

## Cornell Controlled Environment Agriculture



## Hydroponic Lettuce Handbook

This hydroponic greenhouse production system was designed for small operations to provide local production of head lettuce as well as employment to the proprietors. Our research group has experimented with many forms of hydroponics but have found this floating system to be the most robust and forgiving of the available systems. This system is built around consistent production 365 days of the year. This requires a high degree of environmental control including supplemental lighting and moveable shade to provide a target amount of light which, in turn, results in a predictable amount of daily growth.

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Table of Abbreviations and Units

A	Area	Square feet or square meter.
CEA	Controlled Environment Agriculture	Producing plants in a greenhouse or other space.
cm	centimeter	A unit of length
CWF	Cool White Fluorescent	A type of supplemental lighting
DLI	Daily Light Integral	The sum of photosynthetic (PAR) light received by plants in a day.
DO	Dissolved Oxygen	Oxygen concentration in nutrient solution measured in parts per million.
EC	electrical conductivity	An indirect measurement of the strength of a nutrient solution.
HID	High Intensity Discharge	A type of HID supplemental lighting
hp	horsepower	A unit of power
HPS	High Pressure Sodium	A high intensity discharge lamp/luminaire type for supplemental lighting
kPa	kilopascals	A unit of pressure, force per unit area
MH	Metal Halide	A type of HID supplemental lighting
mol	pronounced 'mole'	A number of anything equal to $6.02 \times 10^{23}$ items. We use it to quantify the number of photons between 400-700 nm of PAR light plants receive.
mol/m <sup>2</sup> /d	moles per square meter per day	Integrated PAR light
mol/m <sup>2</sup> /s	moles per square meter per second	Instantaneous PAR light
nm	nanometer	Unit of length in SI, one billionth of a meter
PAR	Photosynthetically Active Radiation	The portion of the electromagnetic spectrum between 400-700 nm plants use for photosynthesis
ppm	parts per million	A unit that describes dimensionless quantities such as volume fractions. For describing carbon dioxide concentrations it is a molar basis.
SI	System Internationale	International system of units aka metric system - built around 7 basic units of measurements
μmol/m <sup>2</sup> /s	micro-mole per square meter per second	Instantaneous PAR light
μS/cm	microsiemens per centimeter	A unit of measurement for electrical conductivity

## Chapter 1: Greenhouse Hardware

Of fundamental importance to hydroponic lettuce production are the physical components of both the germination area and the pond area. It is necessary to have not only an idea of the physical components associated with each area, but also a good understanding of their purposes.

### 1.1 Nursery or Seedling production Area

The first 11 days of lettuce production takes place in the seedling production area. Seedlings develop best under constant lighting conditions with specific, closely controlled temperature, relative humidity, carbon dioxide, and irrigation. These conditions can only be met in a controlled area, whether that is a greenhouse or a growth room, with the following equipment:

Ebb and Flood Benches, Tables, or Ponds  
Solution Tank and Plumbing  
Supplemental Lighting Aspirated sensor Box  
Sensors

#### Ebb and Flood Benches

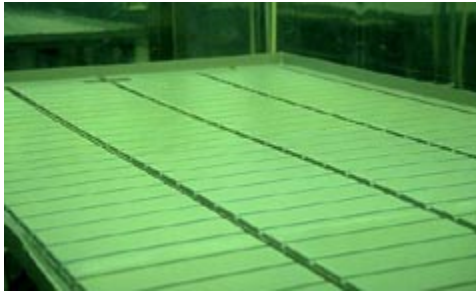


Figure 1. This is a photo of an empty Ebb and Flood bench while the bench is flooding for sub-irrigation.

To uniformly supply the germinating seedlings with water and nutrients, Ebb and Flood benches (approximately 2.5 by 1.3 m or 8 by 4 foot) are periodically (2 to 4 times per day for approximately 15 minutes) flooded. These benches were specifically designed to supply water and nutrients through *sub-irrigation*. Through a pump and piping, the *fertilizer solution* is pumped into the Ebb and Flood bench. The solution is then automatically drained after a given time period.





Figure 2. Bench for seedlings.

