TEN YEARS OF HYDROPONIC LETTUCE RESEARCH

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Abstract
This review article describes the highlights of ten years of hydroponic lettuce (*Lactuca sativa*; butterhead lettuce) research conducted at Cornell University (Ithaca, NY, USA) throughout most of the nineties. Both the nutrient film technique (NFT) and the deep flow system were used for experimentation. Supplemental lighting and CO_2 enrichment strategies were developed in an attempt to minimize the crop production cycle while producing tipburn-free lettuce. A computer model was developed to simulate hydroponic lettuce production under different environment conditions and plant spacings. Based on the research findings, a commercially scaled pilot greenhouse facility was designed, constructed, and operated to demonstrate the economic feasibility of hydroponic lettuce production in upstate New York, USA.

Introduction

Cornell University's Controlled Environment Agriculture (CEA) Program has been involved in greenhouse hydroponic lettuce production research since 1991. This research and development effort has received major financial support from local utility companies and state energy organizations because these organizations were interested in identifying industries that could use electricity during off-peak hours. One of the main goals of the research has been to develop a production system for fresh, high-quality, pesticide-free hydroponic lettuce that is produced close to the final retail market. This proximity to final market increases product freshness and reduces the transportation costs involved with shipping produce over large distances as is customary in the United States. Year-round and rapid production is made possible with accurate greenhouse climate control, including the integration of supplemental lighting, shading, and CO_2 enrichment of the greenhouse air. Especially during the darker winter months, supplemental lighting is needed to sustain sufficiently rapid plant growth required for profitable production. One of the challenges of the location (Ithaca, NY, USA) was to deal with the significant fluctuation in daily light integrals from day-to-day and from season-to-season (Figure 1). Without consistent light integrals, consistent year-round production (i.e., following the same production cycle independent of the outside weather conditions) will be difficult to realize. From Figure 1, it is clear that both supplemental lighting and shading systems are needed throughout the year in order to provide the plants with a consistent daily integrated light level.

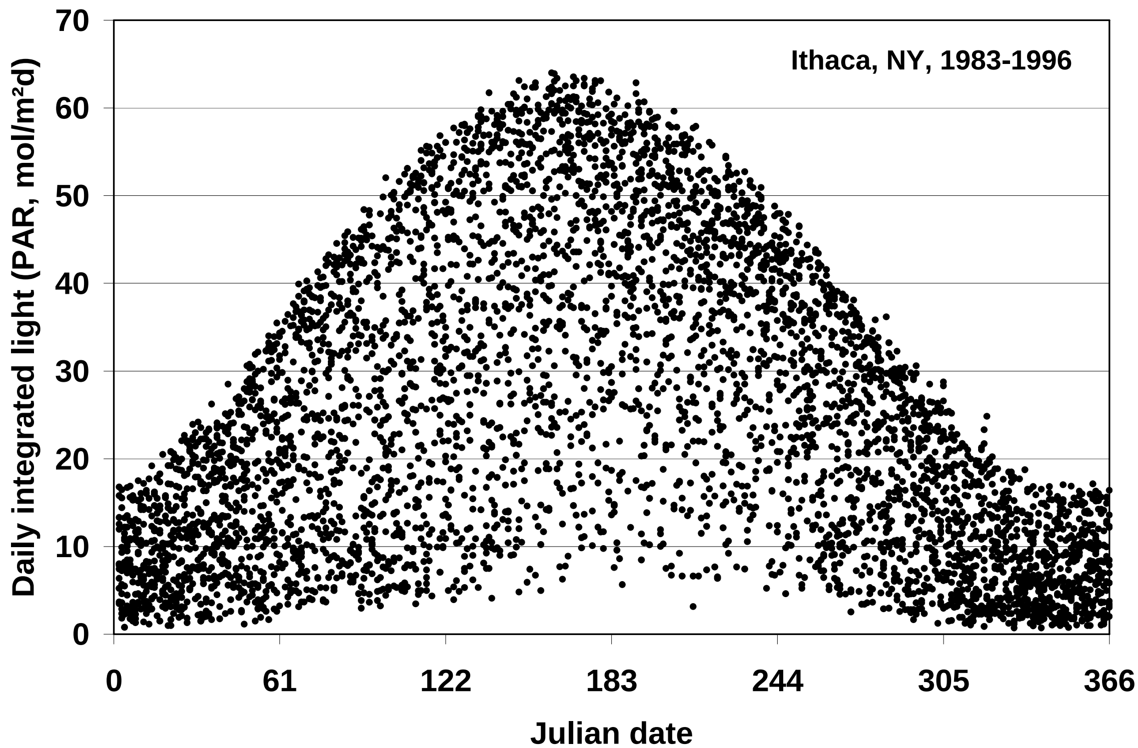

Figure 1. Daily integrated outside solar radiation (in mol-m^{-2}-d^{-1}) for Ithaca, NY, USA, for the period 1983-1996.

