivity (equation 4.11)

Table 4.10 (Continued)

RUN 1	S_i	RUN 2	S_i	RUN 3	S_i
Density[2]	-0.74	Density[2]	-0.75	Density[2]	-0.77
Spaceday	-0.34	Spaceday	-0.41	Spaceday	-0.44
Density[1]	-0.16	Density[1]	-0.16	LAT	-0.17
FRT[i]	-0.16	LAT	-0.16	Density[1]	-0.15
Tinight	-0.10	FRT[i]	-0.15	FRT[i]	-0.14
LAT	-0.09	Tinight	-0.10	Tinight	-0.10
Tiday	-0.09	DTR[i]	-0.09	Tiday	-0.09
SCP	-0.07	Tiday	-0.09	DTR[i]	-0.07
Rampdown	-0.04	SCP	-0.06	KDF	-0.06
ATMTR	-0.02	tau	-0.05	SCP	-0.06
FRDF	-0.00	pcPAR	-0.05	Rampdown	-0.04
FRDFHPS	0.00	ATMTR	-0.04	ATMTR	-0.04
SC	0.01	Rampdown	-0.04	tau	-0.03
DPAR	0.01	FRDFHPS	0.02	pcPAR	-0.03
Rampup	0.04	SC	0.03	wshoot[11]	0.03
Q10	0.05	Rampup	0.04	SC	0.03
wshoot[11]	0.05	FRDF	0.04	Rampup	0.04
KDF	0.16	wshoot[11]	0.04	FRDF	0.04
AMAX	0.18	KDF	0.04	Q10	0.05
LAR	0.33	Q10	0.05	FRDFHPS	0.10
DTR[i]	1.02	AMAX	0.19	LAR	0.17
pcPAR	1.05	LAR	0.23	AMAX	0.23
tau	1.05	EFF	0.95	EFF	0.87
EFF	1.05	DPAR	1.00	DPAR	0.90
Nday	1.36	Nday	1.13	Nday	1.10

Note: RUN 1 uses a PAR_i of 7 mol m^{-2} d^{-1}
RUN 2 uses a PAR_i of 12 mol m^{-2} d^{-1}
RUN 3 uses a PAR_i of 17 mol m^{-2} d^{-1}

Table 4.11 Relative sensitivity of Model1 to a + 5% variation in selected parameters (ranked from the largest negative sensitivity to the largest positive sensitivity) for a crop started on July 15 and grown under three different amounts of daily integrated PAR. See Table 4.10 for an explanation of the parameter names.

RUN 4	S_i	RUN 5	S_i	RUN 6	S_i
Density[2]	-0.73	Density[2]	-0.77	Density[2]	-0.78
Spaceday	-0.41	Spaceday	-0.44	Spaceday	-0.47
Density[1]	-0.17	Density[1]	-0.16	Density[1]	-0.15
FRT[i]	-0.16	FRT[i]	-0.14	FRT[i]	-0.13
ATMTR	-0.10	DTR[i]	-0.12	Tinight	-0.10
Tinight	-0.10	Tinight	-0.10	Tiday	-0.09
Tiday	-0.09	Tiday	-0.09	DTR[i]	-0.07
SCP	-0.06	pcPAR	-0.06	KDF	-0.07
Rampdown	-0.04	tau	-0.06	SCP	-0.06
FRDFHPS	0.00	SCP	-0.06	Rampdown	-0.04
Rampup	0.04	ATMTR	-0.05	pcPAR	-0.04
LAT	0.04	Rampdown	-0.04	tau	-0.04
wshoot[11]	0.05	KDF	0.01	ATMTR	-0.03
Q10	0.05	wshoot[11]	0.03	wshoot[11]	0.02
FRDF	0.07	LAT	0.04	FRDF	0.02
SC	0.09	Rampup	0.04	SC	0.03
KDF	0.14	FRDFHPS	0.04	Rampup	0.04
AMAX	0.17	FRDF	0.04	LAT	0.04
LAR	0.29	SC	0.05	Q10	0.05
DPAR	0.49	Q10	0.05	FRDFHPS	0.07
DTR[i]	0.89	LAR	0.18	LAR	0.12
pcPAR	1.00	AMAX	0.18	AMAX	0.20
tau	1.00	EFF	0.93	EFF	0.87
EFF	1.02	DPAR	0.99	DPAR	0.90
Nday	1.12	Nday	1.10	Nday	1.07

Note: RUN 4 uses a PAR_i of 12 mol m^{-2} d^{-1}
RUN 5 uses a PAR_i of 17 mol m^{-2} d^{-1}
RUN 6 uses a PAR_i of 22 mol m^{-2} d^{-1}

Comparing Tables 4.10 and 4.11 shows a + 5% variation of roughly half of the parameters cause a decrease in final dry weight at harvest 7 (negative S_i) and the other half caused an increase in final dry weight (positive S_i). The order in which the parameters are listed in Tables 4.10 and 4.11 is slightly different for each amount of daily integrated PAR (PAR_i) and for each of the two days of the year (January 15 and July 15). Especially for the small amounts of daily integrated PAR (7 mol m^{-2} d^{-1} on January 15 and 12 mol m^{-2} d^{-1} on July 15), when no or little supplemental lighting was needed to reach the daily target PAR, the order of the parameters (particularly for the larger positive S_i values) differs from the order when larger amounts of daily integrated PAR were used.

Of those parameters causing a significant decrease in final dry weight, the plant density after spacing (Density[2]) and the day at which respacing took place (Spaceday) affect the final dry weight most, followed by the plant density before spacing (Density[1]) and the fraction of the total plant dry weight allocated to the roots (FRT[i]). Remember, in this study, root dry weight is not included in the final dry weight.

The parameters causing a significant increase in the final dry weight at harvest 7 are, listed in decreasing order of significance, the number of days the plant stayed in the greenhouse (Nday), the incoming daily PAR (DPAR), initial light use efficiency for individual leaves (EFF), and the leaf area ratio (LAR). For other parameter variations the simulation model (Model1) was much less sensitive. However, for the smaller amounts of daily integrated PAR requiring little or no supplemental lighting to meet the daily integrated PAR target, three more parameters are shown to have a positive effect on the final dry weight after a 5% increase in the value of the parameter: the percentage of solar radiation in the PAR waveband (pcPAR), the transmissivity of the greenhouse cover (tau) and the daily total solar radiation (DTR[i]). This result is explained by the fact the major part of incoming radiation was provided by sunlight when low light levels were simulated with Model1.

The results of the sensitivity analysis shown in Tables 4.10 and 4.11 indicate the sensitivity of model calculations for plant density (Density[1] and Density[2]), length of time the plants remain in the greenhouse (Nday), day at which the plants are respaced (Spaceday), daily integrated PAR (DPAR), and leaf area ratio (LAR). These five parameters were carefully measured during the experiments. However, the simulation model showed additional sensitivity for the initial light use efficiency for individual leaves (EFF), the actual CO_2 assimilation rate at light saturation for individual leaves (AMAX) and the fraction of the total plant dry weight allocated to the roots (FRT[i]). These three parameters were not measured during the experiments but their values were extracted from the research literature and adjusted for the conditions used during this study.

Chapter 5

Discussion

Compared to this study, a different approach to model lettuce growth was followed by Van Henten (1994). His model used incident PAR, air temperature and CO_2 concentration as input parameters to describe the dynamic behavior of the structural (cell walls and cytoplasm) and non structural (glucose, sucrose and starch) dry weight. The model equations and parameter values were extracted from the research literature. The possibility of modeling fast changing plant responses to different environment conditions is clearly an advantage of this model. These quick plant responses can not be measured unless frequent (destructive) sampling is done. SUCROS87 and the model proposed in this study (LETSGROW.PAS) simulate dry matter production using a time step of one day. This method is unable to simulate rapid changes in plant growth unless a smaller time step is used (e.g., one hour). Van Henten's model is especially useful for continuous optimization of environment parameters using a control algorithm that maximizes the difference between increased returns and additional costs of environment modifications.

Van Henten and Van Straten (1994) used a first order sensitivity analysis to investigate the changing sensitivity of their lettuce growth model over time. In order to determine the sensitivity of the model, small variations in model parameters, inputs and initial conditions were applied and the resulting variation in model output was calculated. The advantage of this approach is the additional information it gives regarding the evolution of the sensitivity over time. For example, the growth model can show a relative large sensitivity to a small variation of a model parameter during the first half of the growing period and a relative small sensitivity to the same variation during the second half of the growing period. Following the method used in this study (Chapter 4), the sensitivity would have been judged low because the sensitivity to a small change in the model parameter is only investigated at the final harvest of the crop and not during any other stage of crop growth and development. The sensitivity analysis applied by Van Henten and

Van Straten is particularly helpful when crop growth models are used to help determine optimum environment control for greenhouse crop production. The focus of this study, however, was on maximum production in the shortest amount of time under very stable environment conditions. Under these circumstances it is sufficient to use the sensitivity analysis described by France and Thornley (1984) which was used in Chapter 4.

Carrier et al. (1994) proposed to modify SUCROS87 to predict hourly assimilation rates of a tomato crop grown with supplemental lighting. Hourly measurements of CO_2 concentration, air temperature and irradiance (supplemental and/or sunlight) were used as input for the model. This approach makes it difficult to use SUCROS87 as a tool to predict future plant growth unless environment conditions in the greenhouse are accurately known on an hourly basis. Generally, environment conditions in the greenhouse are not known until the crop is actually grown. The advantage of the modification proposed by Carrier et al. is the simplicity of modeling daylength extension due to the use of supplemental lighting. In SUCROS87 and in LETSGROW.PAS, the daylength is calculated from the amount of sunlight hours and no provisions for an extended daylength are incorporated in the model.

The assumption was made in this study that all supplemental light reaches the plant as diffuse light, as opposed to all direct light or a combination of diffuse and direct light (like sunlight). No measurements of the quantities of direct and diffuse light inside the greenhouse underneath the supplemental lighting system were performed. Supporting this assumption is the lack of depth and sharpness of shadows from an object underneath a grid of luminaires. The (large) reflector of each luminaire will cause the light to be spread out and thus, light intercepted from various luminaires will be perceived by the plant as coming from all directions. However, it is likely that some light from each luminaire will travel directly from the source to the plant leaf, especially from a horizontally mounted bulb. Following the definitions used for direct and diffuse sunlight, a certain amount of light from a grid of HPS luminaires should be considered as direct light. Careful measurements of the direct and diffuse components of supplemental light, using several luminaire densities, are needed to determine the truth.

In this study it was assumed plants respond to supplemental light the same way they respond to sunlight. Therefore, a certain quantity of sunlight should have the same effect on plants as a similar quantity of supplemental light. However, the light spectra for sunlight and supplemental light are very different. In this study HPS lamps were used in the greenhouse and fluorescent lamps in the growth chamber. Sase et al. (1988) used HPS and MH lamps to grow lettuce in a growth chamber and found morphological differences between lettuce plants grown under these two light sources, as described in Chapter 2. During the experiments, the largest part of the daily integrated PAR (PAR_i) was usually provided by sunlight. Only on very cloudy days and using high PAR_i levels, was the larger part of PAR_i provided by the supplemental lighting system. Since, in most cases, plants received the majority of PAR_i from sunlight, any possible different effect of supplemental light on plant growth was neglected. Further study might reveal at which ratio of supplemental light and sunlight a different plant response becomes evident. A careful examination of daylength effects should be included in such a study. Large differences between plant species can be expected.

Manipulating the daylength can have a significant influence on plant growth and development. This technique is frequently used for floricultural crops to induce flowering. However, some vegetable crops require a minimum dark period to prevent flowering (e.g., spinach) or to enable optimal development (e.g., tomato). The question arises what the influence of daylength is on lettuce? During the first 11 days after seeding the lettuce plants were kept in the growth chamber under continuous supplemental lighting. No negative effects were observed using 24 hours of continuous lighting during this pre-transplant period. Once in the greenhouse, many different supplemental lighting scenarios were tested on the lettuce plants (Table 3.1) resulting in many different daylengths - ranging from the natural daylength to 24 hours of continuous lighting. Using these significantly different daylengths did not result in a significant correlation between daylength and dry weight production. Thus, it can be concluded that the lettuce variety used in this study (***Lactuca sativa*** L., cv. Ostinata) and grown under the environment conditions described in Chapter 4, exhibits a dry weight production dependent of the integrated amount of PAR during a 24-hour period but independent of the daylength. As mentioned before, it appears no light saturation occurred during any of the experiments (Figure 4.13). Future research is needed to investigate in more detail the effect of light saturation on the dry weight production through careful measurement of the CO_2 assimilation rate (A_{max}) under different light intensities, temperatures and CO_2 concentrations.

During the January, February and March experiments the difference between daytime and nighttime lighting was investigated. The advantages of nighttime lighting are: (1) using cheaper electricity during off-peak hours, (2) avoiding possible light saturation which can occur when the supplemental light is added during the daytime, and (3) extending the daylength to increase the time photosynthesis is possible. Two of the daytime and nighttime lighting treatments (February B and March B) were described in Chapter 4 as treatments resulting in a measured final dry weight significantly higher than the predicted final dry weight (Model1). The results of these two treatments are therefore a little suspect. Nevertheless, when the dry weight predictions from Model1 are compared with the measured dry weights, it is clear that, when nighttime lighting was used, the difference between the measured final dry weight and the predicted dry weight was larger than when daytime lighting was used. This result is consistent except for the two highest light level treatments (March A and C), and seems to suggest the nighttime lighting treatments outperformed the daytime lighting treatments. However, the differences between the daytime and nighttime lighting treatments are small and further study is needed to determine whether nighttime lighting produces significantly better results than daytime lighting.

During the April experiment, the timing of the supplemental lighting was delayed by up to two days to study its effect on plant growth. The supplemental lighting was either added every night, or twice the amount every other night, or triple the amount every third night. No significant difference was observed in dry weight production using one of three lighting scenarios. Thus, it appears possible to delay supplemental lighting by a day or two. However, only a relatively low daily PAR_i was used during the experiment (between 8.5 and 9.2 mol m^{-2} d^{-1}); it is questionable whether similar results would be observed at a higher daily PAR_i (e.g., 17 mol m^{-2} d^{-1}). The advantages of delaying supplemental lighting are: (1) a grower can plan to use supplemental lighting only during periods of time when electricity price are low (during the evening or weekend), and (2) a grower can speed up or slow down the growth of a crop somewhat by increasing or decreasing the operating time of the supplemental lighting system. Advantage (1) can lead to an agreement between a grower and the electric utility company resulting in demand-side electricity management.

During the May experiment, three different supplemental lighting intensities were used, leading to different operating times of the three lighting systems to satisfy the same daily integrated PAR (PAR_i) target. No significant dry weight production differences were observed. Thus, a lower light intensity can be used during a longer period of time resulting in a similar dry weight production compared to a higher light intensity during a shorter period of time when the daily PAR_i is kept the same. The advantages of this result are: (1) fewer luminaires need to be installed in the greenhouse, and (2) a lower light intensity will reduce the peak electricity demand of a commercial operation, lowering the demand charge and possibly lowering the highest electricity rate charged to the grower.

The maximum growth rate (dW/dt_{max}) of each of the growth trials was calculated after the equation of a curve fit through the measured average dry weight at each harvest was calculated. It was noticed the maximum growth rate occurred at 30 ± 2 days for nearly all treatments. The question can be asked whether this result is due to a genetic characteristic of the lettuce variety used in this study (possibly triggered by an accumulated degree day effect), or is it due to an artifact of the procedure followed to determine the maximum growth rate? The maximum growth rate for each treatment was determined from the first derivative of the calculated equation of the curve fit through the measured dry weights. A second order exponential polynomial was used to calculate the equation of the curve fit (Chapter 4). When, instead of the second order exponential polynomial, the logistic equation (equation 2.1) was used to fit the measured dry weights, the maximum growth rate was found to occur at 29 ± 2 days (except for most control treatments where the plants were still growing exponentially at the final harvest day). Thus, using a different equation to fit the measured dry weight data resulted in a very small change in the calculated occurrence of the maximum growth rate. It would be more accurate to determine the occurrence of the maximum growth rate from daily dry weight measurements. However, during the experiments dry weights were determined every three or four days. Therefore, a careful consideration should be given to the calculation of dW/dt_{max} as presented in this study.