## Ponds



Figure 3. Seedling area on edge of pond in greenhouse.



Figure 4. Breaker on the end of a wand for hand-watering.

Alternately, the rockwool slabs in trays sitting on a bench (Figure 2) or the edge of a pond (Figure 3) may be overhead watered with a hose that has a breaker (see Figure 4 above) on it that slows the flow of high velocity water so that fragile seedlings are not damaged.

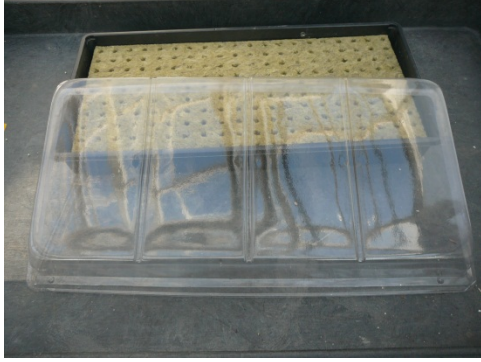


Figure 5. Humidity cover propped against a sheet of rockwool.

*Humidity covers* (Figure 5) are used to provide a high humidity environment around the germinating seeds. They are required if seeding with bare (not pelleted) seed.

### Solution Tank and Plumbing

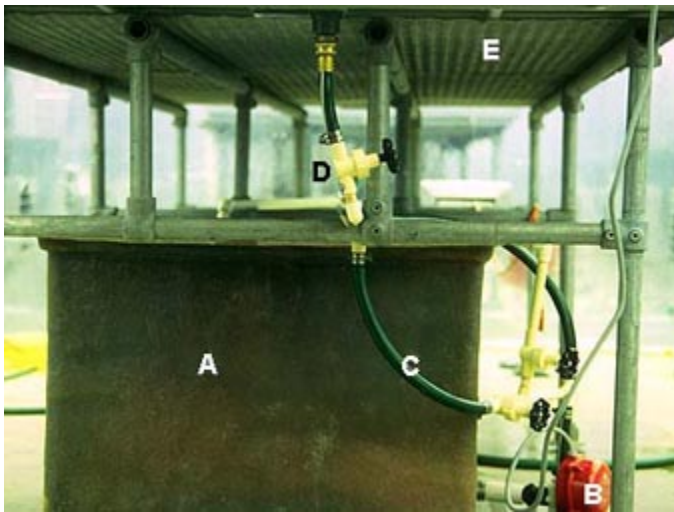


Figure 6. Nutrient solution reservoir fiberglass tank (A), Pump (B), Piping (C), and Valve (D). The bottom of the germination bench can be seen in (E).

A fiberglass tank (A) see Figure 6, holds the nutrient solution used for sub-irrigating the seedlings. A plastic tank could also be used but may not be as strong as the fiberglass. Care must be taken to procure a plastic vessel that will not degrade quickly in sunlight if germination area is in a greenhouse. Any vessel that is used should be sufficiently opaque to prevent algae growth. Approximately 250 L (66 gallons) of nutrient solution is sufficient to prime the system (given above-listed bench size), fill the bench, and provide nutrient solution for the first 11 days of growth for approximately 2000 seedlings. A small (1/50 h.p.) pump (B) is used to pump the solution to the bench. The piping (C) should be flexible to adjust to individual germination area needs. A throttling or gate valve (D) is included to control the flow of the nutrient solution to the Ebb and Flow bench. The bottom of the sub-irrigation bench (E) is visible in the photo above.



The pump may be operated on a time clock so that irrigation can occur without human intervention.

## Lighting

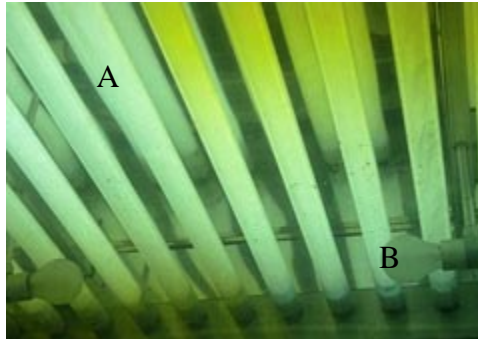


Figure 7. Fluorescent (A) and incandescent (B) lighting in the growth room. Fluorescent lighting is used for plant biomass production and incandescent lighting is used for photoperiod control.