To integrate and demonstrate the research results, it was decided to build a 750 m^2 demonstration greenhouse equipped with the deep flow hydroponic lettuce production system studied during previously conducted research projects. Greenhouse construction was completed in early 1999. At full capacity, the facility produces 945 heads of lettuce each day, seven days per week. It takes 35 days from seed to produce a target minimum fresh shoot mass of 150 g. Cornell University owns the intellectual property rights to the developed technology and plans to license it to prospective greenhouse operators, which would receive thorough training before starting on their own. It is projected that this demonstration greenhouse could be the beginning of a new and high-tech vegetable industry in New York State and beyond.

This review article is not intended to provide significant detail of the research and development conducted over the last ten years with which the author was associated. Rather, it briefly discusses some of the major findings and provides a list of references for interested readers. Additional publications resulting from the work of Cornell's CEA Program can be found in the research literature.

Description of the Developed Production System

During the research trials, butterhead lettuce (*Lactuca sativa*) was germinated in plug trays filled with a peat-vermiculite mixture (1:1, by volume). Trials with different types of media showed that using the peat-vermiculite mixture resulted in better seedling growth and development. However, for commercial lettuce production, the use of rockwool proved more practical. After seeding, the seeds were germinated and grown in an environment controlled growth room for 11 days. The temperature in the growth room was maintained at a constant 24°C with a light intensity of approximately 200 $\mu mol\text{-}m^{-2}\text{-}s^{-1}$. For two days, the seedlings were covered with a transparent plastic cover to raise the humidity level in the airspace surrounding the germinating seeds. In order to increase seedling production, CO_2 enrichment can be applied during the growth room phase. A visual selection of the seedlings was performed at six days after seeding. At least 80% of the seedlings were normally found to be uniform enough (judged on the size of the first true leaf) to be used for final production.

Eleven days after seeding, the seedlings were manually transplanted into the greenhouse production system, either into a NFT system or deep flow hydroponics. In the NFT system, the plants were grown in shallow troughs and somewhat supported by the trough covers. In the deep flow hydroponics system (approximately 30 cm deep), the plants were grown in floating polystyrene boards that provided some support. The advantages of the deep flow hydroponics system included the buffer capacity of the nutrient solution (for water, nutrients, and temperature) and the ease with which plant material could be transported. However, the deep flow hydroponic production system required a gas delivery system to maintain an adequate dissolved oxygen concentration in the nutrient solution.

The greenhouse temperature was maintained at 24°C between 08:00 and 18:00 hr, and at 19°C thereafter. The length of the photoperiod depended on the amount of sunlight received earlier during the day and the daily target light integral required to meet the final harvest date. Supplemental lighting was provided at an intensity of approximately 200 $\mu mol\text{-}m^{-2}\text{-}s^{-1}$ from high-pressure sodium luminaires. CO_2 enrichment was applied by releasing pure CO_2 gas above the plants. CO_2 enrichment was usually halted whenever more than a minimum amount of ventilation was required to maintain the temperature and/or humidity set points, or when no light (either sunlight or supplemental light) was available for photosynthesis.

During the research trials, the initial plant spacing during greenhouse production was approximately 80 $pl\text{-}m^{-2}$ for the first 10 days after transplanting, followed by approximately 35 $pl\text{-}m^{-2}$ for the remaining two weeks. Thirty-five days after seeding, the plants reached a target shoot fresh mass of approximately 150 g, when a daily light integral of 17 $mol\text{-}m^{-2}\text{-}d^{-1}$ was maintained at an ambient CO_2 concentration (350-400 $\mu mol\text{-}mol^{-1}$).

The optimum mineral composition of the nutrient solution was described by Both et al. (1997) and closely resembles a so-called half-strength Hoagland solution. The pH and electrical conductivity (EC) of the nutrient solution was maintained between 5.6 and 6.0 (pH), and 1150 and 1250 $\mu S\text{-}cm^{-1}$ (EC), respectively, when using reversed osmosis (RO) water as the water source during the research trials. In the demonstration greenhouse, municipal water is used and an EC of 1650 $\mu S\text{-}cm^{-1}$ is maintained.

Highlighted Results

1. Crop production

The effects of supplemental lighting and the application of a daily light integral for consistent greenhouse hydroponic lettuce production were described by Both et al. (1997) and shown in Figure 2.