Based on the predicted dry weight production using the simulation Model1 and the sensitivity analysis of the model parameters, future growth trials should include measurements of several plant characteristics. These measurements can increase the reliability of model predictions. One of these measurements is the plant root dry weight. The sensitivity analysis showed model predictions are somewhat sensitive to root dry weights. However, since lettuce plants grown in a hydroponic system are usually rooted in a growth medium, special precautions are needed to gather all the root material produced for an accurate dry weight measurement. Measuring the dry weight of cube, growth medium and root mass at once would simplify the procedure, but is only possible when the dry weights of cube and growth medium are known ahead of time. Other measurements to be included in future growth trials are the actual CO_2 assimilation rate at light saturation for individual leaves (A_{max}) and the initial light use efficiency for individual leaves (EFF). The sensitivity analysis showed model predictions were very sensitive to the value of EFF and to a lesser degree to the value of A_{max}.

In this study, it was assumed plant leaf temperature was the same as the measured ambient air temperature. The leaf temperature of a plant is determined by the amount of irradiation a leaf absorbs and the amount of water it transpires. Therefore, leaf temperature can differ from ambient air temperature. The sensitivity analysis showed model predictions were not very sensitive to ambient air temperature, but leaf temperature was not a parameter in the model. Careful measurements, recommended for future growth trials, are needed to determine the influence of irradiation (solar or supplemental) on leaf temperature. However, determining the leaf temperature of the inner leaves of a growing lettuce head will be a challenge.

In addition to preventing tipburn, the overhead fan used in most of the experiments increased the uniformity of air temperature and CO_2 concentration. Without any additional air mixing and during time periods when no ventilation is needed, little air movement will occur in the greenhouse. This could result in areas where air temperature and CO_2 concentration differ from their values measured at the sensor location. Since any control decision relies on accurate sensor readings of the environment conditions in the greenhouse, the additional air mixing was considered a benefit to the uniformity and control of temperature and CO_2 concentration. The uniformity of light intensity over the growing area is discussed in Appendix A. Although great attention was paid to the lighting system used in this study, designing for a truly uniform light intensity over a growing area is not an easy task. Additional luminaires were used in the design to improve the uniformity. However, in a commercial operation some degree of non-uniformity of light distribution will be likely, possibly causing non uniform plant growth. A commercial grower will have to decide to what extend non-uniform plant growth is acceptable. A carefully designed lighting system can help prevent non-uniform plant growth.

The plant water loss in ml of water per gram of dry weight accumulated was found to be correlated with the daily integrated PAR received by the plants (Chapter 4, Figure 4.10). This result can be used in a control strategy to control the amount of make-up solution needed to keep the nutrient solution at an optimal level, both quantity and quality wise. Such a control strategy would give a grower additional insight, besides the daily light readings, into the growth and development of the lettuce plants. A grower could choose to adjust the daily integrated PAR in order to prevent tipburn by maintaining a water loss of 400 ml per gram of dry weight accumulated. The disadvantage of this strategy is a reduced predictability of the timing of final harvest. This predictability is key to a successful commercial hydroponic lettuce operation.

Goto and Takakura (1992) hypothesized an increase in transpiration rate will increase the transport of Ca through the xylem, thus reducing or preventing tipburn. In this study tipburn was prevented when a lettuce plant transpired at least 400 ml of water per gram of dry weight accumulated. Thus, the results of this study support the hypothesis posed by Goto and Takakura.

Is it possible to increase the dry weight production in the hydroponic NFT system used in this study while maintaining a 35-day growth period or less? To increase the dry weight production a grower can: (1) change cultivars, (2) increase plant spacing (especially in the final growth stage), (3) increase the amount of supplemental lighting, (4) allow as much sunlight as possible to reach the plants by increasing the light transmissivity of the greenhouse (structural components, glazing material), and (5) increase the number of spacings (to increase the dry weight production per m^2 greenhouse area). However, by doing so a grower should be aware of the following consequences: (1) increasing the plant spacing (to less than 78 plants per m^2) and supplemental lighting (to more than 17 mol m^{-2} d^{-1}) will quickly cause tipburn to become a major problem, (2) increasing the plant spacing will decrease the overall greenhouse space efficiency, (3) increasing the supplemental lighting will increase the electricity consumption, and (4) more spacings will increase the labor requirements. In a larger commercial operation, labor requirements can be minimized by an increased use of automation. For small operations, however, automation will not always be cost effective. Another hypothesis, not tested in this study, is that an increase in dry weight production is possible when the temperature set point is relaxed during periods with high irradiance. Thus, the ventilation can be reduced, allowing the CO_2 concentration in the greenhouse to remain high during longer periods of time, further benefitting the rate of photosynthesis.

During the eight months experiments were performed for this study, a total of nearly 32,000 lettuce seeds were seeded and 24,000 seedlings were transplanted into the five greenhouse sections. Almost 18,000 lettuce plants were harvested, dried and dry weights were determined. The large number of data points resulted in a small value of the calculated standard deviation and increased the reliability of the results (Chapter 4). As was shown in Figure 4.15, the calculated standard deviation of the measured final dry weights at harvest 7 increased with increasing final dry weight. Figure 4.15 shows the linear correlation between calculated standard deviation and measured final dry weight. In order to compare treatments with very different dry weights, the coefficient of variation (CV, ratio of the standard deviation and the mean) was calculated for the final harvest of each treatment. On average, the CV was 10.3% (i.e., the CV multiplied by 100%) and changed little from one experiment to another (between 8.5 and 13.4%). The CV for other harvests changed little from the value calculated for harvest 7. Thus, a CV of around 10% was found for the dry weight measurements presented in this study.

The hydroponic system used to grow the lettuce in this study included the use of plastic troughs with covers. Growing plants in shallow troughs (the NFT system) has some advantages: (1) the troughs can be raised on rolling benches to provide a more comfortable working height, (2) troughs can be cleaned easily between production runs, and (3) troughs can simply be replaced in case of failure. However, using troughs to grow plants has disadvantages too: (1) generally, a one dimensional spacing is the only spacing option (i.e., only the distance between troughs is changed, not the distance between plants in the troughs), (2) troughs are relatively expensive, and (3) no buffer of nutrient solution is available to the plant roots in case of pump failure or plumbing leak. Especially the last disadvantage is important for a commercial hydroponic lettuce operation. In the research facility used in this study, several watchful eyes were present to detect any problems as soon as possible. And even then, whole treatments were (nearly) lost due to plumbing leaks, pump failures or an accidental low pH in the nutrient solution. It was felt that most of these problems could have been prevented if the volume of the nutrient solution around the roots was increased. The pond system (or floating lettuce system) dramatically increases the volume of the nutrient solution around the roots from a thin film in the NFT system to a solution depth of around 30 cm. The lettuce plants grown in the pond system are sown in a different growth medium than the one used in this study: rockwool or oasis. At transplant, the small cube of growth medium containing the lettuce plants are wedged into small holes in a Styrofoam board. Many Styrofoam boards float on top of a pond filled with water containing the proper nutrient solution. Extra precaution is needed to maintain the dissolved oxygen (DO) level of the nutrient solution at an acceptable level (e.g., at the saturation level of 8.5 mg l^{-1} at a water temperature of 24 °C). However, the higher the water temperature, the less oxygen can be dissolved in water. The pond system has not only a large buffer capacity for the correct nutrient solution but for heat as well. In addition, moving lettuce plants, for example, from transplant site to final harvest site takes minimum effort because the lettuce floats on water and high space efficiencies are possible because few walk ways are needed. These clear advantages should be carefully considered for future hydroponic lettuce operations. At Cornell, research is under way to investigate the pond system and its possibilities in detail.

To increase the reliability of the experimental data, automatic shading should be installed in the research greenhouse. In this study, a fixed shading screen was installed in early March and in April and May additional layers of white wash were applied to the outside of the greenhouse glazing. Little flexibility was possible with this system making days with little or no sunshine even darker because the shading could not be removed easily from the greenhouse. The shading was started early in the season to enable experimentation with reasonable time periods of supplemental lighting. With automatic shading, bright periods causing light saturation and ultimately wilting of plants, can be avoided as much as possible, while at dark days all available light can enter the greenhouse. An additional advantage of automatic shading is the same material can serve as a night curtain preventing heat from being radiated from the plant environment to the colder glazing material and outside environment. A careful design of an automatic shading system is needed in order to operate it in combination with a supplemental lighting system. Both systems need to operate independently in the limited amount of space between the top of a canopy and the roof of a greenhouse.

In this study, lettuce was grown in five identical greenhouse sections using the all-in, all-out system: at the final harvest all plants were removed from the greenhouse and each section was thoroughly cleaned before a new experiment started. This procedure was followed to prevent the spread of disease and the establishment of disease organisms in air or water. Indeed, no (visible) disease problems other than tipburn were observed during any of the 35 treatments over an eight-month period. However, in a commercial hydroponic lettuce operation, a continuous production system will likely be used because lettuce will be harvested on a daily basis. The possibility exists that in a continuous production system disease prevention can become a major concern. The experience of a large commercial hydroponic lettuce operation (near Montreal, Canada, using the pond system) suggests, however, disease is not a major concern. But no experience exists growing hydroponic lettuce in New York State in a large scale continuous production system using relatively high day and nighttime temperatures (24 and 18.8 °C, respectively).

Chapter 6

Conclusions

- The daily integrated photosynthetically active radiation (PAR_i) needed to grow leaf lettuce (cv. Ostinata) in the hydroponic system used in this study from transplant (11 days after seeding) to a fresh weight of 150 grams (35 days after seeding) is 17 mol m^{-2} d^{-1}.
- Tipburn was entirely prevented by using an overhead fan, which blew ambient air vertically downward on the lettuce plants (started at 18 days after seeding), in combination with a PAR_i less than or equal to 17 mol m^{-2} d^{-1}. The use of the fan did not negatively affect plant dry weight production.
- Tipburn was prevented when the leaf lettuce variety used in this study (cv. Ostinata) transpired at least 400 ml of water per gram of dry weight accumulated, even when a PAR_i above 17 mol m^{-2} d^{-1} was used.
- The difference in dry weight production between leaf lettuce (cv. Ostinata) grown under daytime and nighttime lighting (maintaining the same PAR_i) was small. This result favors the more economical use of off-peak electricity during the off-peak hours at night.
- The result of the April experiment, using delayed supplemental lighting, indicated the possibility to delay supplemental lighting to periods with greater (and, thus, cheaper) availability of electricity. This result suggests the possibility of implementing demand-side electricity management.
- The result of the May experiment, using different supplemental lighting intensities, indicated the possibility of using lower instantaneous light intensities over a longer period of time, compared to higher intensities over shorter periods of time (maintaining the same PAR_i) for similar dry weight production.
- For the environment conditions used during this study, a modified version (LETSGROW.PAS) of the universal crop growth model SUCROS87 could accurately predict the dry weight production of hydroponic leaf lettuce (cv. Ostinata).

- LETSGROW.PAS could use historical average solar radiation data for Ithaca, NY, to accurately predict leaf lettuce (cv. Ostinata) dry weight production.
- A sensitivity analysis of LETSGROW.PAS, investigating the dry weight accumulation at final harvest, revealed the model is particularly sensitive to the: (1) plant density after spacing, (2) day at which respacing took place, (3) number of days the plants stayed in the greenhouse, (4) incoming daily PAR, (5) initial light use efficiency for individual leaves, and (6) leaf area ratio.

Summary

Local lettuce production in New York State is done on a small scale and concentrates on outdoor summer production. Only 6.5% of the fresh lettuce sold in our state is locally grown (New York Agricultural Statistics 1992 - 1993). With large population centers nearby, year-round greenhouse lettuce production has great economic potential. However, the small amount of sunlight received in the winter months prevents a timely crop production. The use of supplemental lighting and carbon dioxide enrichment can significantly speed up crop development. This study investigated the use of supplemental lighting to produce high quality lettuce grown in a hydroponic system in a Controlled Environment Agriculture (CEA) greenhouse.

The main objectives of this study were: (1) to determine how supplemental lighting can be used to ensure a timely and consistent lettuce production, and (2) to provide greenhouse growers and researchers with a computer simulation program to simulate the effects of different daily integrated light levels, indoor temperature, and plant spacing on the growth and development of lettuce.

A greenhouse at the Cornell University Campus was retrofitted to enable computer control of the environment in each of its five identical sections. Temperature, carbon dioxide concentration and daily integrated PAR (Photosynthetically Active Radiation) were carefully monitored and controlled at predetermined set points. The daily integrated PAR from sunlight was supplemented with PAR from High Pressure Sodium (HPS) lamps until the daily total integrated PAR (PAR_i) set point was reached. At that moment, the computer system turned the supplemental lighting off. During treatments, the PAR_i was kept constant from day to day. The experimental design assigned a different PAR_i set point to each treatment.

A bibb lettuce variety (***Lactuca sativa*** L., cv. Ostinata) was grown in a so-called trough system. A thin nutrient solution film was continuously circulated by the lettuce roots (Nutrient Film Technique) while a constant pH (5.8) and nutrient concentration (EC = 0.12 S m^{-1}) were maintained. During the first

11 days after seeding, the lettuce seedlings were kept in a growth chamber under fluorescent lighting with a 24-hour photoperiod. At day 11, the seedlings were transplanted into the greenhouse directly into the troughs. Five different lighting treatments were studied simultaneously in the five greenhouse sections. A total of 35 treatments was conducted during an eight-month period (October 1992 - May 1993). Twice weekly harvests enabled a close observation of plant dry weight production. All treatments were terminated 35 days after seeding.

Leaf lettuce, when grown under high PAR_i, is susceptible to tipburn. Tipburn is the result of a calcium deficiency in rapidly growing young leaves, causing necrosis at the leaf tips. Very little necrosis is tolerated before the lettuce becomes unsalable. In this study, the occurrence of tipburn was prevented by blowing ambient air vertically downward onto the lettuce plants. The air movement increased the amount of water transpired from the lettuce leaves. This increase in transpiration promoted the transport of nutrients, including calcium, from the roots to the leaves. Using this technique, tipburn was prevented entirely when the lettuce plants received a maximum of 17 mol m^{-2} d^{-1} PAR_i and transpired at least 400 ml of water per gram of dry weight produced.

In order to produce a marketable lettuce head of 150 grams fresh weight (equivalent to a dry weight of nearly 7 grams) in 35 days after seeding, a lettuce plant required 17 mol m^{-2} d^{-1} PAR_i during the 24 days it stayed in the greenhouse. During the first 11 days, when the seedlings remained in the growth chamber, each plant accumulated a dry weight of nearly 0.04 grams. Depending on the season, the amount of sunlight received in the greenhouse was supplemented with a varying amount of artificial light (HPS). Little difference was found between adding the supplemental light during the daytime or at night. This result favors the more economical use of off-peak electricity during the off-peak hours at night. Furthermore, it was possible to delay the use of supplemental lighting for a day or two to reach the same dry weight production, provided the accumulated PAR_i over the entire experiment stayed the same. This result indicates the possibility of delaying supplemental lighting to periods with greater (and, thus, cheaper) availability of electricity, and makes the implementation of demand-side electricity management possible. The light intensity of the supplemental lighting did not seem to be important as long as the amount of PAR_i remained the same. This favors the use of lower intensities over longer periods of time compared to higher intensities over shorter periods of time and significantly reduces the peak electricity demand of a hydroponic lettuce operation using supplemental lighting.

A computer simulation program (LETSGROW.PAS) was developed to simulate lettuce dry weight production under various environment conditions. The simulation program is an adaptation of the universal crop growth model SUCROS87. SUCROS87 applied a three point Gaussian integration method to estimate the daily amount of photosynthesis from the available incoming radiation and the amount of leaf area present. However, during this study it was discovered the three-point integration method was not sufficiently accurate in all possible circumstances. Therefore, in the simulation model LETSGROW.PAS, the three point Gaussian integration method was replaced with a five point Gaussian integration method. Another adjustment to SUCROS87 rendered several of its parameters (e.g., A_{max} and EFF) dependent on the carbon dioxide concentration inside the greenhouse in order to model plant response to carbon dioxide enrichment. LETSGROW.PAS could accurately predict growth and development of the hydroponic lettuce used in this study. It required historical daily average (as opposed to actual) solar radiation data for Ithaca, NY, as input data. This feature makes LETSGROW.PAS a very useful tool for growers and researchers interested in the prediction and scheduling of future lettuce production.

Samenvatting

De omvang van de teelt van bladsla in de staat New York is klein en concentreert zich op de vollegrondsteelt in de zomer. Slechts 6,5% van de verse sla die in deze staat wordt verkocht, wordt hier ook geteeld (volgens de New York Agricultural Statistics 1992 - 1993). Met vele grote steden in de directe omgeving lijkt een seizoensonafhankelijke kasslateelt economisch aantrekkelijk. De relatief kleine hoeveelheid zonlicht in de wintermaanden (alhoewel gemiddeld ongeveer twee keer zo veel als in Nederland) maakt een korte teeltduur echter onmogelijk. Het gebruik van kunstmatige belichting en een verhoogde kooldioxide concentratie in de kas kan de gewasontwikkeling aanzienlijk versnellen. Dit onderzoek bestudeerde het gebruik van kunstmatige belichting tijdens de teelt van een hoge kwaliteit bladsla in een gootsysteem in een kas met computer-gestuurde klimaatregeling.