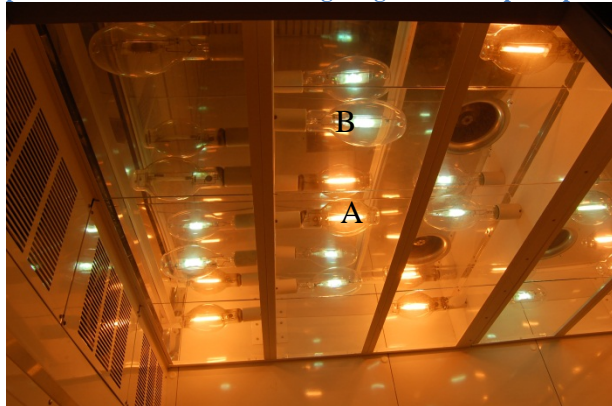


Figure 8. High Pressure Sodium (A) and Metal Halide (B) lamps in a growth chamber.

### ***Germination Room***

In general, a separate room for germination of seedlings is very energy intensive. Our experience was that the improvement in growth obtained by utilizing a germination room was not worth the large amount of energy such a room used and its' use was discontinued. Cool white fluorescent (CWF) lamps (A, see Figure 7) or High Pressure Sodium/Metal halide (A,B, see Figure 8) are recommended. Heat generated by the lamps must be dissipated from the germination area in order to maintain the temperature set points. Use of incandescent lamps (B) is discouraged because the red light emitted from these lamps causes the seedlings to 'stretch'. Fluorescent lamps are rich in blue light, which cause compact and sturdy seedlings.

## Greenhouse



Figure 9. High Intensity Discharge (HID) luminaire in a greenhouse.

If germination of seedlings is performed in a greenhouse, high intensity discharge (HID) luminaires such as high pressure sodium (HPS) or metal halide (MH) are recommended (Figure 9).

### **Configuration and Intensity**

Lamps should be configured for a uniform distribution of light over the entire growing area. Light intensity is maintained at no less than  $50 \mu\text{mol}/\text{m}^2/\text{s}$  of PAR (*Photosynthetically Active Radiation*) during the first 24 hours the seeds are kept in the germination area. This level of illumination prevented stretching of the seedlings while minimizing the tendency of supplemental lighting to dry out the surface of the medium.

The following calculation may be used for determination of hourly PAR.

$$\text{Hourly PAR} = \left( \frac{100 \mu\text{mol}}{\text{m}^2\text{s}} \right) \left( \frac{60 \text{ s}}{1 \text{ min}} \right) \left( \frac{60 \text{ min}}{1 \text{ hour}} \right) \left( \frac{1 \text{ mol}}{1 \times 10^6 \mu\text{mol}} \right) = 0.36 \frac{\text{mol}}{\text{m}^2\text{hour}}$$

Sum the accumulated hourly PAR values for a daily PAR value.

For the remaining 10 days, the light intensity is maintained at  $250 \mu\text{mol}/\text{m}^2/\text{s}$ . The photoperiod (or day length) is 24 hours. Shorter photoperiods are acceptable if the light intensity is increased to provide the same total daily accumulated light ( $\sim 22 \text{ mol}/\text{m}^2/\text{d}$ ). Anecdotal evidence shows that some lettuce seedlings can tolerate  $30 \text{ mol}/\text{m}^2/\text{d}$ .

Note for germination rooms: Light output of CWF and HID lamps decays over time. Thus, it is important to measure the light output of the lamps regularly. If the light intensity drops below an acceptable level (e.g.  $200 \mu\text{mol}/\text{m}^2/\text{s}$ ), new lamps should be installed. A quantum sensor can be used to measure the amount of PAR.



Figure 10. Aspirated box in a greenhouse. A fan draws air from the bottom of the box over the sensors.



Figure 11. Aspirated box opening on bottom of box.