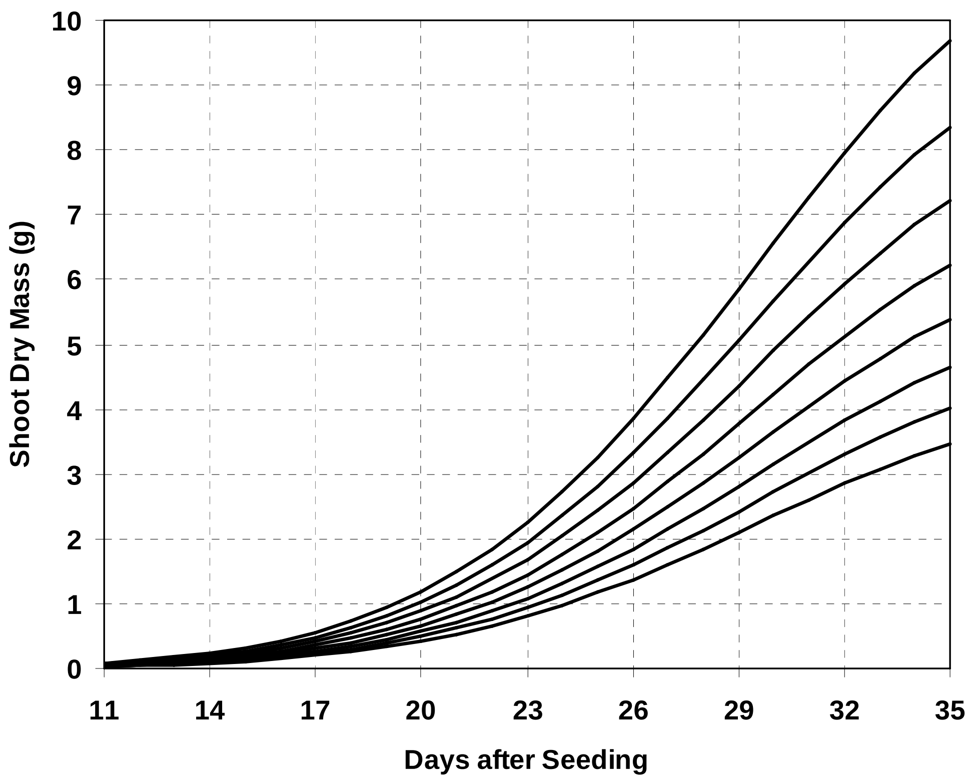

Figure 2. Fitted growth curves for butterhead lettuce (cultivar Ostinata) based on the daily integrated light level maintained during the production cycle (35 days). The curves represent lettuce growth for daily light integrals of 8, 10, 12, 14, 16, 18, 20, and 22 mol-m^{-2}-d^{-1} (from bottom to top). A second order exponential polynomial of the form DM = exp[a + b(t) + c(t^2)] was used to approximate the experimentally measured plant growth. The coefficient 'a' was found to be a function of the daily integrated light level: a = -8.596 + 0.0743(Daily light integral). The coefficients 'b' and 'c' were constant with values of 0.4822 and –0.006225, respectively. Tipburn was observed when more than 17 mol-m^{-2}-d^{-1} was provided to the plants.

It was shown that a daily light integral of no more than 17 mol-m^{-2}-d^{-1} was required to guarantee sufficiently rapid production without causing tipburn damage to lettuce plants. Overhead fans were used to improve the greenhouse air movement, which stimulated plant transpiration and delayed the onset of tipburn. Tipburn is a physiological disorder caused by calcium deficiency in the rapidly growing tips of developing lettuce leaves. Increased plant transpiration increased the transport of calcium from the roots to the developing lettuce leaves. Tipburn needs to be avoided since its presence will significantly reduce the salability of the crop. Both (1995) reported that lettuce plants need to transpire at least 400 mL per gram of dry mass accumulated in order to be free of tipburn (Figure 3). Ciolkosz et al. (1998) further investigated how to prevent tipburn damage in lettuce plants by examining the rate of plant transpiration and mechanical ways to increase evapotranspiration (by using air circulation fans that blow air down onto the crop).