De belangrijkste vraagstellingen van dit onderzoek waren:

1) Hoe kan kunstmatige belichting worden gebruikt om een voorspelbare slaproductie te garanderen?
2) Kan een computersimulatieprogramma tuinders en onderzoekers helpen bij de voorspelling van slaproductie, wanneer verschillende dagtotalen licht, verschillende temperaturen en verschillende plantdichtheden worden toegepast?

Allereerst werd een kas op de campus van Cornell University gerenoveerd zodat in elk van de vijf identieke compartimenten een computergestuurd klimaat gerealiseerd kon worden. Nauwkeurige metingen van de temperatuur, de kooldioxide concentratie en het dagtotaal licht (geintegreerde "Photosynthetically Active Radiation", PAR_i) werden door de computer opgeslagen en deze parameters werden op van te voren vastgelegde streefwaarden gehandhaafd. Het dagtotaal licht, afkomstig van de zon, werd aangevuld met licht van hoge druk natrium lampen totdat de streefwaarde voor het dagtotaal was bereikt. Op dat moment schakelde de computer de lampen in de kas uit. Per experiment werd het dagtotaal licht van dag tot dag op een vaste streefwaarde gehandhaafd. Afhankelijk van het

experimentele ontwerp werden verschillende streefwaarden aan ver-schillende experimenten toegewezen.

De bladsla van het soort ***Lactuca sativa*** L., cv. Ostinata werd in een gootsysteem geteeld. Een kleine hoeveelheid water werd constant langs de wortels van de sla gepompt (Nutrient Film Technique), terwijl een constante zuurgraad (pH = 5,8) en voedingsconcentratie (EC = 0.12 S m^{-1}) van de oplossing gehandhaafd werden. Gedurende de eerste elf dagen na zaaien werden de slaplantjes in een klimaatkamer opgekweekt onder TL belichting met een belichtingsperiode van 24 uur. Op de elfde dag werden de plantjes naar de kas overgebracht en direct in de gootjes geplaatst. Vijf verschillende belichtingsbehandelingen werden tegelijkertijd bestudeerd in de vijf kascompartimenten. In totaal werden 35 verschillende belichtings-proeven uitgevoerd gedurende een periode van acht maanden (augustus 1992 - mei 1993). De droge stof productie van de slaplanten werd nauwkeurig gevolgd door ze twee keer per week te oogsten. Alle experimenten werden 35 dagen na zaaien beëindigd.

Bladsla, groeiend onder hoge dagtotalen licht, is gevoelig voor rand. Rand is het gevolg van een gebrek aan calcium in de snel groeiende jonge bladeren en manifesteert zich als necrose aan de top van het blad. Een kleine aantasting door rand maakt de sla al snel onverkoopbaar. In dit onderzoek kon rand voorkomen worden door een constante verticale neerwaartse luchtstroom op de bladsla te creëren. Deze luchtstroom verhoogde de verdamping van de slabladeren. De verhoogde verdamping vergrootte het transport van voedingsstoffen, inclusief calcium, van de wortels naar de bladeren. Rand werd geheel voorkomen wanneer de planten een dagtotaal van niet meer dan 17 mol m^{-2} d^{-1} (PAR_i) ontvingen en tenminste 400 ml water verdampten per gram geproduceerde droge stof.

Om een verkoopbare krop sla met een vers gewicht van 150 gram (oftewel een droge stof gewicht van bijna 7 gram) te telen in een tijdsduur van 35 dagen, bleek een dagtotaal licht nodig van 17 mol m^{-2} d^{-1} gedurende de 24 dagen dat de sla in de kas verbleef. Gedurende de eerste elf dagen in de klimaatkamer groeide de sla tot een droge stof gewicht van bijna 0,04 gram. Eenmaal in de kas, en afhankelijk van het seizoen, werden verschillende hoeveelheden kunstlicht gebruikt om de dagtotalen te realiseren. Het maakte weinig verschil of het kunstlicht gedurende de dag of 's nachts werd toegevoegd. Het lijkt voordeliger om de belichting 's nachts toe te voegen tijdens de goedkopere nachtstroom uren. Het was tevens mogelijk om de toediening van kunstmatige belichting een dag of twee uit te stellen mits de totale hoeveelheid licht over de gehele groeiperiode constant bleef. Dit resultaat maakt het mogelijk om te wachten met de belichting totdat de electriciteitsprijs lager is (bijvoorbeeld in het weekeinde) en maakt de tuinder minder afhankelijk van de beschikbaarheid en prijs van de electriciteit. De intensiteit van de kunstmatige belichting bleek weinig invloed te hebben zolang het dag-totaal hetzelfde bleef. Het piek stroomgebruik van een slatuinder die kunstmatige belichting gebruikt kan dus verlaagd worden door een lagere intensiteit te gebruiken verspreid over een langere tijdsduur in plaats van een hogere intensiteit over een kortere tijdsduur.

Een computersimulatieprogramma (LETSGROW.PAS) werd ontwikkeld om de droge stof productie van bladsla onder verschillende klimaatsomstandigheden te simuleren. Dit simulatieprogramma is gebaseerd op en een toepassing van het gewasgroeimodel SUCROS87. SUCROS87 gebruikt een driepunts Gaussische integratiemethode om, gebaseerd op de dagtotaal licht en het totale bladoppervlak, de hoeveelheid assimilatie te berekenen. Tijdens dit onderzoek bleek de driepunts-integratiemethode niet voldoende nauwkeurig in alle mogelijke omstandigheden. Vandaar dat in het simulatie programma LETSGROW.PAS de driepunts Gaussische integratiemethode is vervangen door een vijfpunts Gaussische integratiemethode. SUCROS87 werd verder aangepast door verschillende variabelen (bijvoorbeeld A_{max} en EFF) afhankelijk te maken van de kooldioxide concentratie in de kas. Deze aanpassing maakte het mogelijk om de toediening van kooldioxide te modelleren. LETSGROW.PAS kon de slagroei, onder de klimaatsomstandigheden gebruikt in deze studie, nauwkeurig voorspellen. Het programma gebruikte historische dagelijks gemiddelde zonnestralingsgegevens (in tegenstelling tot werkelijk gemeten gegevens) voor Ithaca, NY, als input-waarden. Hierdoor is LETSGROW.PAS een zeer bruikbaar hulpmiddel voor tuinders en onderzoekers die geïnteresseerd zijn in de voorspelling en planning van toekomstige slaproductie.

Appendix A

Lighting Uniformity Analysis

The "Design" data were calculated with the computer program Lumen-Micro (Version 5, Lighting Technologies, Inc., Boulder, CO). The data listed under the caption "Implementation" were found after careful PAR measurements in the research greenhouse. A calibrated LI-COR quantum-sensor recorded the PAR readings in µmol m^{-2} s^{-1}. See also Both et al., 1994b, and Albright and Both, 1994.

<u>Using 20 luminaires over the growing area (4.5 by 3.7 m):</u>

	Design	Implementation
Average	182	230
Average ± 15%	155 - 209	196 - 265
Min - Max	115 - 214	140 - 278
Standard Deviation	25	30
Growing Area (m^2)	16.7	16.7
Number of Data Points	110	63
Number of Measurements m^{-2}	6.6	3.8
Number of Luminaires	20	20
Number of Luminaires m^{-2}	1.20	1.20

	Design	(Recommendation)	Implementation	(Recommendation)
Min/Avg	0.63	(≥0.80)	0.61	(≥0.80)
Min/Max	0.54	(≥0.70)	0.50	(≥0.70)
Uniformity Coefficient 1	0.88	(≥0.75)	0.90	(≥0.75)
Uniformity Coefficient 2	0.86	(≥0.75)	0.87	(≥0.75)
Fraction within ± 15%	0.80	(1.00)	0.79	(1.00)

<u>Using 17 luminaires over the growing area (4.5 by 3.7 m):</u>

	Design	Implementation
Average	149	196
Average ± 15%	126 - 171	167 - 225
Min - Max	102 - 167	130 - 244
Standard Deviation	16	26
Growing Area (m^2)	16.7	16.7
Number of Data Points	110	63

Number of Measurements m^{-2}	6.6		3.8	
Number of Luminaires	17		17	
Number of Luminaires m^{-2}	1.02		1.02	
		(Recommendation)		
Min/Avg	0.68	(≥0.80)	0.66	(≥0.80)
Min/Max	0.61	(≥0.70)	0.53	(≥0.70)
Uniformity Coefficient 1	0.91	(≥0.75)	0.89	(≥0.75)
Uniformity Coefficient 2	0.89	(≥0.75)	0.87	(≥0.75)
Fraction within ± 15%	0.89	(1.00)	0.73	(1.00)

<u>Using 11 luminaires over the growing area (4.5 by 3.7 m):</u>

	Design		Implementation	
Average	95		123	
Average ± 15%	81 - 109		105 - 141	
Min - Max	70 - 106		79 - 151	
Standard Deviation	10		16	
Growing Area (m^2)	16.7		16.7	
Number of Data Points	110		63	
Number of Measurements m^{-2}	6.6		3.8	
Number of Luminaires	11		11	
Number of Luminaires m^{-2}	0.66		0.66	
		(Recommendation)		
Min/Avg	0.74	(≥0.80)	0.64	(≥0.80)
Min/Max	0.66	(≥0.70)	0.52	(≥0.70)
Uniformity Coefficient 1	0.91	(≥0.75)	0.89	(≥0.75)
Uniformity Coefficient 2	0.90	(≥0.75)	0.87	(≥0.75)
Fraction within ± 15%	0.92	(1.00)	0.73	(1.00)

<u>Definitions:</u>

$$\text{Uniformity Coefficient 1} = 1 - [(\Sigma|Y_i - Y_{ave}|)/(n * Y_{ave})]$$

$$\text{Uniformity Coefficient 2} = 1 - CV = 1 - [\sqrt{(\Sigma(Y_i - Y_{ave})^2/(n - 1))}]/Y_{ave}$$

where:

Y_i = PAR reading at location i
Y_{ave} = Average PAR reading over the growing area
n = Number of PAR readings over the growing area
CV = Coefficient of Variation

<u>Recommendations for a lighting uniformity analysis:</u>

- Include only the actual growing area in the lighting uniformity analysis (i.e., exclude any areas, such as walk ways, at the edges of the growing area).
- For growing areas up to 20 m^2: Take 4 measurements per m^2, i.e., one measurement in the center of each 0.25 m^2 (0.5 by 0.5 m).
- For growing areas above 20 m^2: Take 1 measurement per m^2, i.e., one measurement in the center of each m^2 (1 by 1 m).
- Use one of the Uniformity Coefficients and distribution graphs (Figures A.1, A.2 and A.3) to compare lighting uniformity amongst designs.
- Design for a Uniformity Coefficient of at least 0.75 (preferably at least 0.90) and the fraction within ± 15% of the average PAR value should be close to 1.

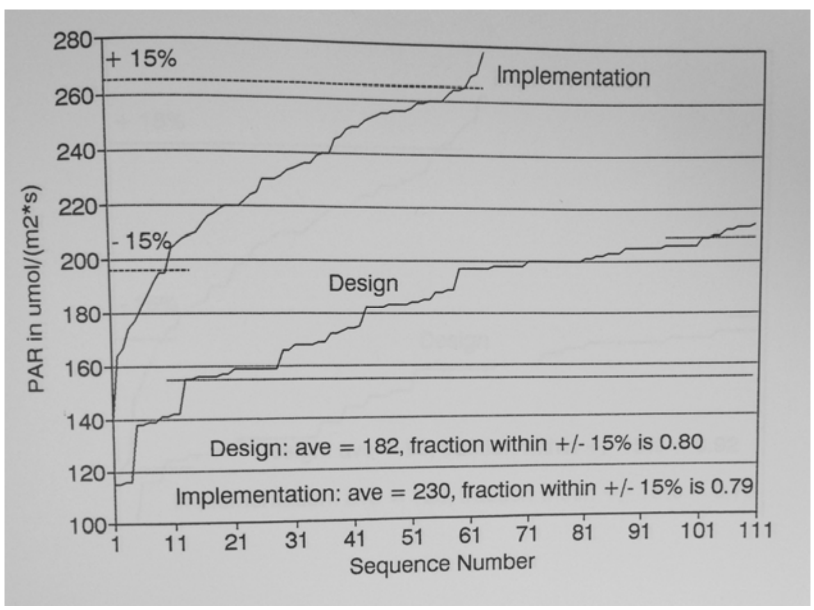

Figure A.1 Distribution graph of the amount of PAR in the research greenhouse while 20 luminaires were burning over the growing area.

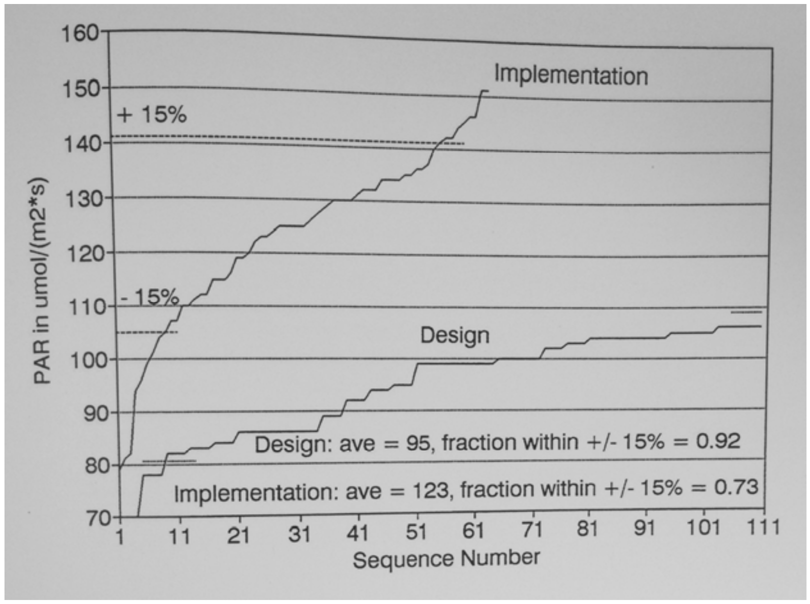

Figure A.2 Distribution graph of the amount of PAR in the research greenhouse while 17 luminaires were burning over the growing area.

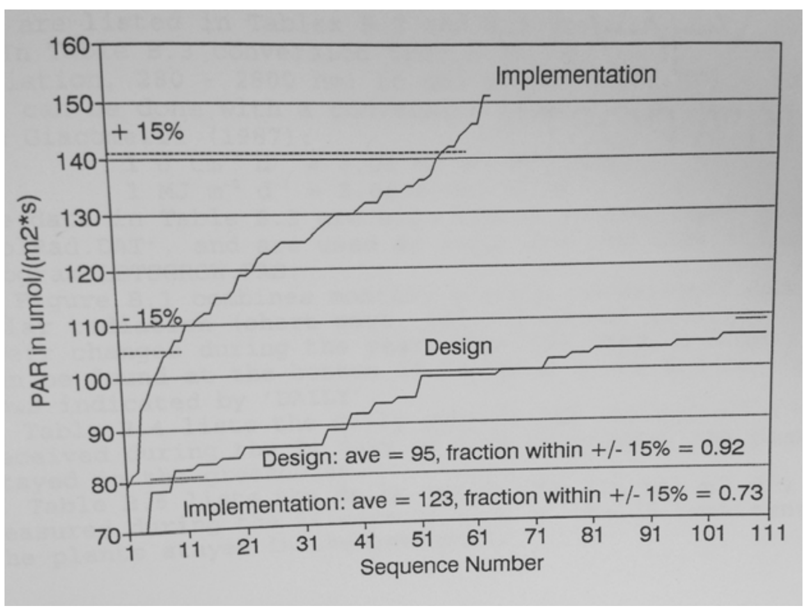

Figure A.3 Distribution graph of the amount of PAR in the research greenhouse while 11 luminaires were burning over the growing area.

Appendix B

Weather Data

Table B.1 shows the average hourly and daily temperature data for Ithaca, NY, calculated from weather data collected over a nine-year period (1983 - 1991). For the same period and location, the relative humidity and solar radiation (short wave, 280 - 2800 nm) data were collected and are listed in Tables B.2 and B.3 respectively.