This is an example of an aspirated box (Figure 10) which houses and protects the sensors the computer uses to make control decisions from light or localized temperature fluxes. Most greenhouse control systems supply their own aspirated boxes with sensors included that will be used for environmental monitoring. Aspirated boxes can be home-made but care must be taken so that the air is drawn over the sensors so that heat is not added to the air from the fans. The position of the box should be close to the plant canopy to measure the environmental parameters at the plant level. This may not be possible in all germination areas. The box is equipped with a small fan which draws air past the sensors (Figure 11). Sensors are located upstream from the fan.

### ***Sensors***

See "Sensors" under Chapter 3: Computer Technology for full details.

## 1.2 Pond Area

The concepts involved in the pond area are the following:

Pond Size  
Pond Solution  
Construction  
Pond Design  
Lighting  
Paddle Fan  
Aspirated Box

### ***Pond Size***

For example, for the production of 1245 heads per day a 660 m<sup>2</sup> growing area is required. The lettuce plants are grown in the pond area for 24 days. This includes one re-spacing of the plants at Day 21, from 97 plants m<sup>-2</sup> to 38 plants/sq m.

### ***Pond Solution***

Equal portions of *Stock Solutions A and B* (see formulas in appendix) are added to reverse-osmosis RO water to achieve an EC of 1200 μS/cm or 1.2 dS/cm.

### ***Construction***



Figure 12. Empty pond with liner.



Figure 13. Edge of pond detail. The inside edges of two separate ponds made of wood and separated by structural members is shown on left. The right hand picture shows a concrete pond.

There are three main options for pond construction.

- The pond may be sunken in the greenhouse floor, with the pond surface just above the floor (not pictured).
- A containerized pond with concrete or wooden walls (Figure 12) can be constructed on top of the floor of the greenhouse.
- The pond can be built on an island of fill with the ponds built into the fill so that the water level is closer to waist level to lessen the amount of bending that must be performed when working with the crop. An important note is that a greenhouse that uses this system must be sufficiently tall so that supplemental lighting is not too close to the plants (not pictured).

In any case, the pond floor can be layered with sand to cushion any sharp edges from puncturing the polyethylene lining. A heavy plastic (for example, 0.5 mm poly) liner is then installed as the major barrier for leak protection. Proper precautions should be taken to avoid leaks.

### **Design**

The pond area is designed to allow for one *plant spacing (also called re-spacing)* on Day 21. To facilitate the spacing process, multiple ponds run in parallel. The plants are grown in one of the ponds between days 11 and 21. After re-spacing (from 97 plants m<sup>-2</sup> to 38 plants m<sup>-2</sup>) the plants are moved to one of the remaining ponds where they will be grown for two weeks (day 21 through day 35).

### **Lighting**

Uniform light distribution is required in the Pond Growing Area. A supplemental light intensity within the range of 100-200  $\mu\text{mol}/\text{m}^2/\text{s}$  (for a total of 17  $\text{mol}/\text{m}^2/\text{d}^1$  of both natural and supplemental lighting) at the plant level is recommended. It should be noted that 17  $\text{mol}/\text{m}^2/\text{d}$  is the light integral that worked best for the particular cultivar of boston bibb lettuce that we used. For some cultivars, 15 or  $\text{mol}/\text{m}^2/\text{d}$  is the maximum amount of light that can be used before the physiological condition called tipburn occurs. High pressure sodium (HPS) lamps are a type of High Intensity Discharge (HID) lamp, and are used to supply light. These lamps are relatively efficient, have a long life (~25,000 hours, generally these lamps lose 1% output for every 1000 hours), and slowly decay in output over time. There is a recent development in the manufacturing process for metal halide lamps that gives them a lifetime similar to high pressure sodium lamps. Metal halide lamps have a spectrum that is slightly more efficient for plant growth than high pressure sodium lamps. A new bulb produced by the Philips corporation has exaggerated the benefits of metal halide lamps including shifting more light production to the blue and red portions of the spectrum and decreasing the heat output of the luminare. Independent lighting consultants have specialized software to determine proper number and placement of lamps needed for a specific and uniform light intensity. It is critical to have the correct lighting system installation.