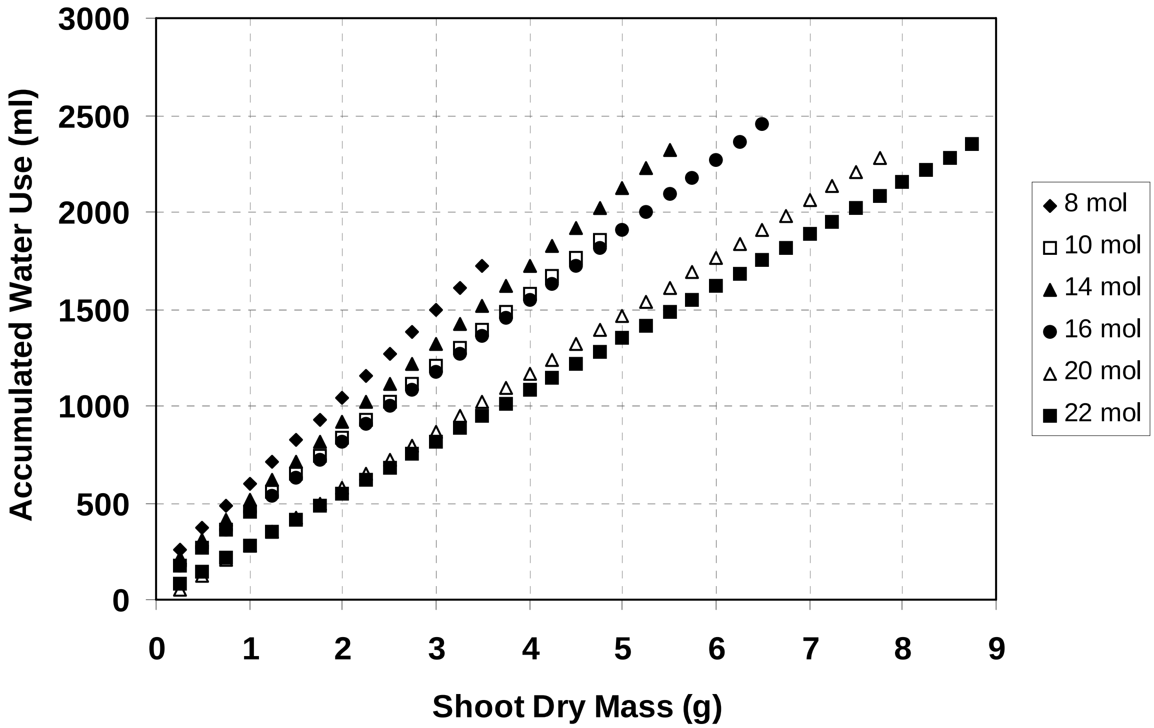

Figure 3. Accumulated water use (plant transpiration) for lettuce plants (cultivar Ostinata) grown under six different daily integrated light levels. Tipburn did not occur on plants grown under a daily integrated light level of 17 mol-m^{-2}-d^{-1} or less. Based on these results, it was determined that the plants need to transpire at least 400 mL per gram of dry mass accumulated (i.e., the minimum required slope of the lines in this graph) in order not to develop tipburn.

Lettuce growth analyses revealed a linear relationship between the total accumulated light level (since seeding) and the final shoot dry mass (Figure 4). In addition, good correlations were found between leaf area and shoot fresh mass, as well as between shoot fresh and dry mass (Figure 5).

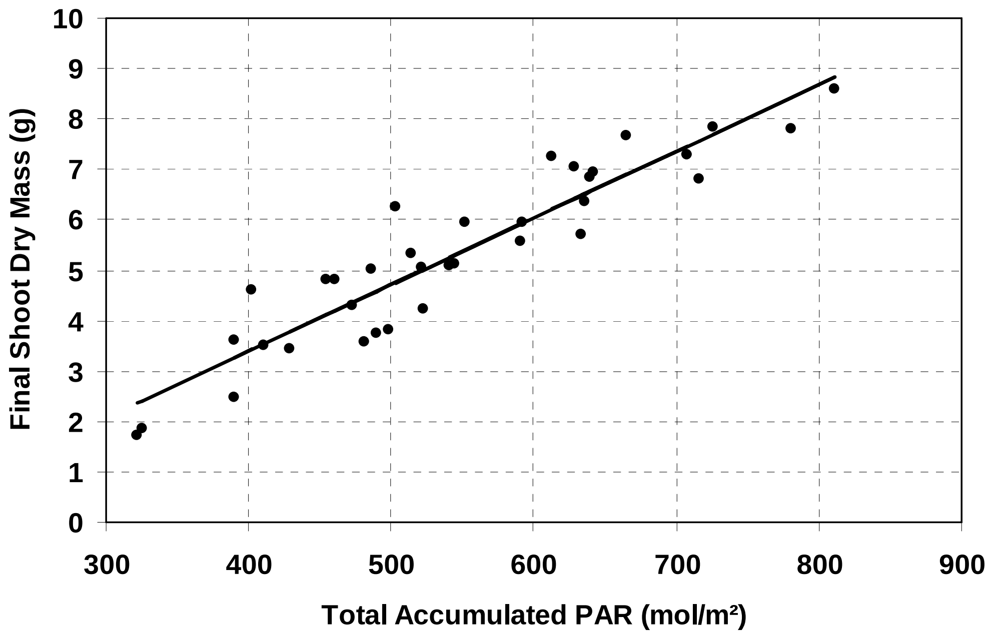

Figure 4. Linear relationship between lettuce (cultivar Ostinata) final shoot dry mass and total accumulated light levels (since seeding). The equation for the line is: DM = -1.886 + 0.0132(Accumulated light); R^2 = 0.87.