In Table B.3 conversion from J cm^{-2} d^{-1} (short wave radiation, 280 - 2800 nm) to mol m^{-2} d^{-1} (PAR, 400 - 700 nm) can be done with a conversion factor described by Ting and Giacomelli (1987):

$$1 \text{ J cm}^{-2} \text{ d}^{-1} = 0.01 \text{ MJ m}^{-2} \text{ d}^{-1}, \text{ and}$$
$$1 \text{ MJ m}^{-2} \text{ d}^{-1} = 2.0804 \text{ mol m}^{-2} \text{ d}^{-1}.$$

The data in Table B.3 are also listed in the input-file 'SolRad.DAT', and are used as input for the simulation program LETSGROW.PAS.

Figure B.1 combines monthly average temperature and solar radiation (short wave, 280 - 2800 nm) data to trace their changes during the year. The data used in Figure B.1 can be found at the bottom of Tables B.1 and B.3 in the rows indicated by 'DAILY'.

Table B.4 lists the daily outside PAR (in mol m^{-2} d^{-1}) received during the 24 days of each experiment the plants stayed in the greenhouse.

Table B.5 lists the daily inside PAR (in mol m^{-2} d^{-1}) measured during the 24 days of each of the 35 treatments the plants stayed in the greenhouse.

Table B.1 Average hourly and daily temperature in °C for Ithaca, NY, for a nine year period (1983 - 1991).

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0-1	-5.2	-4.9	-1.0	4.2	9.3	13.3	15.9	15.1	11.8	7.3	2.6	-2.7
1-2	-5.3	-5.1	-1.3	3.8	8.9	12.8	15.4	14.7	11.4	7.0	2.4	-2.8
2-3	-5.5	-5.3	-1.5	3.4	8.6	12.4	15.0	14.4	11.1	6.8	2.2	-2.9
3-4	-5.6	-5.4	-1.6	3.1	8.3	12.1	14.7	14.1	10.8	6.5	2.1	-3.0
4-5	-5.7	-5.6	-1.8	2.9	8.0	11.8	14.4	13.9	10.6	6.4	2.1	-3.1
5-6	-5.8	-5.7	-2.0	2.8	8.2	12.3	14.7	13.9	10.4	6.2	1.9	-3.2
6-7	-5.9	-5.8	-2.0	3.4	9.6	14.0	16.2	14.8	10.8	6.3	1.8	-3.2
7-8	-5.9	-5.7	-1.3	4.8	11.7	16.4	18.6	16.9	12.5	7.1	1.9	-3.3
8-9	-5.4	-4.7	0.0	6.5	13.6	18.3	20.8	19.3	14.7	8.7	2.8	-2.9
9-10	-4.4	-3.4	1.3	7.8	15.1	19.6	22.4	21.1	16.7	10.3	3.9	-2.1
10-11	-3.4	-2.4	2.4	8.9	16.1	20.7	23.5	22.3	18.1	11.8	4.8	-1.3
11-12	-2.7	-1.6	3.3	9.9	16.9	21.5	24.4	23.3	19.0	12.8	5.5	-0.7
12-13	-2.1	-1.0	4.0	10.7	17.4	22.2	25.0	24.0	19.6	13.4	6.1	-0.3
13-14	-1.8	-0.6	4.6	11.2	17.8	22.6	25.3	24.5	20.0	13.9	6.5	-0.1
14-15	-1.6	-0.4	4.8	11.5	17.9	22.8	25.5	24.6	20.1	14.0	6.6	0.0
15-16	-1.8	-0.6	4.8	11.5	17.9	22.7	25.5	24.4	19.9	13.8	6.3	-0.2
16-17	-2.4	-1.0	4.5	11.2	17.5	22.4	25.2	23.9	19.4	12.9	5.6	-0.8
17-18	-3.2	-1.9	3.7	10.6	16.8	21.8	24.6	23.1	18.3	11.4	4.7	-1.4
18-19	-3.9	-2.8	2.5	9.5	15.7	20.8	23.6	21.5	16.4	9.8	4.1	-1.8
19-20	-4.3	-3.5	1.5	8.0	14.0	18.9	21.6	19.4	14.7	8.9	3.7	-2.0
20-21	-4.5	-3.9	0.8	6.8	12.3	16.8	19.4	17.7	13.7	8.3	3.4	-2.2
21-22	-4.7	-4.2	0.2	6.1	11.2	15.4	18.1	16.7	13.0	7.8	3.1	-2.3
22-23	-4.9	-4.4	-0.2	5.4	10.4	14.6	17.3	16.0	12.5	7.5	2.9	-2.4
23-24	-5.1	-4.7	-0.6	4.9	9.9	13.9	16.5	15.4	12.1	7.2	2.7	-2.6
DAILY	-4.2	-3.5	1.0	7.0	13.0	17.5	20.2	19.0	14.9	9.4	3.7	-2.0

Table B.2 Average hourly and daily relative humidity in % for Ithaca, NY, for a nine year period (1983 - 1991).

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0-1	79	80	79	79	80	83	86	84	85	86	84	81
1-2	80	81	79	80	81	83	87	85	85	86	84	82
2-3	80	81	80	81	82	84	87	85	86	87	85	82
3-4	80	81	81	82	82	85	88	85	86	88	85	82
4-5	80	81	81	82	83	85	88	86	86	88	85	82
5-6	81	82	82	83	83	85	88	86	87	88	85	82
6-7	81	82	82	81	80	80	85	84	86	88	86	82
7-8	81	82	79	77	73	73	79	80	83	86	85	83
8-9	79	79	74	72	67	67	73	74	77	82	83	81
9-10	76	75	70	67	63	62	69	69	72	77	80	79
10-11	73	71	66	64	60	59	65	65	67	72	77	76
11-12	71	69	63	61	57	56	62	61	65	69	75	74
12-13	70	67	61	59	55	54	59	58	62	66	72	72
13-14	69	67	59	58	54	53	58	57	62	64	71	71
14-15	68	67	58	57	53	52	57	56	61	64	70	71
15-16	69	67	58	57	53	52	57	57	62	65	71	72
16-17	71	69	59	57	54	53	58	58	63	68	74	75
17-18	74	72	62	59	56	55	61	62	68	75	77	76
18-19	76	75	66	63	60	59	66	70	76	79	79	78
19-20	77	77	71	69	68	69	76	78	80	82	81	79
20-21	77	78	73	73	73	76	81	80	82	83	82	80
21-22	78	79	75	75	77	78	83	82	83	84	83	80
22-23	78	79	77	77	78	80	84	83	84	85	83	80
23-24	79	80	78	78	80	81	85	83	84	86	83	81
DAILY	76	76	71	70	69	69	74	74	76	79	80	78

Table B.3 Average hourly and daily total solar radiation data in J cm^{-2} for Ithaca, NY, for a nine year period (1983 - 1991).

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0-1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1-2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2-3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3-4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4-5	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0
5-6	0.0	0.0	0.0	2.5	13.8	20.7	14.6	4.2	0.0	0.0	0.0	0.0
6-7	0.0	0.0	5.3	26.1	47.3	60.2	50.0	32.9	15.7	3.7	0.0	0.0
7-8	1.1	9.2	35.4	61.5	91.9	106.8	95.7	76.9	53.4	29.5	8.9	1.0
8-9	19.3	38.2	73.8	101.7	138.1	152.7	146.7	125.2	95.8	64.2	32.8	16.1
9-10	48.1	71.3	111.3	136.8	175.6	195.6	192.2	166.6	139.4	97.3	56.1	38.9
10-11	72.5	100.0	146.5	167.4	201.6	224.8	222.6	199.3	167.6	121.6	71.8	58.1
11-12	86.7	117.3	166.4	186.8	206.6	239.8	238.3	221.0	178.7	134.0	78.5	70.7
12-13	89.6	120.7	170.1	183.9	206.2	239.3	238.3	225.7	178.3	129.7	81.0	69.4
13-14	77.8	110.6	158.5	173.0	193.9	227.5	225.8	211.6	161.8	118.4	70.1	58.9
14-15	60.2	89.1	132.1	147.2	168.6	200.3	202.3	177.8	131.4	89.9	49.9	41.6
15-16	34.6	60.5	96.3	110.1	134.7	159.0	163.5	140.9	99.0	53.5	25.2	19.9
16-17	8.9	28.1	55.4	70.0	93.4	116.7	117.3	94.3	59.1	20.5	4.3	2.1
17-18	0.0	3.3	17.2	34.0	52.7	69.7	71.5	47.8	19.3	1.2	0.0	0.0
18-19	0.0	0.0	0.2	5.5	17.5	29.4	28.5	12.3	0.6	0.0	0.0	0.0
19-20	0.0	0.0	0.0	0.0	0.2	3.0	2.2	0.1	0.0	0.0	0.0	0.0
20-21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21-22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22-23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23-24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DAILY	499	748	1169	1407	1742	2046	2010	1737	1300	864	479	377
in mol m^{-2} d^{-1}:	10.4	15.6	24.3	29.3	36.2	42.6	41.8	36.1	27.0	18.0	10.0	7.8

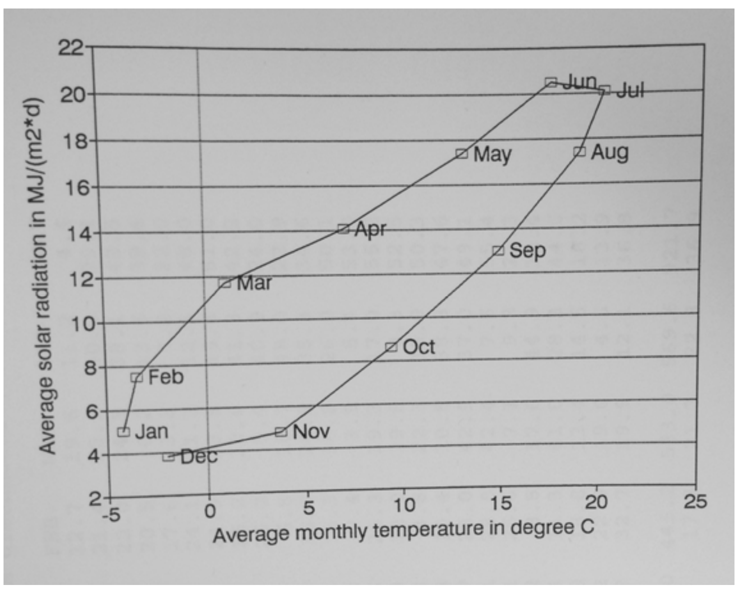

Figure B.1 Average monthly solar radiation (short wave, 280 – 2800 nm) versus average monthly temperature for Ithaca, NY.

Table B.4 Outside solar radiation data in mol m^{-2} d^{-1} during the 24 days the lettuce plants remained in the greenhouse (October 1992 - May 1993).

DAY	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY
11	35.4	11.1	5.1	13.5	12.7	19.6	11.2	4.4
12	12.3	19.4	4.0	2.6	21.4	22.2	40.0	29.1
13	18.5	17.7	4.1	3.1	22.0	24.8	38.1	43.5
14	26.0	1.2	3.4	13.1	20.5	6.2	13.5	39.6
15	31.6	4.3	3.5	3.5	17.6	13.3	7.2	22.0
16	25.2	13.9	2.4	10.1	24.1	11.3	12.5	48.0
17	33.8	20.3	2.6	4.4	21.9	33.9	13.6	51.0
18	33.6	3.3	5.2	3.1	15.2	10.6	41.3	42.2
19	32.9	22.8	6.4	3.3	25.2	9.4	40.9	24.0
20	32.8	6.9	9.7	2.9	6.8	18.7	48.0	22.9
21	31.3	4.1	2.1	5.7	10.7	24.8	35.3	34.6
22	9.7	4.7	7.8	6.8	5.3	38.8	26.0	50.1
23	22.2	13.9	4.9	9.8	7.4	3.9	5.4	53.0
24	9.9	12.7	9.1	4.6	26.3	19.3	17.0	55.2
25	18.3	13.2	5.1	12.9	12.0	39.8	8.3	52.5
26	23.3	8.7	12.2	10.3	4.8	22.3	13.9	50.3
27	4.4	12.7	16.1	20.8	19.4	10.8	38.8	47.6
28	15.4	13.2	3.0	11.7	23.0	42.9	37.0	49.1
29	10.8	25.4	1.4	3.1	28.8	42.4	7.6	55.4
30	19.7	25.8	3.2	8.1	25.6	7.1	9.8	21.3
31	12.8	23.3	12.6	4.2	8.8	17.6	44.9	12.4
32	9.1	29.6	17.1	15.4	11.3	41.0	28.3	44.6
33	17.0	2.2	13.5	21.9	18.8	13.4	14.5	18.2
34	2.4	6.0	4.4	5.2	22.9	19.0	4.5	13.9
35	21.3	10.5	1.8	11.2	32.7	19.9	12.1	36.8
SUM	509.4	326.7	160.6	211.0	445.2	533.0	569.6	921.7
AVE	20.4	13.1	6.4	8.4	17.8	21.3	22.8	36.9

Table B.5 Inside PAR measurements in mol m^{-2} d^{-1} during the 24 days the lettuce plants remained in the greenhouse (October 1992 - May 1993). Day 11 and 35 are transplant and final harvest day respectively on which the plants stayed in the greenhouse for approximately half the day.

DAY	Oct A	Oct B	Oct C	Oct D	Oct E	Nov A	Nov B	Nov C	Nov D	Nov E	Dec A	Dec C
11	8.9	8.9	8.9	8.9	8.9	7.5	3.0	5.0	10.0	12.5	0.9	1.0
12	20.0	22.4	15.0	10.0	6.2	13.0	6.0	10.0	18.0	20.0	2.7	3.0
13	20.0	25.0	15.0	10.0	9.3	9.4	11.2	10.2	9.7	20.0	12.5	2.6
14	20.0	25.0	15.7	13.0	13.0	11.1	11.9	11.4	10.6	20.0	12.5	2.6
15	20.0	25.0	15.8	15.8	15.8	0.4	0.4	0.3	0.3	0.4	12.5	2.2
16	20.0	25.0	15.3	12.6	12.6	5.4	5.8	5.2	5.2	21.0	12.5	2.1
17	20.0	25.0	16.9	16.9	16.9	11.0	5.0	6.0	15.0	20.3	12.5	1.6
18	20.0	25.0	16.8	12.4	16.8	15.0	13.0	13.3	20.0	18.3	12.5	1.6
19	20.0	25.0	16.5	12.1	16.5	14.3	1.9	10.1	17.0	1.9	12.5	3.2
20	20.0	25.0	16.4	12.3	16.4	15.0	13.1	13.6	20.0	29.2	12.5	4.2
21	20.0	25.0	15.7	10.5	15.7	15.0	4.7	10.0	20.0	23.3	12.5	5.4
22	19.3	21.1	15.0	10.6	4.9	0.5	0.5	0.5	0.5	1.7	12.5	1.4
23	19.4	22.0	15.1	10.0	11.1	14.9	2.9	10.1	19.8	19.9	12.5	4.6
24	20.0	25.0	15.0	11.4	5.0	15.0	7.8	10.0	20.1	24.4	12.5	3.1
25	17.6	20.7	15.1	10.0	9.2	15.0	6.4	10.0	20.1	23.3	12.5	5.3
26	20.0	23.8	15.0	10.2	11.7	15.0	8.0	10.0	20.1	25.0	12.5	3.1
27	18.6	20.8	15.0	10.0	2.2	15.0	5.2	10.0	20.0	22.6	12.5	6.6
28	10.5	11.3	12.2	7.3	7.7	13.4	1.5	10.0	18.5	18.2	12.5	8.6
29	19.8	21.6	15.0	10.0	5.4	15.0	5.2	10.0	20.0	22.3	12.5	1.9
30	20.0	25.0	15.0	12.7	9.9	15.0	9.5	20.0	20.0	25.0	12.5	1.3
31	20.0	22.6	15.0	10.0	6.4	15.0	7.6	10.0	20.1	25.0	12.5	2.1
32	19.0	20.8	15.0	10.0	4.6	15.0	6.8	10.0	20.1	24.6	12.5	7.3
33	20.0	24.7	15.0	11.2	8.5	15.0	6.8	10.0	20.1	25.0	12.5	8.2
34	15.6	17.4	13.8	10.0	1.2	14.0	1.3	10.0	18.8	19.1	12.5	7.4
35	5.4	5.4	5.4	5.4	5.4	7.5	2.1	5.0	10.0	10.9	6.3	1.5
SUM	454.1	538.5	364.6	273.3	241.3	302.4	147.6	230.7	394.0	473.9	284.9	91.9
AVE	18.9	22.4	15.2	11.4	10.1	12.6	6.2	9.6	16.4	19.8	11.9	3.8