Because the CEA lettuce program is production-intensive, lighting and electrical power usage is high. Local utility companies should have information on special rates and rebate programs for new industries and Controlled Environment Agriculture facilities.

## Lighting Configuration and High Intensity Discharge (HID) Lamps

The number and position of the lamps were determined using a specialized lighting configuration computer program.

Figure 9 shows a high pressure sodium (HPS) lamp and luminaire used for supplemental lighting. These lamps provide the recommended *Photosynthetically Active Radiation (PAR)* needed to supplement natural light. The computer control program records the irradiance and adjusts (on and off) the supplemental lighting system to achieve a predetermined total light level each day. For the lettuce production the recommended level is 17 mol/m<sup>2</sup>/d.

## Paddle Fan



**Figure 14. Paddle fan to increase vertical air movement and therefore evapotranspiration. This is important for the prevention of tipburn. A 17 mol/m<sup>2</sup>/d DLI target has to be matched with sufficient downward air flow to prevent tip burn. Without the air flow, we were not able to go over 12 mol/m<sup>2</sup>/d.**

An overhead fan (paddle fan - Figure 14) is used to blow air vertically down onto the lettuce plants at the rate of 140 cubic feet per minute per square foot of pond area. The airflow increases plant transpiration. This increase in transpiration increases the transport of nutrients, especially calcium, from the roots to the young, fast-growing lettuce leaves. The greater rate of nutrient transport provides sufficient amounts of calcium to the leaves and, therefore, prevents tipburn. Without this airflow, lettuce must be grown under reduced light levels (for example at 12 mol/m<sup>2</sup>/d instead of 17 mol/m<sup>2</sup>/d but realize that this data is only for cultivar *Ostinata* which is no longer available), which slows the rate of growth. The actual daily light integral target that can be achieved with and without vertical airflow before tip burn occurs is a function of cultivar selection, spacing and airflow. The numbers given above are examples of what has been



successful in our situation and are not the only solution and no attempt was made to establish airflow maxima and minima.

## Aspirated Box

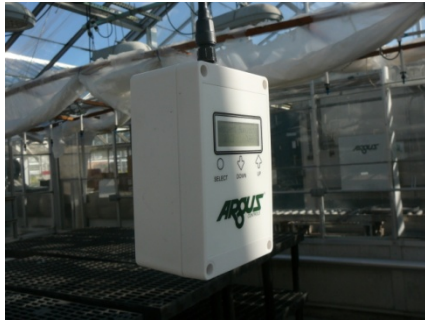


Figure 15. Aspirated box with digital output screen in greenhouse.

The aspirated box located in the pond area has the same function as the aspirated box in the germination area.

## Chapter 2: System Components

### System Component Information

**Note:** References to company and brand names are used for identification purposes only and do not necessarily constitute endorsements over similar products made by other companies.

#### 2.1 Dissolved Oxygen Sensor

Most manufacturers recommend that dissolved oxygen sensors be calibrated daily. Modern sensors are fairly stable and will probably not go out of calibration in such a short time period. Remember that your data is only as good as your calibration, so be sure to calibrate all sensors on a regular basis.

A hand-held sensor (~\$600 in 2013) is always an essential trouble-shooting tool and should always be available. If the facility is one acre or larger, an in-line sensor may be a worthwhile investment.

Model: Orion 820, hand held, battery operated

Manufacturer: Orion Research Inc., Boston, MA

Some other manufacturers that make this same quality meter are YSI, Oakton and Extech

#### 2.3 Compact Submersible Centrifugal Pump

Specifications: 0.02 HP, 75 W, max 1.5 Amps

#### 2.4 Flow Meters



**Figure 16. Model: H-03216-04: 65 mm variable area aluminum flow meter with valve and glass float for O<sub>2</sub>. Manufacturer: Cole Parmer Instrument Co., Niles, IL**

Specifications: Max. flow rate for O<sub>2</sub> = 46 ml/min.