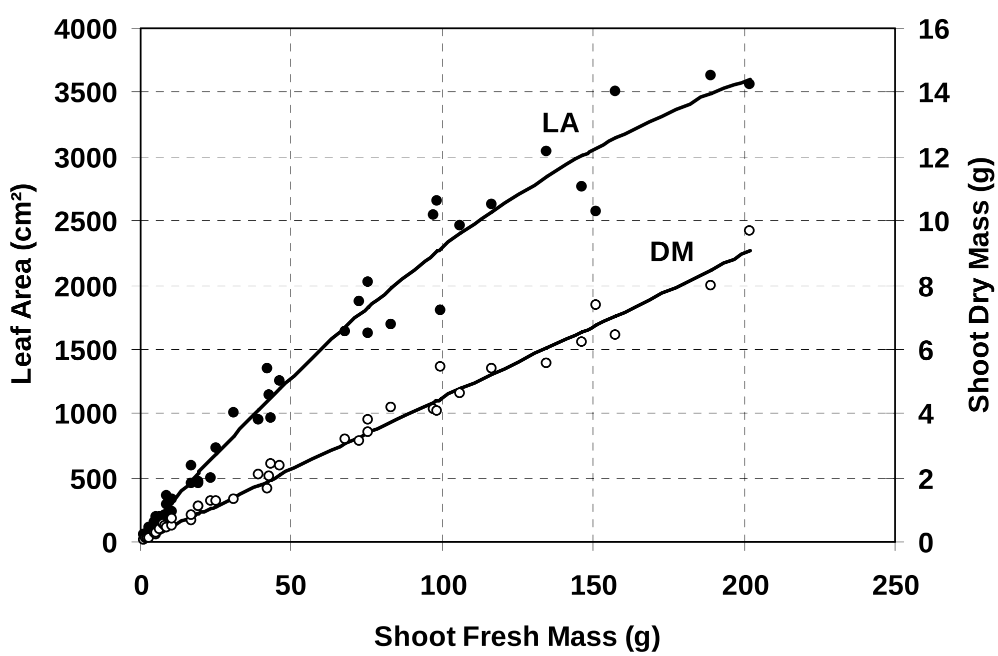

Figure 5. Correlations between lettuce (cultivar Ostinata) leaf area and shoot dry mass, and between shoot dry and fresh mass. The equation for the leaf area line is: LA = 22.77 + 27.57(FM) – 0.04880 $(FM)^2$; R^2 = 0.97. The equation for the shoot dry mass is: DM = 0.045(FM); R^2 = 0.97.

2. CO_2 Enrichment

The usefulness of carbon dioxide enrichment of the greenhouse air for increased lettuce growth, and the interaction between carbon dioxide enrichment and the use of supplemental lighting was reported by Both et al. (1998). It was shown that the number of hours of supplemental lighting required to reach the daily target light integral could be reduced by increasing the carbon dioxide concentration in the greenhouse (Figure 6).