Table B.5 (Continued)

DAY	Dec D	Dec E	Jan A	Jan B	Jan C	Jan D	Jan E	Feb A	Feb B	Feb C	Feb D	Feb E
11	5.7	1.0	3.5	3.5	3.7	3.8	3.7	2.3	2.2	2.3	2.6	2.4
12	18.9	2.8	1.5	12.5	7.5	1.3	1.3	15.4	12.5	17.5	11.1	17.5
13	15.0	7.5	2.0	12.5	7.5	1.7	1.7	15.3	12.5	17.5	12.1	18.3
14	15.0	7.5	6.1	12.9	8.4	12.5	7.5	16.0	12.5	17.5	10.2	18.2
15	15.0	7.5	2.3	12.5	7.5	12.5	7.5	14.6	12.5	17.5	10.0	17.5
16	15.0	7.5	5.7	12.5	8.0	12.5	7.5	16.7	12.5	17.5	13.5	17.9
17	15.0	7.5	2.9	12.5	7.5	12.5	7.5	16.5	12.5	17.5	13.4	17.9
18	15.0	7.5	2.1	12.5	7.5	12.5	7.5	13.9	12.5	17.5	8.7	17.5
19	15.0	7.5	1.8	12.5	7.5	12.5	7.5	18.6	14.4	17.5	16.2	20.0
20	15.0	7.5	1.6	12.5	7.5	12.2	7.5	12.5	12.5	17.1	4.1	17.5
21	15.0	7.5	3.7	12.5	7.5	12.5	7.5	12.5	12.5	17.5	6.7	17.5
22	15.0	7.5	4.6	12.5	7.6	12.5	7.5	12.5	12.5	17.3	4.0	17.5
23	15.0	7.5	5.5	12.5	7.8	12.5	7.5	12.5	12.5	17.5	4.7	17.5
24	15.0	7.5	2.7	12.5	7.5	12.5	7.5	16.2	14.7	17.5	17.1	19.6
25	15.0	7.5	7.0	12.9	8.9	12.5	7.5	12.6	12.5	17.5	7.8	17.5
26	15.0	7.5	7.4	13.3	9.2	12.5	7.5	12.5	10.7	16.3	3.3	17.5
27	15.0	7.5	9.9	15.9	12.2	12.5	11.6	13.8	12.5	17.5	12.5	18.1
28	15.0	7.9	6.2	12.6	8.0	12.5	7.5	14.0	12.5	17.5	13.6	18.4
29	15.0	7.5	1.9	12.5	7.5	12.2	7.5	15.4	13.7	17.5	16.8	19.2
30	15.0	7.5	5.2	12.5	7.9	12.5	7.5	15.1	13.1	17.5	16.3	19.1
31	15.0	7.5	3.0	12.5	7.5	12.5	7.5	12.5	12.5	17.5	5.6	17.5
32	15.0	7.5	7.7	13.6	9.2	12.5	7.5	12.5	12.5	17.5	7.4	17.5
33	15.0	7.5	10.9	16.2	13.1	13.0	11.9	13.6	12.5	17.5	11.4	17.5
34	15.0	7.0	3.1	12.5	7.6	12.5	7.5	14.1	12.5	17.5	13.2	17.5
35	7.5	3.8	3.2	6.4	3.0	3.0	3.0	5.9	6.1	7.1	9.5	9.3
SUM	362.1	172.5	111.5	307.3	197.1	272.2	175.7	337.5	299.9	410.1	251.8	425.9
AVE	15.1	7.2	4.7	12.8	8.2	11.3	7.3	14.1	12.5	17.1	10.5	17.7

Table B.5 (Continued)

DAY	Mar A	Mar B	Mar C	Mar D	Mar E	Apr B	Apr C	Apr D	May B	May C	May D
11	4.3	4.7	4.8	4.9	6.0	2.2	2.2	2.1	2.2	1.4	1.5
12	22.5	17.5	22.5	17.5	13.4	8.7	12.7	10.1	18.6	22.2	21.1
13	22.5	17.5	22.5	17.6	13.5	10.2	12.8	9.4	17.2	19.7	20.5
14	16.1	13.2	22.5	17.5	4.4	7.0	9.1	12.0	16.4	19.3	19.9
15	17.8	16.7	22.5	17.5	8.9	5.4	3.2	3.1	11.4	13.3	13.4
16	17.0	14.0	20.8	17.5	7.0	6.9	9.3	4.8	17.6	18.7	21.3
17	18.7	17.5	22.5	17.5	11.1	7.5	5.6	12.8	18.2	20.4	22.4
18	20.0	13.8	22.5	17.5	5.5	14.8	16.6	12.5	16.4	17.8	19.0
19	21.7	15.2	22.5	17.5	7.4	13.3	11.2	11.5	12.1	13.5	14.1
20	22.2	16.1	22.5	17.5	8.1	11.5	13.4	16.1	11.0	12.1	12.7
21	22.5	17.5	22.5	17.5	11.5	11.2	8.2	8.7	13.2	14.4	14.7
22	22.5	17.5	22.5	17.5	13.3	10.0	12.4	7.8	15.4	17.6	16.8
23	18.3	11.5	19.3	17.5	2.1	4.6	2.4	9.7	15.5	18.2	17.4
24	20.6	13.8	21.8	17.5	5.5	7.9	10.7	6.1	16.2	18.5	17.9
25	22.5	17.5	22.5	17.6	14.3	5.5	3.3	3.3	14.9	16.6	16.9
26	22.5	17.5	22.5	17.5	10.9	7.6	10.3	12.9	15.3	17.6	17.5
27	20.2	13.8	22.3	17.5	5.3	11.1	10.4	8.8	14.5	16.5	16.6
28	22.5	17.5	22.5	18.7	16.6	11.6	15.5	9.5	15.2	17.1	17.0
29	22.5	17.5	22.6	18.9	16.4	5.4	3.3	10.7	16.5	18.3	18.1
30	19.1	12.8	19.0	17.5	3.8	5.9	8.6	3.8	9.9	10.7	11.3
31	22.5	16.7	22.5	17.5	8.6	12.2	12.2	11.0	7.3	8.2	8.9
32	22.5	17.5	22.6	18.8	16.3	10.0	14.2	15.7	14.6	17.4	16.4
33	21.8	15.3	22.2	17.5	7.1	7.3	5.2	5.4	9.8	11.2	11.4
34	22.5	17.3	22.5	17.5	9.1	4.3	6.3	2.1	8.2	9.2	9.4
35	3.0	2.8	5.8	3.8	3.3	1.5	1.5	1.5	4.4	4.8	4.8
SUM	488.3	372.7	518.7	415.3	229.4	203.6	220.6	211.4	332.0	374.7	381.0
AVE	20.4	15.5	21.6	17.3	9.6	8.5	9.2	8.8	13.8	15.6	15.9