## **Chapter 3: Computer Technology and Monitoring**

Computer technology is an integral part in the production of hydroponic lettuce. A computer control system (example: Argus, Hortimax, Priva) should be used to control the abiotic environment. Different sensors are used to monitor greenhouse environment parameters. These parameters include temperature of greenhouse air and nutrient solution, relative humidity and carbon dioxide concentration of greenhouse air, light intensities from sunlight and supplemental lighting, pH, Dissolved Oxygen (DO) levels, and Electrical Conductivity (EC) of the nutrient solution. Sensors will communicate the environmental conditions to the control computer which will activate environmental control measures such as heating, ventilation, and lighting.

### **3.1 Biological Significance of Environmental Parameters**

#### **Temperature**

Temperature controls the rate of plant growth. Generally, as temperatures increase, chemical processes proceed at faster rates. Most chemical processes in plants are regulated by enzymes which, in turn, perform at their best within narrow temperature ranges. Above and below these temperature ranges, enzyme activity starts to deteriorate and as a result chemical processes slow down or are stopped. At this point, plants are stressed, growth is reduced, and, eventually, the plant may die. The temperature of the plant environment should be kept at optimum levels for fast and successful maturation. Both the air and the water temperature must be monitored and controlled.

#### **Relative Humidity**

The relative humidity (RH) of the greenhouse air influences the transpiration rate of plants. High RH of the greenhouse air causes less water to transpire from the plants, which causes less transport of nutrients from roots to leaves and less cooling of the leaf surfaces. High humidities can also cause disease problems in some cases. For example, high relative humidity encourages the growth of botrytis and mildew.

#### **Carbon Dioxide or CO<sub>2</sub>**

The CO<sub>2</sub> concentration of the greenhouse air directly influences the amount of photosynthesis (growth) of plants. Normal outdoor CO<sub>2</sub> concentration is around 390 parts per million (ppm). Plants in a closed greenhouse during a bright day can deplete the CO<sub>2</sub> concentration to 100 ppm, which severely reduces the rate of photosynthesis. In greenhouses, increasing CO<sub>2</sub> concentrations to 1000-1500 ppm speeds growth. CO<sub>2</sub> is supplied to the greenhouse by adding liquid CO<sub>2</sub>. Heaters that provide carbon dioxide as a by-product exist but we do not recommend these because they often provide air contaminants that slow the growth of the lettuce.

#### **Lights**

Light measurements are taken with a quantum sensor, which measures Photosynthetically Active Radiation (PAR) in the units  $\mu\text{mol}/\text{m}^2/\text{s}$ . PAR is the light which is useful to plants for the

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process of photosynthesis. Measurements of PAR give an indication of the possible amount of photosynthesis and growth being performed by the plant. Foot-candle sensors and lux meters are inappropriate because they do not directly measure light used for photosynthesis.

### **Dissolved Oxygen**

Dissolved oxygen (DO) measurements indicate the amount of oxygen available in the pond nutrient solution for the roots to use in respiration. Lettuce will grow satisfactorily at a DO level of at least 4 ppm. If no oxygen is added to the pond, DO levels will drop to nearly 0 ppm. The absence of oxygen in the nutrient solution will stop the process of respiration and seriously damage and kill the plant. Pure oxygen is added to the recirculation system in the ponds. Usually the level is maintained at 8 (7-10, no advantage to 20) ppm. For sufficiently small systems, it is possible to add air to the solution through an air pump and aquarium air stone but the dissolved oxygen level achieved will not be as high as can be achieved with pure oxygen.

### **pH**

The pH of a solution is a measure of the concentration of hydrogen ions. The pH of a solution can range between 0 and 14. A neutral solution has a pH of 7. That is, there are an equal number of hydrogen ions ( $H^+$ ) and hydroxide ions ( $OH^-$ ). Solutions ranging from pH 0-6.9 are considered acidic and have a greater concentration of  $H^+$ . Solutions with pH 7.1-14 are basic or alkaline and have a greater concentration of  $OH^-$ .

The pH of a solution is important because it controls the availability of the fertilizer salts. A pH of 5.8 is considered optimum for the described lettuce growing system, however a range of 5.6-6.0 is acceptable. Nutrient deficiencies may occur at ranges above or below the acceptable range.