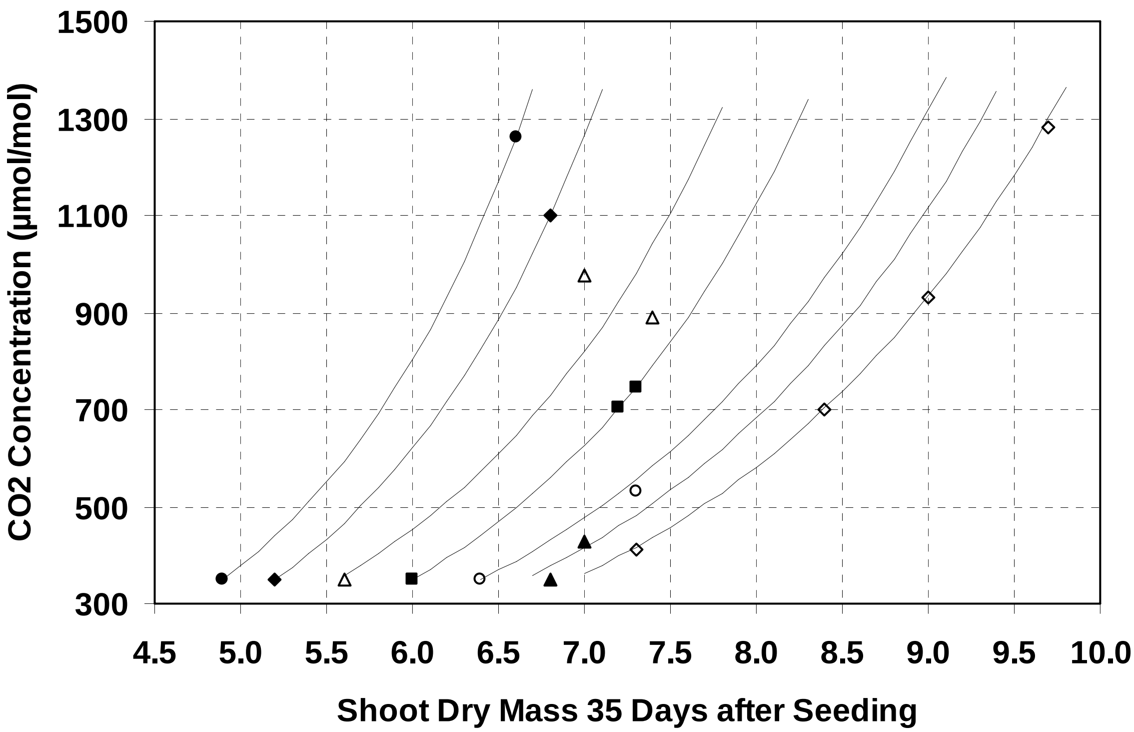

Figure 6. Lettuce (cultivar Vivaldi) shoot dry mass production at 35 days after seeding versus average aerial CO_2 concentration (µmol-mol^{-1}) during the light period. The curved lines indicate the required daily integrated light level (mol-m^{-2}-d^{-1}) from 11 through 17 mol-m^{-2}-d^{-1} (in steps of 1 mol-m^{-2}-d^{-1} from left to right).

Used primarily during the winter months, this technique can result in substantial monetary savings to the lettuce grower. For example, instead of providing 17 mol-m^{-2}-d^{-1} at ambient CO_2 concentrations to reach a target shoot dry mass of 7 g (equivalent with a shoot fresh mass of approximately 150 g), 12 mol-m^{-2}-d^{-1} can be provided while maintaining a CO_2 concentration of approximately 1300 µmol-mol^{-1} (Figure 6). DeVilliers et al. (1999) reported on a control strategy that determined, on an hourly basis, whether to operate the supplemental lighting or the CO_2 enrichment system for optimum lettuce production without tipburn.

3. Deep Flow Hydroponics

- Dissolved Oxygen Concentration

The effects of different dissolved oxygen concentrations in the nutrient solution on lettuce growth in deep flow hydroponics were described by Goto et al. (1996). Dissolved oxygen concentrations of at least 4 mg/L were recommended for optimum lettuce growth and development. Severe plant stress was observed at DO concentrations below 2 mg/L

- Nutrient Solution Temperature

Thompson et al. (1998) reported on shoot and root temperature effects on lettuce growth in deep flow hydroponics. It was found possible to produce a quality lettuce crop even when grown at continuously elevated greenhouse aerial temperatures (above 24°C during the light period) but only if the root zone temperature (nutrient solution) was kept below 20°C. This result showed that successful lettuce production is possible in warmer climates when the temperature of the root zone environment is maintained at appropriate levels.

- Root and Shoot Growth

Figure 7 shows typical root and shoot growth for lettuce plants grown in a floating hydroponics system under a daily integrated light level of 16 mol-m^{-2}-d^{-1} (Both et al., 1999a).