Appendix C

Computer Code of LETSGROW.PAS

```
Program LETSGROW(Input,Output);

{***************************************************************}
{*Title:   LETSGROW, Lettuce Growth model based on the growth model *}
{*         SUCROS87, as described by Spitters et al. (1989) in      *}
{*         "Simulation and systems management in crop protection"   *}
{*         by R. Rabbinge, S.A. Ward and H.H. van Laar (editors).   *}
{*Purpose: This program simulates the growth of lettuce in a        *}
{*         greenhouse, from the moment the lettuce is transplanted  *}
{*         into the greenhouse to the final harvest, i.e., from day *}
{*         11 to day 35.                                            *}
{*Input:   Average monthly solar radiation data for Ithaca          *}
{*         (1983-1991).                                             *}
{*Output:  Daily dry weight accumulation from transplant to harvest.*}
{*Author:  A.J. Both, Dept. of Agr. & Bio. Eng., Cornell University.*}
{*Date:    Started on February 3, 1993, completed October 17, 1994. *}
{*         Copyright, A.J. Both, January 1995, ALL RIGHTS RESERVED. *}
{***************************************************************}

{$N+}

Uses Crt, Graph;

Label loop1, loop2;

Type
    vector2 = array[1..2] of real;
    vector5 = array[1..5] of real;
    array24 = array[1..24] of real;
    array25 = array[11..35] of real;
    array365 = array[0..365] of real;

Const
    KDF = 0.72;  {extinction coefficient for diffuse PAR flux, ha/ha}
    SCP = 0.2;   {scattering coefficients of leaves for PAR         }
    RD = PI/180; {factor to convert degrees to radians              }

Var

    density,    {plant density before and after spacing, plants/m2  }
    lai,        {leaf area index, m2 leaf area/m2 ground area       }
```

```
wshoot,      {weight of the shoots in kg/ha                      }
wroot        {weight of the roots in kg/ha                       }
: vector2;

GSDST,       {distance in Gaussian integration                   }
GSWT         {weighting factor in Gaussian integration           }
: vector5;

Jan_rad,Feb_rad,Mar_rad,Apr_rad, {outside hourly solar radiation}
May_rad,Jun_rad,Jul_rad,Aug_rad, {for each month of the year    }
Sep_rad,Oct_rad,Nov_rad,Dec_rad
: array24;


ResultArray,    {daily dry weight data, calculated with SUCROS87}
FRT,            {fraction of the total plant dry weight         }
                {allocated to the roots, for day 11 to day 35   }
DWdata          {daily dry weight data, derived from curve fits }
: array25;

Sol_rad,     {daily total solar radiation for Ithaca, J/(cm2*d)  }
DTR          {daily total solar radiation, J/m2 per day          }
: array365;


DAY,         {day number, julian date                            }
H,I,J,K,     {counters                                           }
Startday,    {julian date of the start of the calculations       }
Nday,        {number of days the lettuce stays in the greenhouse }
space,       {index indicating before (1) or after (2) spacing   }
select,      {number used to distinguish different user input    }
Spaceday,    {number of days between transplant and spacing      }
CurrentDay,  {julian date of the current day                     }
Rampup,      {hour when temp. is ramped up in the morning,       }
             {24 hour clock                                      }
Rampdown,    {hour when temp. is ramped down in the afternoon    }
Count,       {loop counter used in the main program              }
Age,         {plant age, starting at transplant (=11), in days   }

{***************************************************************}
{*The following variables are needed for drawing of the curves *}
{***************************************************************}

xpixlo,      {lowest pixel number needed to draw the x-axis      }
xpixhi,      {higest pixel number needed to draw the x-axis      }
ypixlo,      {lowest pixel number needed to draw the y-axis      }
ypixhi,      {higest pixel number needed to draw the y-axis      }
xstart,      {start x pixel number                               }
ystart,      {start y pixel number                               }
```

```
ystartsim,  {simulated start y pixel number                     }
xnext,      {succeeding x pixel number                          }
ynext,      {succeeding y pixel number                          }
ynextsim,   {succeeding simulated y pixel number                }
nticx,      {number of tic marks on the x-axis                  }
nticy,      {number of tic marks on the y-axis                  }
delx,       {pixelnumber between tic marks on the x-axis        }
dely,       {pixel number between tic marks on the y-axis       }
grDriver,   {graphics driver                                    }
grMode,     {graphics mode                                      }
ErrCode,    {error code                                         }
Counter     {loop counter used in the procedure Plot_curve      }
: integer;

tavg,       {average temperature based on day and night temps   }
pnight,     {% of each 24 hours that tinight is maintained      }
maints,     {maintenance respiration of the crop @ standard temp}
            {(25 deg. C), kg CH2O/(ha*day)                      }
maint,      {maintenance resp. of the crop, kg CH2O/(ha*day)    }
teff,       {effect of temp on the rate of maintenance resp, [-]}
gtw,        {growth rate of the crop, kg Dry Matter/(ha*day)    }
q10,        {increase in rate of maintenance processes/10 Deg C }
groot,      {growth rate of the roots, kg Dry Matter/(ha*day)   }
gtops,      {growth rate of the shoots, kg Dry Matter/(ha*day)  }
ratio,      {ratio of plant density after and before spacing    }
lar,        {leaf area ratio, ha leaf area/kg dry weight        }
tiday,      {daytime temp setpoint inside the greenhouse        }
tinight,    {nighttime temp setpoint inside the greenhouse      }
InputPAR,   {daily PAR used to grow the crop, mol/(m2*d)        }

{***********************************************************}
{*The following variables, written in capitals, were borrowed *}
{*from SUCROS87.                                            *}
{***********************************************************}

DEC,        {sun declination angle, degrees                     }
LAT,        {latitude of the location, degrees, (42.3 = Ithaca) }
SINLD,      {intermediate variable for calculating daylength    }
COSLD,      {intermediate variable for calculating daylength    }
DAYL,       {daylength, hours/24 hrs period                     }
DSINB,      {integral of SINB over the day, s/day               }
DSINBE,     {as DSINB, but with a correction for lower atmo-    }
            {spheric transmission at lower solar elevations     }
SC,         {solar constant, corrected for the varying earth-   }
            {sun distance, W/m2                                 }
ATMTR,      {atmospheric transmission coefficient, [-]          }
FRDF,       {fraction of the total radiation that is diffuse,[-]}
DPAR,       {daily PAR, J/(m2*d)                                }
HOUR,       {hour during the day, hour                          }
```

```
SINB,        {sine of the solar inclination above the horizon,[-]}
pcPAR,       {percent of solar radiation in the PAR waveband     }
PAR,         {instantaneous flux of PAR, J/(m2*s)                }
PARDF,       {instantaneous diffuse flux of incoming PAR,J/(m2*s)}
PARDR,       {instantaneous direct flux of incoming PAR, J/(m2*s)}
PARt,        {help variable for the instantaneous PAR, J/(m2*s)  }
PARDFt,      {help variable for the inst. diffuse PAR, J/(m2*s)  }
PARDRt,      {help varaible for the inst. direct PAR, J/(m2*s)   }
PARSUM,      {daily integrated PAR in mol/(m2*d)                 }
PARDFSUM,    {daily integrated diffuse PAR in mol/(m2*d)         }
PARDRSUM,    {daily integrated direct PAR in mol/(m2*d)          }
REFL,        {crop reflection coefficient for PAR, [-]           }
CLUSTF,      {cluster factor, [-]                                }
KBL,         {extinction coefficient for the direct component    }
             {of the direct PAR flux, ha/ha                      }
KDRT,        {extinction coefficient for total direct PAR flux,  }
             {ha/ha                                              }
LAIC,        {partial cumulated LAI at various crop depths, ha/ha}
PARLDF,      {absorbed diffuse PAR per unit leaf area, J/(m2*s)  }
PARLT,       {absorbed total direct PAR per unit leaf area,      }
             {J/(m2*s)                                           }
PARLDR,      {absorbed direct component of direct PAR per unit   }
             {leaf area, J/(m2*s)                                }
PARLSH,      {absorbed PAR for shaded leaves per unit leaf area, }
             {J/(m2*s)                                           }
PARLSL,      {absorbed PAR for sunlit leaves per unit leaf area, }
             {J/(m2*s)                                           }
PARLPP,      {direct PAR absorbed by leaves perpendicular to the }
             {direct beam, J/(m2*s)                              }
FSLLA,       {fraction of sunlit leaf area, [-]                  }
FGROS,       {instantaneous CO2 assimilation rate of the crop,   }
             {kg/(ha*hr)                                         }
AMAX,        {actual CO2 assimilation rate at light saturation   }
             {for individual leaves, kg/(ha*hr)                  }
ASSSH,       {CO2 assimilation rate of shaded leaves, kg/(ha*hr) }
ASSSL,       {CO2 assimilation rate of sunlit leaves, kg/(ha*hr) }
DTGA,        {daily total gross CO2 assimilation of the crop,    }
             {kg/(ha*day)                                        }
ASRQ,        {assimilate (CH2O) requirement for dry matter       }
             {production, kg/kg                                  }
EFF,         {initial light use efficiency for individual leaves,}
             {kg CO2/ha*hr per W/m2                              }
GPHOT,       {daily total gross CO2 assimilation,kg CH2O/(ha*day)}
AvgSolarPAR, {solar PAR received inside the greenhouse and      }
              {calculated from average radiation data for Ithaca,}
              {NY in J/(m2*d)                                    }
HPSPAR,      {PAR received from HPS luminaires in J/(m2*d)       }
FRDFHPS,     {fraction of diffuse radiation of HPSPAR  [-]       }
```

```
      {**********************************************************}
      {*The following variables are used for drawing of the curves.*}
      {**********************************************************}

    xmin,       {value of the lowest tic mark on the x-axis         }
    xmax,       {value of the highest tic mark on the x-axis        }
    ymin,       {value of the lowest tic mark on the y-axis         }
    ymax        {value of the highest tic mark on the y-axis        }
    : real;

    data1,      {input file                                         }
    data2       {output file                                        }
    : text;

    Junk1       {character string in the input file                 }
    : string[8];


Function ASIN(arg:real):real; {calculates the arcsin of the argument}
Begin
     ASIN:=ARCTAN(ARG/(SQRT(1-(ARG*ARG))));
End; {function ASIN}

Function power(a,b:real):real; {calculates a to the power b}
Begin
     power:=exp(b*ln(a));;
End; {function power}

Function AMAX1(p,q:real):real; {determines the maximum of two values}
Begin
     IF p > q THEN AMAX1:=p
     ELSE AMAX1:=q;
End; {function AMAX1}

Function AMIN1(p,q:real):real; {determines the minimum of two values}
Begin
     IF p > q THEN AMIN1:=q
     ELSE AMIN1:=p;
End; {function AMIN1}

Procedure Initialize;
{*************************************************************}
{*Initialize all the relevant variables                      *}
{*before the calculations start.                             *}
{*************************************************************}
Begin
      {*The next variable is borrowed from SUCROS87*}

    Q10:=2.0;  {increase in rate of maintenance processes/10 Deg C }
```

```
  {*The next 8 variables specify some of the conditions during*}
  {*the growth trials in the greenhouse at the Cornell Campus *}

space        :=1;    {index for values before spacing}
lat          :=42.3; {latitude of the location: Ithaca ,NY}
Nday         :=24;   {number of days the plants grow in the}
       (greenhouse}
Spaceday     :=10;   {number of days between transplant and}
       {spacing}
FRT[11]      :=0.31; {initial fraction of the total plant dry}
                     {weight allocated to the roots, at day 11}
Rampup       :=7;    {hour when temp. is ramped up in the}
       {morning}
Rampdown     :=17;   {hour when temp. is ramped down in the}
       {afternoon}
pnight       :=(24-(Rampdown-Rampup))/24;
                     {fraction of each 24 hours the night}
       {temperature is maintained}

  {*The next 7 variables are INITIAL values and               *}
  {*can be changed by the user.                                *}

wshoot[space]:=29.1; {initial weight of the shoots in kg/ha}
InputPAR     :=17;   {daily PAR in mol/(m2*d)}
Startday     :=166;  {Julian date for the start of the}
       {simulation}
Density[1]   :=78;   {Plant density before spacing, plants/m2}
Density[2]   :=39;   {Plant density after spacing, plants/m2}
Tiday        :=24;   {Daytime temperature set point, deg C}
Tinight      :=18.8; {Nighttime temperature set point, deg C}

  {*The next 3 variables are calculated from the user input.   *}

wroot[space] :=wshoot[space]*FRT[11];
                     {initial weight of the roots in kg/ha}
tavg         :=pnight*tinight+(1.0-pnight)*tiday;
                     {weighed average temperature, deg C}
teff         :=power(q10,0.1*(tavg-25.0));
                     {factor accounting for the effect of}
                     {temperature on maintenance respiration}

{*****************************************************************}
{*Set all the cells of each array to zero.                        *}
{*****************************************************************}

FOR i:= 1 TO 2 DO
Begin
     lai[i]  :=0.0;  {leaf area index, m2 LA/m2 ground area}
```

```
    End; {FOR}

    FOR i:= 1 TO 5 DO
    Begin
         GSDST[i]:=0.0;  {distance in Gaussian integration}
         GSWT[i] :=0.0;  {weighting factor in Gaussian integration}
    End; {FOR}

    FOR i:= 1 TO 24 DO
    Begin
      {*Average outside hourly solar radiation for the 15th         *}
      {*of each month for Ithaca, NY.                                *}
         Jan_rad[i]:=0.0;Feb_rad[i]:=0.0;
         Mar_rad[i]:=0.0;Apr_rad[i]:=0.0;
         May_rad[i]:=0.0;Jun_rad[i]:=0.0;
         Jul_rad[i]:=0.0;Aug_rad[i]:=0.0;
         Sep_rad[i]:=0.0;Oct_rad[i]:=0.0;
         Nov_rad[i]:=0.0;Dec_rad[i]:=0.0;
    End; {FOR}

    FOR i:= 11 TO 35 DO
    Begin
        FRT[i]:=0.0;        {fraction of the total plant dry weight}
                            {allocated to the roots}
        DWdata[i]:=0.0;     {daily dry weight data, derived from}
           {curve fits}
        ResultArray[i]:=0.0;  {daily dry weight data,}
                              {calculated with SUCROS87}
    End; {FOR}

    FOR i:= 0 TO 365 DO
    Begin
        Sol_rad[i]:=0.0;    {daily solar radiation in J/(cm2*d)}
        DTR[i]:=0.0;        {daily solar radiation in J/(cm2*d)}
    End; {FOR}

End; {Procedure Initialize}


Procedure Read_weather_data;
{**************************************************************}
{*This procedure reads average hourly solar radiation data for     *}
{*the 15th of each month from the inputfile SolRad.dat.            *}
{**************************************************************}
Begin
    Assign(Data1,'c:\SolRad.dat');  {!SPECIFY FILENAME AND PATH!}
    Reset (Data1);
    Readln(Data1); {The first line of the data file contains}
                        {names of months}
```

```
    For J:=1 to 24 Do
    Begin
      Read(Data1,Junk1,Jan_rad[J],Feb_rad[J],Mar_rad[J],Apr_rad[J]);
      Read(Data1,May_rad[J],Jun_rad[J],Jul_rad[J],Aug_rad[J]);
      Readln(Data1,Sep_rad[J],Oct_rad[J],Nov_rad[J],Dec_rad[J]);
    End;

End; {Procedure Read_weather_Data}


Procedure Cal_daily_sol_rad;
{*****************************************************************}
{*Calculate the daily solar radiation for each day of the year in  *}
{*kJ/(m2*d), and outside the greenhouse.                           *}
{*****************************************************************}
Begin
     {*Adding hourly radiation data for the fifteenth of each month*}
     FOR j:=1 TO 24 DO
     Begin
          Sol_rad[15] :=Sol_rad[15]  + (JAN_rad[j] * 10);
                                                {in kJ/(m2*d)}
          Sol_rad[46] :=Sol_rad[46]  + (FEB_rad[j] * 10);
          Sol_rad[74] :=Sol_rad[74]  + (MAR_rad[j] * 10);
          Sol_rad[105]:=Sol_rad[105] + (APR_rad[j] * 10);
          Sol_rad[135]:=Sol_rad[135] + (MAY_rad[j] * 10);
          Sol_rad[166]:=Sol_rad[166] + (JUN_rad[j] * 10);
          Sol_rad[196]:=Sol_rad[196] + (JUL_rad[j] * 10);
          Sol_rad[227]:=Sol_rad[227] + (AUG_rad[j] * 10);
          Sol_rad[258]:=Sol_rad[258] + (SEP_rad[j] * 10);
          Sol_rad[288]:=Sol_rad[288] + (OCT_rad[j] * 10);
          Sol_rad[319]:=Sol_rad[319] + (NOV_rad[j] * 10);
          Sol_rad[349]:=Sol_rad[349] + (DEC_rad[j] * 10);
     END; {FOR}

     Sol_rad[365]:=(Sol_rad[15]-Sol_rad[349])*16/31+Sol_rad[349];
     Sol_rad[0]:=Sol_rad[365];

     {*Interpolate for the days between the 15th of each month*}

     FOR i:= 1 TO 14 DO
Sol_rad[i]:=(Sol_rad[15]-Sol_rad[365])*i/15+Sol_rad[0];
     FOR i:= 16 TO 45 DO
Sol_rad[i]:=(Sol_rad[46]-Sol_rad[15])*(i-15)/31+Sol_rad[15];
     FOR i:= 47 TO 73 DO
Sol_rad[i]:=(Sol_rad[74]-Sol_rad[46])*(i-46)/28+Sol_rad[46];
     FOR i:= 75 TO 104 DO
Sol_rad[i]:=(Sol_rad[105]-Sol_rad[74])*(i-74)/31+Sol_rad[74];
     FOR i:= 106 TO 134 DO
Sol_rad[i]:=(Sol_rad[135]-Sol_rad[105])*(i-105)/30+Sol_rad[105];
```

```
     FOR i:= 136 TO 165 DO
Sol_rad[i]:=(Sol_rad[166]-Sol_rad[135])*(i-135)/31+Sol_rad[135];
     FOR i:= 167 TO 195 DO
Sol_rad[i]:=(Sol_rad[196]-Sol_rad[166])*(i-166)/30+Sol_rad[166];
     FOR i:= 197 TO 226 DO
Sol_rad[i]:=(Sol_rad[227]-Sol_rad[196])*(i-196)/31+Sol_rad[196];
     FOR i:= 228 TO 257 DO
Sol_rad[i]:=(Sol_rad[258]-Sol_rad[227])*(i-227)/31+Sol_rad[227];
     FOR i:= 259 TO 287 DO
Sol_rad[i]:=(Sol_rad[288]-Sol_rad[258])*(i-258)/30+Sol_rad[258];
     FOR i:= 289 TO 318 DO
Sol_rad[i]:=(Sol_rad[319]-Sol_rad[288])*(i-288)/31+Sol_rad[288];
     FOR i:= 320 TO 348 DO
Sol_rad[i]:=(Sol_rad[349]-Sol_rad[319])*(i-319)/30+Sol_rad[319];
     FOR i:= 350 TO 364 DO
Sol_rad[i]:=(Sol_rad[365]-Sol_rad[349])*(i-349)/16+Sol_rad[349];

     FOR i:= 0 TO 365 DO
     Begin
         Sol_rad[i]:=Sol_rad[i]*1000;
                        {in J/(m2*d), short wave radiation}
         DTR[i]:=Sol_rad[i];
     End; {FOR}

END; {Procedure Cal_daily_sol_rad}


Procedure Cal_daily_FRT;
{****************************************************************}
{*Calculates the daily FRT (fraction of the total plant dry weight *}
{*allocated to the roots) of the lettuce plants, starting at       *}
{*day 11 (transplant day) and continuing to day 35 (5 weeks old).  *}
{****************************************************************}
Begin
      {*Next five values were estimated from results of the growth *}
      {*trials by Wheeler et al., 1994.                            *}
    FRT[11]:=0.31;   {*11 = transplant day*}
    FRT[14]:=0.21;
    FRT[21]:=0.14;
    FRT[28]:=0.06;
    FRT[35]:=0.05;   {*35 = final harvest*}


      {*linear interpolation for days between transplant           *}
      {*and final harvest.                                          *}
    FOR i:= 12 TO 13 DO
        FRT[i]:=(FRT[11]-FRT[14])*(14-i)/(14-11)+FRT[14];
    FOR i:= 15 TO 20 DO
        FRT[i]:=(FRT[14]-FRT[21])*(21-i)/(21-14)+FRT[21];
```

```
    FOR i:= 22 TO 27 DO
        FRT[i]:=(FRT[21]-FRT[28])*(28-i)/(28-21)+FRT[28];
    FOR i:= 29 TO 34 DO
        FRT[i]:=(FRT[28]-FRT[35])*(35-i)/(35-28)+FRT[35];

End; {Procedure Cal_daily_FRT}


Procedure Respace;
{******************************************************************}
{*Calculate the new root and shoot weights and the new LAI        *}
{*after spacing.                                                  *}
{******************************************************************}
Begin
    ratio:=density[2]/density[1];
    wshoot[space]:=wshoot[space-1]*ratio;
    wroot[space]:=wroot[space-1]*ratio;
    lai[space]:=lai[space-1]*ratio;

End; {Procedure Respace}


Procedure Cal_daily_solar_radiation_parameters;
{******************************************************************}
{*This procedure was called ASTRO in SUCROS87, but is slightly    *}
{*changed. Computes daylength (DAYL) from daynumber (Currentday,  *}
{*julian date) and latitude (LAT). Also computes the daily        *}
{*integral of the sine of the solar inclination (DSINB), the daily *}
{*integral of SINB with a correction for lower atmospheric        *}
{*transmission at lower solar elevations (DSINBE) and corrects the *}
{*solar constant (SC).                                            *}
{******************************************************************}
Begin
      {*Declination of the sun as a function of Currentday, degrees*}
     DEC:=-ASIN(SIN(23.45*RD)*COS(2*PI*(Currentday+10)/365))/RD;

      {*Intermediate variables for calculating                    *}
      {*the solar inclination (=elevation).                       *}
     SINLD:=SIN(LAT*RD)*SIN(DEC*RD);
     COSLD:=COS(LAT*RD)*COS(DEC*RD);

      {*Daylength (photoperiod) in hours.                         *}
     DAYL:=12+24/PI*ASIN(SINLD/COSLD);

      {*Daily integral of the sine of solar inclination (SINB) in  *}
      {*sec/day.                                                  *}
     DSINB:=3600*(DAYL*SINLD+24*COSLD*SQRT(1-SQR(SINLD/COSLD))/PI);

      {*Daily integral of SINB with a correction for lower        *}
```

```
      {*atmospheric transmission at lower solar elevations          *}
      {* in sec/day.                                                 *}
     DSINBE:=3600*(DAYL*(SINLD+0.4*(SQR(SINLD)+0.5*SQR(COSLD)))+
             12*COSLD*(2+3*0.4*SINLD)*SQRT(1-SQR(SINLD/COSLD))/PI);

      {*Solar constant, corrected for a varying earth-sun distance *}
     SC:=1370*(1+0.033*COS(2*PI*Currentday/365));

End; {procedure Cal_daily_solar_radiation_parameters}


Procedure Cal_daily_PAR_and_fractions_solar_and_supplemental_PAR;
{***************************************************************}
{*This procedure was called DRADIA in SUCROS87, but is changed.    *}
{*Computes daily photosynthetically active radiation (DPAR) inside *}
{*the greenhouse from user input and calculates the daily PAR      *}
{*received from sunlight and from the HPS lamps.                   *}
{***************************************************************}
Begin
      {*The daily PAR in the greenhouse is an input value given by *}
      {*the user.                                                  *}
     DPAR:=InputPAR*240338;
      {*J/(m2*d) PAR*}
      {*1 MJ/(m2*d) short wave radiation (280 - 2800 nm) =         *}
      {*2.0804 mol/(m2*d) PAR (400 - 700 nm), Ting & Giacomelli    *}
      {*(1987). For a combination of solar and supplemental        *}
      {*irradiation the assumption is made that half of the energy *}
      {*of the short wave radiation falls in the PAR waveband.     *}
      {*Therefore 1 MJ/(m2*d) PAR = 4.1608 mol/(m2*d) PAR.         *}
      {*To convert mol/(m2*d) to J/(m2*d) PAR,                     *}
      {*multiply by 1E6/4.1608.                                    *}
      {*The percentage of the solar radiation (short wave, 280 -   *}
      {*2800 nm) in the PAR waveband (400 - 700 nm) changes with   *}
      {*the amount of cloud cover: for a very cloudy day the value *}
      {*is 60% and for a very sunny day 45% (Goudriaan, personal   *}
      {*communications, 1994). The assumption was made that for    *}
      {*these experiments a very cloudy day corresponded with an   *}
      {*InputPAR of 7 mol/(m2*d) and a sunny day with 22           *}
      {*mol/(m2*d). For an InputPAR of 7 mol/(m2*d) the percentage *}
      {*was set at 60% and for an InputPAR of 22 mol/(m2*d) the    *}
      {*percentage was set at 50%. For values of InputPAR between  *}
      {*7 and 22 mol/(m2*d) a linear interpolation was used to     *}
      {*calculate the percentage.                                  *}
     pcPAR:=-0.00667*InputPAR+0.647;

      {*Solar PAR received inside the greenhouse and calculated    *}
      {*from average radiation data for Ithaca, NY in J/(m2*d).    *}
      {*0.57 = tau, or the transmissivity of the greenhouse cover. *}
     AvgSolarPAR:=DTR[Currentday]*pcPAR*0.57;       {*J/(m2*d) PAR*}
```

```
     {*tau is smaller for the summer months due to extra shading  *}
     IF (Currentday >= 60) And (Currentday <= 270) Then
        AvgSolarPAR:=DTR[Currentday]*pcPAR*0.28;      {*J/(m2*d) PAR*}

     {*PAR received from HPS luminaires in J/(m2*d)                *}
     HPSPAR:=DPAR-AvgSolarPAR;                        {*J/(m2*d) PAR*}

     {*PAR from HPS lamps can not be negative                      *}
     IF HPSPAR <= 0.0 THEN HPSPAR:=0.0;

End; {procedure                                                    }
     {Cal_daily_PAR_and_fractions_solar_and_supplemental_PAR      }


Procedure Cal_above_canopy_radiation;
{*****************************************************************}