### **Electrical Conductivity**

Electrical conductivity (EC) is a measure of the dissolved salts in a solution. As nutrients are taken up by a plant, the EC level is lowered since there are fewer salts in the solution. Alternately, the EC of the solution is increased when water is removed from the solution through the processes of evaporation and transpiration. If the EC of the solution increases, it can be lowered by adding pure water, e.g., reverse osmosis water). If the EC decreases, it can be increased by adding a small quantity of a concentrated nutrient stock solution. When monitoring the EC concentration, be sure to subtract the base EC of your source water from the level detected by your sensor.

### **Monitoring**

The following parameters should be monitored. Specific sensor recommendations will not be made here.

Temperature, see Figure 12.

Relative Humidity, see Figure 12.

Carbon Dioxide Concentration (Infra Red Carbon Dioxide Sensor)

Light (Quantum PAR sensor), see Figure 13.

Dissolved Oxygen, see Figure 14.

pH

## Electrical Conductivity (EC)



Figure 17. Quantum PAR sensor to measure light available for photosynthesis. Foot-candle sensor and lux meters are inappropriate because they are designed to quantify the sensitivity of the human eye and overestimate (~25%) the light available for photosynthesis



Figure 18. Dissolved oxygen sensor. DO levels should be greater than 4 ppm to prevent growth inhibition. Visible signs of stress may be observed at 3 ppm.

### 3.3 Set-points

Air Temperature	24 C Day/19 C Night (75 F/65 F)
Water Temperature	No higher than 25C, cool at 26C, heat at 24C
Relative Humidity	minimum 50 and no higher than 70%
Carbon Dioxide	1500 ppm if light is available, ambient (~390 ppm) if not
Light	17 mol m <sup>2</sup> /d combination of solar and supplemental light
D O	7 mg/L or ppm, crop failure if less than 3 ppm
pH	5.6-6

EC

1150-1250  $\mu\text{S}/\text{cm}$  above the source water

## Chapter 4: Lettuce Production

### Lettuce Production

This handbook is directed toward a daily production of 5 ounce (150 grams) heads of leaf lettuce. The production of the lettuce crop is separated into two growing areas. Seeds are started in a germination area where they germinate and grow for 11 days. They should be shaded from full sun on the first day after germination, but can then be exposed to full light ( $17 \text{ mol}/\text{m}^2/\text{d}$ ) or slightly greater. On Day 11, the plants are transported to the greenhouse and transplanted into the pond area where they are grown until re-spacing on day 21 and finally harvested on Day 35.

### Germination Area Stage

Germination Area stage is scheduled for Production Days 0-11 and may occur in a growth chamber or nursery area in the greenhouse.

#### Day 0 - Sowing

Production begins with the making of the germination media. The media fills 7 plug trays of 200 plugs each (1" rockwool cubes that are 10 x 20 cells per sheet). One lettuce seed is placed into each plug. This can be done with an automated seeding machine such as a drum seeder or a vacuum seeder. Rockwool should be moistened with nutrient solution that has a relatively low pH such as 4.5 to remove pockets of high pH contaminants.

The trays are placed into the germination area which may be an Ebb and Flood bench, a table, or on a float in the pond. Trays on an Ebb and Flood bench are sub-irrigated with RO water for 1/4 hour every 12 hours. For the initial 24 hours, lighting is maintained at  $50 \mu\text{mol}/\text{m}^2/\text{s}$  with a photoperiod (day length) of 24 hours to ensure good germination if a germination room is used. The temperature is set for 20C (68F) in the germination room. The seed trays may be covered with plastic humidity covers to ensure a high relative humidity which prevents desiccation.

#### Day 1 - Environmental Adjustment

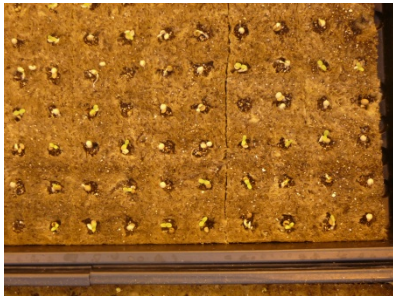




A fertilizer solution is added to the top or sub-irrigation water 24 hours after sowing. The EC of the water is maintained at 1200  $\mu\text{S}/\text{cm}^1$  above source water EC. The pH of the solution is adjusted to 5.8 with possible addition of a base, potassium hydroxide (KOH) and nitric acid when it is too high.