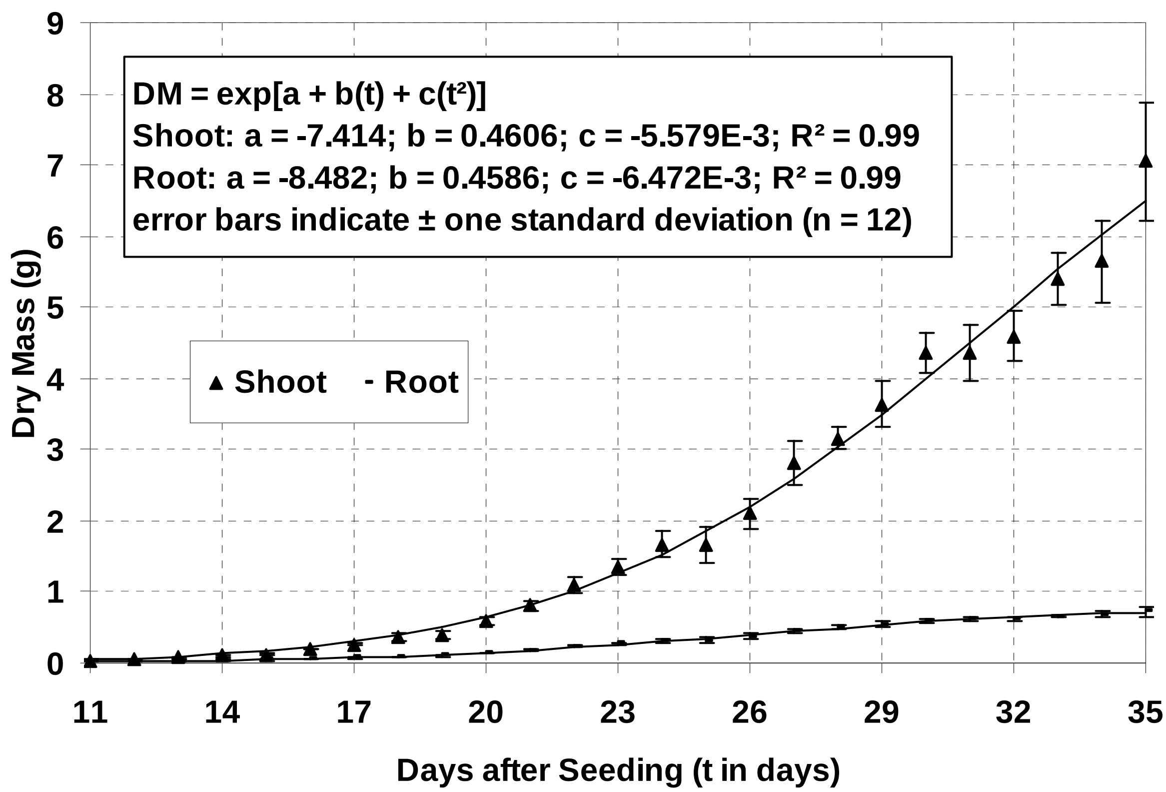

Figure 7. Root and shoot growth of lettuce plants (cultivar Vivaldi) grown in a floating hydroponics system under a daily integrated light level of 16 mol-m^{-2}-d^{-1}.

4. Crop Modeling

A crop model (LETSGROW; described by Both, 1995) was developed to simulate hydroponic lettuce production under a range of environment conditions. An outdoor crop model (SUCROS87) was adapted for greenhouse lettuce production. The model allowed for daily changing photoperiods (as a result of controlling the light integral to a daily target) as well as CO_2 enrichment. The model predictions were compared to the results of production trials. In most cases, model predictions closely followed experimentally observed plant growth and development (Figure 8).