{*This procedure was called RADIAT in SUCROS87, but is changed.   *}
{*Computes the instantaneous radiation (PAR), and its diffuse and *}
{*direct components, above the canopy in J/m2*s = W/m2.          *}
{*****************************************************************}
Begin
     {*Sine of the solar elevation, which changes during the day. *}
     SINB:=AMAX1(0,SINLD+COSLD*COS(2*PI*(HOUR+12)/24));
     {*Instantaneous PAR.                                          *}
     PAR:=DTR[Currentday]*pcPAR*0.57*SINB*(1+0.4*SINB)/DSINBE;
     {*in W/m2*}

     {*More shading was used in the greenhouse betweem March 1 and*}
     {*Sept 27.                                                    *}
     IF (Currentday >= 60) And (Currentday <= 270) Then
        PAR:=DTR[Currentday]*pcPAR*0.28*SINB*(1+0.4*SINB)/DSINBE;
     {*in W/m2*}

     {*The following calculation of ATMTR and FRDF is different   *}
     {*from the calculation found in SUCROS87. The current         *}
     {*calculation method was provided by J. Goudriaan (personal  *}
     {*communication, August 1994) and is an update of the method *}
     {*previously used in SUCROS87.                                *}
     ATMTR:=DTR[Currentday]*SINB*(1+0.4*SINB)/DSINBE/(SC*SINB);
     IF (ATMTR<=0.22) THEN
        FRDF := 1
     ELSE
     Begin
         IF (ATMTR > 0.22) AND (ATMTR <= 0.35) THEN
            FRDF := 1 - 6.4 * power((ATMTR - 0.22),2)
         ELSE
            FRDF := 1.47 - 1.66 * ATMTR
     End; {*ELSE*}
```

```
     FRDF:=AMAX1(FRDF,0.15+0.85*(1-EXP(-0.1/SINB)));

      {*Fractions of instantaneous diffuse and direct PAR from     *}
      {*sunlight.                                                  *}
     PARDF:=PAR*FRDF;
     PARDR:=PAR-PARDF;

      {*Add the supplemental light to the sunlight. The supple-    *}
      {*mental light is all assumed to be diffuse and evenly       *}
      {*distributed over the time of the day sunlight is available *}
      {*(DAYL).                                                    *}
     FRDFHPS:=1.0;
     PARDF:=PARDF+(FRDFHPS*HPSPAR)/(3600*DAYL);
     PARDR:=PARDR+((1-FRDFHPS)*HPSPAR)/(3600*DAYL);
           {*As long as FRDFHPS = 1.0, PARDR will be unchanged*}

End; {procedure Cal_above_canopy_radiation}


Procedure Cal_canopy_radiation_profile;
{*******************************************************************}
{*This procedure was called RADPRF in SUCROS87 and is              *}
{*unchanged. Computes the radiation profile within the canopy      *}
{*and gives instantaneous values of absorbed radiation for         *}
{*successive leaf layers.                                          *}
{*******************************************************************}
Begin

      {*canopy reflection coefficient for PAR, 400 - 700 nm*}
    REFL:=(1-SQRT(1-SCP))/(1+SQRT(1-SCP));

      {*cluster factor; ratio between empirical and*}
      {*theoretical value of KDF*}
    CLUSTF:=KDF/(0.8*SQRT(1-SCP));

      {*extinction coeff. for the direct component of*}
      {*the direct PAR, ha/ha*}
    KBL:=(0.5/SINB)*CLUSTF;

      {*extinction coeff. for the total direct PAR, ha/ha          *}
    KDRT:=KBL*SQRT(1-SCP);

      {*absorbed PAR per unit leaf area in J/(m2*s) for            *}
      {*diffuse, total direct, and direct component of direct PAR  *}
    PARLDF:=(1-REFL)*PARDF*KDF*EXP(-KDF*LAIC);
    PARLT:=(1-REFL)*PARDR*KDRT*EXP(-KDRT*LAIC);
    PARLDR:=(1-SCP)*PARDR*KBL*EXP(-KBL*LAIC);

      {*absorbed PAR per unit leaf area in J/(m2*s) for            *}
```

```
      {*shaded and sunlit leaves                                 *}
    PARLSH:=PARLDF+(PARLT-PARLDR);
    PARLSL:=PARLSH+(1-SCP)*KBL*PARDR;

      {*direct PAR absorbed by leaves perpendicular to           *}
      {*the direct beam in J/(m2*s)                              *}
    PARLPP:=PARDR*(1-SCP)/SINB;

      {*fraction of sunlit leaf area                             *}
    FSLLA:=EXP(-KBL*LAIC)*CLUSTF;

End; {procedure Cal_canopy_radiation_profile}


Procedure Cal_daily_assimilation;
{*****************************************************************}
{*This procedure was called DASS in SUCROS87 in which the three    *}
{*point Gaussian integration method is replaced by a five point    *}
{*for greater accuracy. Adjustments of AMAX and EFF are calculated *}
{*for those treatments were CO2 enrichment was used in the         *}
{*greenhouse. Computes potential daily assimilation (DTGA in kg    *}
{*CO2/ha/d) from the amount of sunlight absorbed by the leaves.    *}
{*****************************************************************}
Begin
    {*ten constants needed for the five points Gaussian integration*}
    GSDST[1]:= 0.0469101;
    GSDST[2]:= 0.2307653;
    GSDST[3]:= 0.5;
    GSDST[4]:= 0.7692347;
    GSDST[5]:= 0.9530899;
    GSWT[1]:= 0.1184634;
    GSWT[2]:= 0.2393143;
    GSWT[3]:= 0.2844444;
    GSWT[4]:= 0.2393143;
    GSWT[5]:= 0.1184634;

    Cal_daily_solar_radiation_parameters;
    Cal_daily_PAR_and_fractions_solar_and_supplemental_PAR;

    DTGA:=0.0;

      {*A pulsed CO2 enrichment system was used during the experi- *}
      {*ments: the target CO2 concentration in the greenhouse was  *}
      {*set at 1000 ppm, but the enrichment stopped as soon as     *}
      {*venting was needed to maintain the inside set point        *}
      {*temperature. Elevated CO2 concentrations increase the      *}
      {*values of AMAX and EFF. For an ambient CO2 concentration   *}
      {*(350 ppm) the values for AMAX and EFF are 40 and 0.45      *}
      {*respectively. For a CO2 concentration of 1000 ppm AMAX     *}
```

```
  {*increases to a value of 50 and EFF increases according to  *}
  {*the equation EFF = 0.6*(Conc-Gamma)/(Conc+2*Gamma), where  *}
  {*Conc = CO2 concentration in ppm and Gamma = CO2 compensa-  *}
  {*tion point (around 50 ppm) (Goudriaan, personal communi-   *}
  {*cations, 1994). For the current experiments the assumption *}
  {*was made little venting was needed to maintain inside      *}
  {*temperature for InputPAR = 7 mol/(m2*d) resulting in a CO2 *}
  {*concentration of 1000 ppm. For an InputPAR of 22 mol/      *}
  {*(m2*d) it was assumed a lot of venting was needed to       *}
  {*maintain temperature, dropping the CO2 concentration to    *}
  {*350 ppm. Remember that for the low InputPAR little         *}
  {*supplemental lighting was needed to reach the daily target *}
  {*light level and for the high InputPAR a lot. The more      *}
  {*supplemental lighting was needed, the more heat was re-    *}
  {*leased in the greenhouse, the more venting was needed to   *}
  {*maintain the set point temperature. No CO2 enrichment for  *}
  {*experiments between March 28 and Sepember 27 was used.     *}
IF (Currentday >= 87) And (Currentday <= 270) Then
Begin
     EFF  :=0.45;
     AMAX :=40;
End
  {*A linear interpolation is used to determine the values of  *}
  {*AMAX and EFF for CO2 concentrations between 350 and 1000   *}
  {*ppm.                                                       *}
ELSE
Begin
     EFF  :=-0.00467*InputPAR+0.553;
     AMAX :=-0.667*InputPAR+54.7;
End;

  {*Help variables keeping track of the daily PAR in J/(m2*d)  *}
PARSUM:=0.0;
PARDFSUM:=0.0;
PARDRSUM:=0.0;

FOR I:=1 TO 5 DO
Begin
      {*selection of the time during the day                   *}
    HOUR:=12+DAYL*0.5*GSDST[I];
    Cal_above_canopy_radiation;
    FGROS:=0.0;

      {*Help variables keeping track of the instantaneous PAR  *}
      {*in J/(m2*s)                                            *}
    PARt:=PAR;
    PARDFt:=PARDF;
    PARDRt:=PARDR;
```

```
        FOR J:=1 TO 5 DO
        Begin
                  {*selection of canopy depths,                     *}
                  {*starting from the top                           *}
            LAIC:=LAI[space]*GSDST[J];
            Cal_canopy_radiation_profile;

                  {*assimilation of the shaded leaf area,           *}
                  {*kg CO2/(ha leaf*hr)                             *}
            ASSSH:=AMAX*(1-EXP(-EFF*PARLSH/AMAX));
            ASSSL:=0.0;

                  {*assimilation of the sunlit leaf area,           *}
                  {*kg CO2/(ha leaf*hr)                             *}
            FOR K:=1 TO 5 DO
            Begin
                PARLSL:=PARLSH+PARLPP*GSDST[K];
                ASSSL:=ASSSL+AMAX*(1-EXP(-PARLSL*EFF/AMAX))*GSWT[K];
            End; {FOR K}

                  {*hourly total gross assimilation,                *}
                  {*kg CO2/(ha soil*hr)                             *}
FGROS:=FGROS+((1-FSLLA)*ASSSH+FSLLA*ASSSL)
                                              *LAI[space]*GSWT[J];
        End; {FOR J}

           {*integration of instantaneous assimilation to           *}
           {*a daily total                                          *}
        DTGA:=DTGA+FGROS*DAYL*GSWT[I];

           {*Help variables keeping track of the daily PAR in       *}
           {*J/(m2*d)                                               *}
        PARSUM:=PARSUM+PARt*3600*DAYL*GSWT[I];
        PARDFSUM:=PARDFSUM+PARDFt*3600*DAYL*GSWT[I];
        PARDRSUM:=PARDRSUM+PARDRt*3600*DAYL*GSWT[I];

    End; {FOR I}

      {*conversion from assimilated CO2 to CH2O (carbohydrates)    *}
    GPHOT:=DTGA*30/44;

End; {Procedure Cal_daily_assimilation}


Procedure Input_crop_and_temperature_data;
{*****************************************************************}
{*Gives user the option to change crop and temperature data      *}
{*****************************************************************}
Var
```

```
    select:integer;

Begin

  ClrScr;

  Repeat
    writeln;
    writeln;
    writeln('This is a list of crop scheduling and temperature
      data');
    writeln;
    write  ('Enter the number corresponding to the variable you
      wish');
    writeln(' to change.');
    writeln;
    writeln('Enter "0" (if needed repeatedly) to return to the main
      menu');
    writeln;
    writeln;
    write  ('1) The seedling dry weight (gram/seedling) at day 11');
    writeln (' is: ',wshoot[space]/(10*Density[space]):6:5);
    writeln;
    write  ('2) The daily PAR (mol/(m2*d) used to grow the crop is:
      ');
    writeln(InputPAR:3:1);
    writeln;
    writeln('3) The transplant day is (Julian date): ',Startday:3);
    writeln;
    write  ('4) The initial plant density is (plants/m2):');
    writeln(' ',Density[1]:3:0);
    writeln;
    writeln('5) The final plant density is (plants/m2):
      ',Density[2]:3:0);
    writeln;
    writeln('6) The daytime temperature set point is (C):
      ',Tiday:3:1);
    writeln;
    writeln('7) The nighttime temperature set point is (C):
      ',Tinight:3:1);
    writeln;
    readln(select);
    if select = 1 then
    begin
      writeln;
      writeln('Enter the new initial dry weight (in
      grams/seedling)');
      readln (wshoot[space]);
      wshoot[space]:=wshoot[space]*10.0*Density[space];
```

```
                {converted from grams/seedling to kg/ha}
  wroot[space]:=wshoot[space]*FRT[11];
  Input_crop_and_temperature_data;
end;  {if select = 1}
if select = 2 then
begin
  writeln;
  writeln('What is the daily PAR used to grow the crop?');
  writeln('For best results use a number between 7 and 22
  mol/(m2*d)');
  readln(InputPAR);
  Input_crop_and_temperature_data;
end;  {if select = 2}
if select = 3 then
begin
  writeln;
  write('On which Julian date were the plants transplanted');
  writeln(' into greenhouse #15? ');
  readln(Startday);
  Input_crop_and_temperature_data;
end;  {if select = 3}
if select = 4 then
begin
  writeln;
  writeln('What is the initial plant density (plants/m2)? ');
  readln(Density[1]);
  Input_crop_and_temperature_data;
end;  {if select = 4}
if select = 5 then
begin
  writeln;
  writeln('What is the plant density after spacing (plants/m2)?
  ');
  readln(Density[2]);
  Input_crop_and_temperature_data;
end;  {if select = 5}
if select = 6 then
begin
  writeln;
  writeln('What is the set point day temperature (C) in the
  greenhouse?');
  readln(Tiday);
  Input_crop_and_temperature_data;
end;  {if select = 6}
if select = 7 then
begin
  writeln;
  writeln('What is the set point night temperature (C) in the
  greenhouse?');
```

```
      readln(Tinight);
      Input_crop_and_temperature_data;
    end;  {if select = 7}
  Until select = 0;
  ClrScr;

End; {Procedure Input_crop_and_temperature_data}


Procedure Prepare_output;
{*******************************************************************}
{*Prepares the output file letsgrow.dat                            *}
{*******************************************************************}
Begin
     Assign (data2, 'c:\LETSGROW.DAT'); {!SPECIFY FILENAME AND PATH!}
     Rewrite (data2);
     writeln (data2,'Day     DW head    Age');       {*heading*}
End; {Procedure Prepare_output}


Procedure Output_data;
{*******************************************************************}
{*Write results of the calculations to a data file named           *}
{*LETSGROW.DAT and to an array called ResultArray. The units are   *}
{*grams dry weight/head.                                           *}
{*******************************************************************}
Begin
      writeln(data2,Currentday:3,wshoot[space]/(10*Density[space])
                                                      :10:2,Age:8);
      ResultArray[Age]:=wshoot[space]/(10*Density[space]);
End; {Procedure Output_data}


Procedure Main_menu;
{*******************************************************************}
{*Shows the main menu to the user who is then able to interact     *}
{*with the program by changing centain variables that are used in  *}
{*the calculations.                                                *}
{*******************************************************************}
Var
   select:integer;

Begin

ClrScr;

Repeat
  writeln;
  writeln('******* WELCOME TO THE PROGRAM LETSGROW ********');
```

```
  writeln;
  writeln('            This is the MAIN MENU of the program');
  writeln('                        ---------');
  writeln;
  writeln('Enter the following numbers corresponding to the parameters');
  writeln('you wish to review/change, or to start the calculations.');
  writeln;
  writeln;
  writeln('1) To start the daily dry weight calculations');
  writeln;
  writeln('2) Lettuce production and temperature data');
  writeln;
  readln(select);
  if select = 2 then Input_crop_and_temperature_data;
Until select = 1;
ClrScr;

End; {Procedure Main_menu}


Procedure Fill_array;
{*****************************************************************}
{*Fills an array with the dry weight data calculated from the     *}
{*equations  for the curve fittings of the greenhouse lettuce     *}
{*experiments.                                                    *}
{*****************************************************************}
Begin
     For i:=11 to 35 Do
         DWdata[i]:=exp(-8.426+(0.0593*InputPAR)+0.4822*i
                                                   -0.006225*i*i);
End; {Procedure Fill_array}


Procedure Draw_grid;
{*****************************************************************}
{*Draws the axes, tic marks and the horizontal grid lines for the *}
{*growth curve plot.                                              *}
{*****************************************************************}
Begin
     SetTextStyle(1,0,2);
     OutTextXY(100,1,'Dry weight production versus days after
                                 seeding');
     nticx:=12;
     nticy:=10;
     xpixlo:=100;
     xpixhi:=600;
     ypixhi:=40;
     ypixlo:=300;
     delx:=round((xpixhi-xpixlo)/nticx);
```

```
     dely:=round((ypixhi-ypixlo)/nticy);
     Line(xpixlo,ypixlo,xpixhi,ypixlo);               {bottom line}
     Line(xpixlo,ypixlo,xpixlo,ypixhi);               {left line}
     Line(xpixlo,ypixlo+dely*nticy,xpixhi,ypixlo+dely*nticy);
                                                      {top line}
     Line(xpixlo+delx*nticx,ypixlo,xpixlo+delx*nticx,ypixhi);
                                {right line}

     For j:=1 To (nticy+1) Do                   {y-axis tic marks}
         Line(xpixlo,ypixlo+dely*(j-1),xpixlo-10,ypixlo+dely*(j-1));

     For j:=1 To (nticx+1) Do                   {x-axis tic marks}
         Line(xpixlo+delx*(j-1),ypixlo+7,xpixlo+delx*(j-1),ypixlo);

     SetLineStyle(DottedLn,0,NormWidth);

     For j:=2 To nticy Do                 {horizontal grid lines}
         Line(xpixlo,ypixlo+dely*(j-1),xpixhi,ypixlo+dely*(j-1));

End; {Procedure Draw_grid}


Procedure Axes_scales;
{*************************************************************}
{*Sets the minimum and maximum values on the x and y axes.   *}
{*************************************************************}
Begin
     xmin:=11;
     xmax:=35;
     ymin:=0;
     ymax:=10;
End; {Procedure Axes_scales}


Procedure Label_axes;
{*************************************************************}
{*Labels the axes of the growth curve plot,                  *}
{*and describes the lines.                                   *}
{*************************************************************}
Begin
     SetTextStyle(2,0,5);
     OutTextXY(100,310,'11   13   15   17   19    21   23   25   27
                                29    31   33   35');
     SetTextStyle(1,0,1);
     OutTextXY(250,325,'Days since seeding');
     SetTextStyle(2,1,5);
     OutTextXY(65,30,'0  1  2  3   4  5  6   7  8  9  10');
     SetTextStyle(1,1,1);
     OutTextXY(15,20,'Dry weight in grams per head');
```

```
     SetTextStyle(2,0,4);
     OutTextXY(15,335,'Enter <RETURN> to continu the program');
     OutTextXY(125,50,'--- solid line from fitted real data');
     OutTextXY(125,70,'- - dotted line from simulation');
End; {Procedure Label_axes}


Procedure Plot_curve;
{*****************************************************************}
{*Draws the sigmoid growth curves in the plot.                  *}
{*****************************************************************}
Begin
     Counter:=11;
     xstart:=xpixlo;
     ystart:=ypixlo;
     ystartsim:=ypixlo;
     j:=1;
     delx:=round(delx/2);
     Repeat
           xnext:=xpixlo+delx*j;
           ynext:=ypixlo+round((ypixhi-ypixlo)*
      (DWdata[Counter+1])/(ymax-ymin));
           ynextsim:=ypixlo+round((ypixhi-ypixlo)*
      (ResultArray[Counter+1])/(ymax-ymin));

           SetLineStyle(SolidLn,0,NormWidth);
           Line(xstart,ystart,xnext,ynext);     {curve fitted line}
           SetLineStyle(DottedLn,0,NormWidth);
           Line(xstart,ystartsim,xnext,ynextsim);  {simulated line}
           xstart:=xnext;
           ystart:=ynext;
           ystartsim:=ynextsim;
           j:=j+1;
           Counter:=Counter+1;
     Until Counter = 35;
     Readln;
End; {procedure Plot_curve}


{*****************************************************************}
{*                         MAIN PROGRAM                         *}
{*****************************************************************}
BEGIN

REPEAT

  {run the procedures that prepare the program for the calculations}

  Initialize;          {give relevant parameters an initial value}
```

```
Read_weather_data;    {read solar radiation data from input file}
Cal_daily_sol_rad;    {calculate daily solar radiation for the}
                                  {whole year}
Cal_daily_FRT;        {calculate daily fraction of the total}
                      {plant dry weight allocated to the roots}
Prepare_output;       {prepare the output file "LETSGROW.DAT"}
Main_menu;            {show the main menu to the user}

writeln('to abort run, type CONTROL BREAK, NOW !!!!!');
writeln('to continue the calculations type "0" ');
readln (select);

{start the calculations}

Count := 0;
Age   :=11;

write('1. Currentday = ',Startday:3,', wshoot =');
writeln(' ',wshoot[space]/(10*Density[1]):7:4,' grams DW/head');

ResultArray[Age]:=wshoot[1]/(10*Density[1]);

Spaceday   := Startday + Spaceday;
Currentday := Startday;
Output_Data;

    {Calculate the dry weight production between transplant day  }
    {and space day.                                              }

loop1: For Currentday := (Startday + 1) TO Spaceday DO
Begin
    {Reset Currentday to Jan 1 if the previous day was Dec 31;   }
    {this if-then loop is needed for a crop started in Dec and   }
    {harvested in Jan.                                           }
     IF Currentday > 365 THEN
     Begin
          Currentday := Currentday - 365;
          Spaceday   := Spaceday - 365;
          Startday   := Currentday - 1;
          Nday       := Nday - Count;
          goto loop1;
     End; {IF}

    {The equation for lar was derived from the DEC and MAR       }
    {experiments when leaf area, fresh and dry weight            }
    {measurements were performed.                                }
     lar:=1E-5*(23.9/(wshoot[space]/(10*Density[space]))+
        615.4-24.1*(wshoot[space]/(10*Density[space])));
                                          {in ha/kg = 10 m2/gr}
```

```
     lai[space]:=wshoot[space]*lar;           {in ha/ha = m2/m2   }

    {Calculate the daily dry weight production.                 }
     Cal_daily_assimilation;

    {Maintenance respiration expressed as a carbohydrate loss    }
    {in kg/(ha*d).                                               }
     maints:=wshoot[space]*0.03+wroot[space]*0.015;
     maint:=amin1(gphot,maints*teff);

    {Assimilate requirement for dry matter conversion from       }
    {carbohydrates to dry matter in kg/kg.                       }
     ASRQ:=1.46*(1-FRT[Age])+1.44*FRT[Age];

    {Total growth rate in kg DM/(ha*d).                          }
     gtw:=(gphot-maint)/ASRQ;

    {Growth rate of roots and shoots (tops) in kg DM/(ha*d).     }
     groot:=gtw*FRT[Age];
     gtops:=gtw*(1-FRT[Age]);

    {Accumulated shoot and root dry weight in kg/ha.             }
     wshoot[space]:=wshoot[space]+gtops;
     wroot[space]:=wroot[space]+groot;

    {Write the accumulated shoot dry weight to the screen.       }
     write('1. Currentday = ',Currentday:3,', wshoot =');
     writeln(' ',wshoot[space]/(10*Density[space]):7:4,'
                                         grams DW/head');

     Age  :=Age + 1;

    {Write the accumulated shoot dry weight to the output file.  }
     Output_data;

     Count:=Count + 1;

End; {FOR}

space:=2;
Respace;
writeln('respacing took place');


    {Calculate the dry weight production between space day       }
    {and harvest day.                                            }

loop2: FOR Currentday := (Spaceday + 1) TO (Startday + Nday) DO
Begin
```

```
{Reset Currentday to Jan 1 if the previous day was Dec 31;    }
{this if-then loop is needed for a crop started in Dec and    }
{harvested in Jan.                                            }
 IF Currentday > 365 THEN
 Begin
      Currentday := Currentday - 365;
      Spaceday   := Currentday - 1;
      Startday   := 365 - Startday;
      Nday       := Nday - Startday;
      Startday   := 0;
      goto loop2;
 End; {IF}

{The equation for lar was derived from the DEC and MAR        }
{experiments when leaf area, fresh and dry weight             }
{measurements were performed.                                 }
 lar:=1E-5*(23.9/(wshoot[space]/(10*Density[space]))+
     615.4-24.1*(wshoot[space]/(10*Density[space])));
                                          {in ha/kg = 10 m2/gr}
 lai[space]:=wshoot[space]*lar;           {in ha/ha = m2/m2   }

{Calculate the daily dry weight production.                   }
 Cal_daily_assimilation;

{Maintenance respiration expressed as carbohydrate loss       }
{in kg/(ha*d).                                                }
 maints:=wshoot[space]*0.03+wroot[space]*0.015;
 maint:=amin1(gphot,maints*teff);

{Assimilate requirement for dry matter conversion from        }
{carbohydrates to dry matter in kg/kg.                        }
 ASRQ:=1.46*(1-FRT[Age])+1.44*FRT[Age];

{Total growth rate in kg DM/(ha*d).                           }
 gtw:=(gphot-maint)/ASRQ;

{Growth rate of roots and shoots (tops) in kg DM/(ha*d).      }
 groot:=gtw*FRT[Age];
 gtops:=gtw*(1-FRT[Age]);

{Accumulated shoot and root weight in kg/ha.                  }
 wshoot[space]:=wshoot[space]+gtops;
 wroot[space]:=wroot[space]+groot;

{Write the accumulated shoot weight to the screen.            }
 write('2. Currentday = ',Currentday:3,', wshoot =');
 writeln(' ',wshoot[space]/(10*Density[space]):7:4,'
                                          grams DW/head');
```

```
       Age:=Age + 1;

      {Write the accumulated shoot dry weight to the output file.  }
       Output_data;

  End; {FOR}

  close (data1);
  close (data2);

  writeln ('Calculations complete!!!');
  writeln ('Type "0" to show the graph of the results');
  readln(select);
  ClrScr;

{*************************************************************}
{*                    Make a graph of the results            *}
{*************************************************************}
  Fill_array;
  grDriver:=Detect;
  InitGraph(grDriver,grMode,'c:\tp\bgi'); {!SPECIFY PATH STATEMENT!}
  Errcode:=GraphResult;
  If ErrCode = grOK then
  Begin
     TextBackground(Black);
     TextColor(White);
     Draw_grid;
     Axes_scales;
     Label_axes;
     Plot_curve;
     CloseGraph;
     ClrScr;
     writeln;
     writeln('Would you like to do another run?');
     writeln;
     writeln('Enter "0" if you do, enter "1" if you do not');
     readln(Select);
  End
  Else
  Begin
     writeln('Graphics error: ',GraphErrorMsg(ErrCode));
     Readln;
  End;

UNTIL Select = 1;

ClrScr;

END. {program LETSGROW}
```