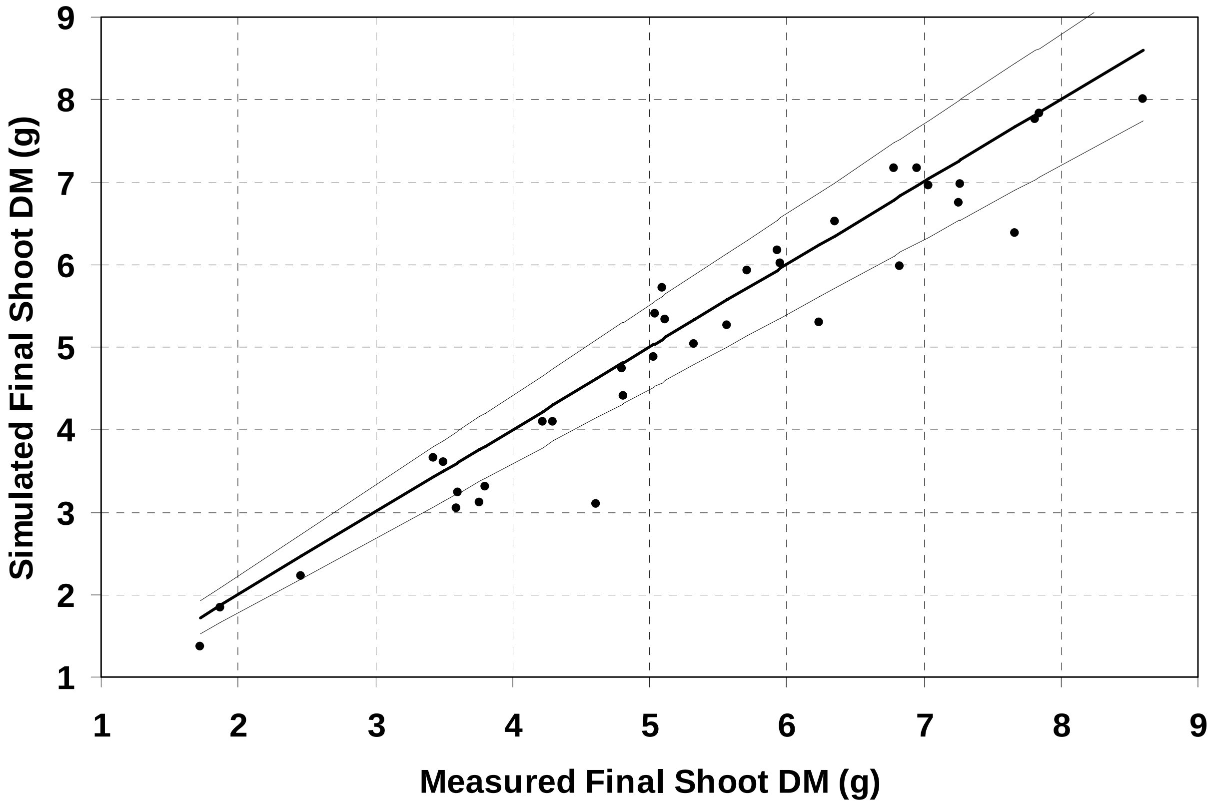

Figure 8. Comparison of the LETSGROW crop growth model predictions with experimentally measured shoot dry mass at final harvest (35 days after seeding; cultivar Ostinata). The model predictions were based on the measured daily integrated light levels provided during the experiments. The region with acceptable crop model predictions falls between the upper and lower lines, which indicate the region of plus or minus one standard deviation from the measured final shoot dry mass data.

Albright et al. (1999) developed a technique that calculates dimensionless growth curves that simplify the incorporation of predictive plant growth models into greenhouse environment control software. Only five parameters were needed to fully characterize lettuce growth and development for a diverse set of production data reported in the literature: greenhouse temperature, CO_2 concentration, daily integrated light level, nitrate concentration in the nutrient solution, and the root zone temperature.

5. Controlling the Greenhouse Light Environment

Albright et al. (2000) developed a control algorithm capable of providing a fixed daily light integral independent of the amount of outside solar radiation received. The control algorithm directs, in hourly increments, the operation of the lighting and shading system. The algorithm allows for maximum use of solar radiation, while preventing the daily light integral from overshooting its target. In addition, the algorithm operates the supplemental lighting systems as much as possible during off-peak hours in order to reduce electricity costs. A US Patent (Patent No. 5,818,734) was granted for this control algorithm.

6. Demonstration Greenhouse

A 750 m^2 glass-clad gutter-connected greenhouse was constructed near Cornell University in Ithaca, NY, USA (Both et al., 1999b). Glass was used in the roof and sidewalls for optimum light transmission (Photo 1). The greenhouse is mechanically ventilated and equipped with an evaporative cooling system.

Photo 1. Outside view of the 750 m^2 hydroponic lettuce demonstration greenhouse in Ithaca, NY, USA. This facility produces 945 heads of lettuce every day of the year using the floating hydroponics system. The total production cycle is 35 days; 11 days in an environment controlled growth room and 24 days in the greenhouse. At 150 g per head (fresh mass), this greenhouse facility has the potential to produce just over 51,000 kg of edible biomass annually (83 kg-m^{-2} of growing area-yr^{-1}).

A shade curtain can be deployed to reduce solar radiation on the crop. A supplemental lighting system consisting of 600-watt high-pressure sodium lamps is providing a uniform light intensity of approximately 180 $\mu mol\text{-}m^{-2}\text{-}s^{-1}$ at canopy level. Vertical airflow fans were installed to increase air movement over the crop. A CO_2 enrichment system was installed to enrich the greenhouse air. At full capacity, the facility produces 945 heads of lettuce each day, seven days per week (Photo 2).

Photo 2. Inside view of the hydroponic lettuce demonstration greenhouse. The lettuce plants are supported by floating polystyrene boards in which holes are drilled at the desired plant spacing. In order to increase space utilization, the plants are respaced once (10 days after transplant). Every day, 945 plants are harvested and 945 seedlings are added. Accurate control of the supplemental lighting and shading systems results in a consistent daily light integral of 17 $mol\text{-}m^{-2}\text{-}d^{-1}$.

7. Recent Modifications

In addition to butterhead lettuce, romaine (cos) lettuce is successfully being grown in the demonstration greenhouse. Plant spacing has been adjusted, resulting in a final plant spacing of 37.7 $pl\text{-}m^{-2}$ and a daily production of 1245 lettuce heads. This modification increases the potential annual biomass production to 110 $kg\text{-}m^{-2}$ of growing $area\text{-}yr^{-1}$.

Summary

Over a period of ten years, research was conducted on hydroponic lettuce production in the NFT and floating hydroponics systems. A crop production system was developed that maximizes lettuce growth and development while preventing tipburn. The results of the research efforts were used to design, construct, and operate a commercially scaled hydroponic lettuce demonstration greenhouse. It is projected that this demonstration greenhouse could be the beginning of a new and high-tech vegetable industry in New York State and beyond.

More detailed information about the research and the demonstration greenhouse can be found in the research literature (see the attached bibliography) and on the following web site: http://www.cornellcea.com

Acknowledgements

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