References

Albright, L. D. and A.J. Both (1994). Comparison of luminaires: efficacies and system design. Proceedings of the International Lighting for Plants in Controlled Environments Workshop. University of Wisconsin, Madison, WI. March 27-30, 1994. In Press. (*later published in NASA Conference Publication CP-3309. pp. 281-297, and available at https://www.controlledenvironments.org/*).

Bertin, N. and E. Heuvelink (1993). Dry matter production in a tomato crop: comparison of two simulation models. Journal of Horticultural Science 68(6):995-1011.

Both, A.J., L.D. Albright, R.W. Langhans, R.A. Reiser and B.G. Vinzant (1994a). Hydroponic lettuce production influenced by integrated supplemental light levels in a controlled environment agriculture facility: experimental results. Acta Horticulturae. In Press. (*later published as Acta Horticulturae 418:45-51*).

Both, A.J., L.D. Albright, R.W. Langhans, B.G. Vinzant and P.N. Walker (1994b). Electric energy consumption and light output of nine 400 watt high pressure sodium luminaires and a greenhouse application of the results. Acta Horticulturae. In Press (*later published as Acta Horticulturae 418:195-202.*).

Carrier, M., L. Gauthier and A. Gosselin (1994). Adaptation of the SUCROS87 crop growth model to the use of supplemental lighting for greenhouse tomatoes. Unpublished manuscript, Laval University, Quebec, Canada.

Critten, D.L. (1993). A review of the light transmission into greenhouse crops. Acta Horticulturae 328:9-31.

Dayan, E., H. van Keulen, J.W. Jones, I. Zipori, D. Shmuel and H. Challa (1993a). Development, calibration and validation of a greenhouse tomato growth model: I. Description of the model. Agricultural Systems 43:145-163.

Dayan, E., H. van Keulen, J.W. Jones, I. Zipori, D. Shmuel and H. Challa (1993b). Development, calibration and validation of a greenhouse tomato growth model: II. Field calibration and validation. Agricultural Systems 43:165-183.

France, J. and J.H.M. Thornley (1984). Mathematical models in agriculture. Butterworths, London, UK. 335 p.

Gary, C., J.W. Jones and J.J. Longuenesse (1993). Modelling daily changes in specific leaf area of tomato: the contribution of the leaf assimilate pool. Acta Horticulturae 328:205-210.

Goto, E. and T. Takakura (1988). The effect of artificial light on the growth of lettuce. Acta Horticulturae 230:313-318.

Goudriaan, J. (1982). Some techniques in dynamic simulation. In 'Simulation of plant growth and crop production', F.W.T. Penning de Vries and H.H. van Laar (eds.). Simulation Monographs. Center for Agricultural Publishing and Documentation (PUDOC), Wageningen, the Netherlands. Pp. 66-84.

Goudriaan, J. (1986). A simple and fast method for the computation of daily totals of crop photosynthesis. Agricultural and Forest Meteorology. 38:249-254.

Heinen, M., A. de Jager and H. Niers (1991). Uptake of nutrients by lettuce on NFT with controlled composition of the nutrient solution. Netherlands Journal of Agricultural Science 39:197-212.

Keulen, H. van, F.W.T. Penning de Vries and E.M. Drees (1982). A summary model for crop growth. In 'Simulation of plant growth and crop production', F.W.T. Penning de Vries and H.H. van Laar (eds.). Simulation Monographs. Center for Agricultural Publishing and Documentation (PUDOC), Wageningen, the Netherlands. Pp.87-97.

Lanczos, C. (1988). Applied analysis. Dover Publications, Inc. New York. 539 p.

Marsh, L.S. (1987). A model of greenhouse hydroponic lettuce production: daily selection of optimum air temperatures and comparison of greenhouse covers. Ph.D. Dissertation. Cornell University, Ithaca, NY. 198 p.

Penning de Vries, F.W.T. and H.H. van Laar (1982). Simulation of growth processes and the model BACROS. In 'Simulation of plant growth and crop production', F.W.T. Penning de Vries and H.H. van Laar (eds.). Simulation Monographs. Center for Agricultural Publishing and Documentation (PUDOC), Wageningen, the Netherlands. Pp.114-135.

Sase, S., H. Ikeda and T. Takezono (1988). Plant production in the artificial environment. Acta Horticulturae 230:323-328.

Spitters, C.J.T. (1986). Separating the diffuse and direct component of global radiation and its implications for modeling canopy photosynthesis, Part II: Calculation of canopy photosynthesis. Agricultural and Forest Meteorology 38:231-242.

Spitters, C.J.T., H.A.J.M. Toussaint and J. Goudriaan (1986). Separating the diffuse and direct component of global radiation and its implications for modeling canopy photosynthesis, Part I: Components of incoming radiation. Agricultural and Forest Meteorology 38:217-229.

Spitters, C.J.T., H. van Keulen and D.W.G. van Kraalingen (1989). A simple and universal crop growth simulator: SUCROS87. In 'Simulation and systems management in crop protection', R. Rabbinge, S.A. Ward and H.H. van Laar (eds.). Simulation Monographs 32. Center for Agricultural Publishing and Documentation (PUDOC), Wageningen, the Netherlands. Pp. 147-181.

Ting, K.C. and G.A. Giacomelli (1987). Availability of solar photosynthetically active radiation. Transactions of the ASAE 30(5):1453-1457.

Van Henten, E.J. and J. Bontsema (1991). Optimal control of greenhouse climate. In 'Mathematical and control applications in agriculture and horticulture', Y. Hashimoto and W. Day (eds.). Workshop Series, Vol 1. Pergamon Press, Oxford, UK. Pp. 27-32.

Van Henten, E.J. (1994). Validation of a dynamic lettuce growth model for greenhouse climate control. Agricultural Systems 45:55-72.

Van Henten, E.J. and G. Van Straten (1994). Sensitivity analysis of a dynamic growth model of lettuce. Journal of Agricultural Engineering Research 59:19-31.

Versteeg, M.N. and H. van Keulen (1986). Potential crop production prediction by some simple calculation methods, as compared with computer simulations. Agricultural Systems 19:249-272.

Wheeler, R.M., C.L. Mackowiak, J.C. Sager, N.C. Yorio, W.M. Knott and W.L. Berry (1994). Growth and gas exchange by lettuce stands in a closed, controlled environment. Journal of the American Society for Horticultural Science 119(3):610-615.

Wit, C.T. de (1965). Photosynthesis of leaf canopies. Agricultural Research Reports no. 663. Center for Agricultural Publishing and Documentation (PUDOC), Wageningen, the Netherlands. 57 p.