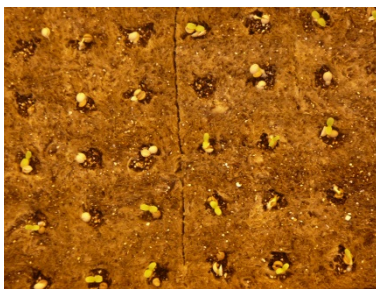
The temperature is raised to 25C and the lights increased to 250  $\mu\text{mol}/\text{m}^2/\text{s}$ . These environmental factors are maintained for the remainder of the crops' time in the germination area. Sub-irrigation continues for 1/4 hour every 12 hours until Day 6. The photoperiod remains at 24 hours. If hand-watering is used the same watering frequency does not need to be used but care must be takes so that the media does not dry out.

### Day 2 - Decreasing Humidity



The humidity covers in place on Days 0 and 1 are removed on Day 2. At this time, the seed has germinated and the radicle has started to penetrate into the soil, as can be seen in the above photo. High humidity levels during the first two days of germination are to ensure the seed does not desiccate. Low lights levels during the first 24 hours work in conjunction with the high humidity to prevent excessive seed drying.

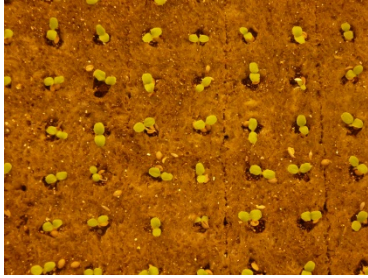
### Day 3 - Removing Double Seedlings



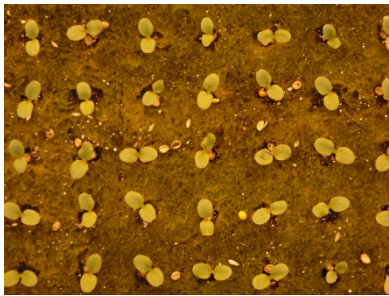
Any double seedlings should be removed from the plugs on Days 3 or 4 to ensure a uniform crop. Any seedlings that are particularly large should be removed so they do not suppress the growth of neighboring plants. Also, germination percentage can be determined to monitor seed

quality and proper growing conditions at this stage. It is critical to have consistent environmental conditions and consistent plant growth during this stage.

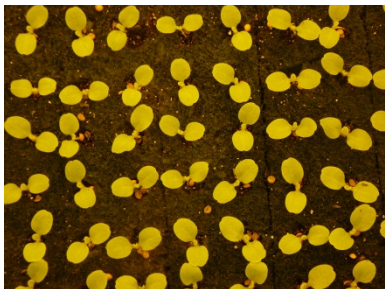
Day 4



Day 5



Day 6 - Increasing Watering Frequency



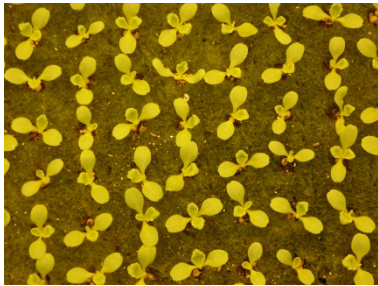
The lettuce seedlings have grown to such a size that they now require watering more frequently. The sub-irrigation system if using an ebb and flood table is scheduled for flooding four times per

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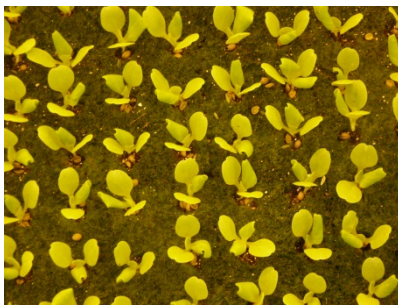
day, or every six hours, for 1/4 hr (15 min). If top watering with a breaker once a day should suffice.

The following is a series of photos showing the growth of an individual lettuce seedling over a 5 day period.

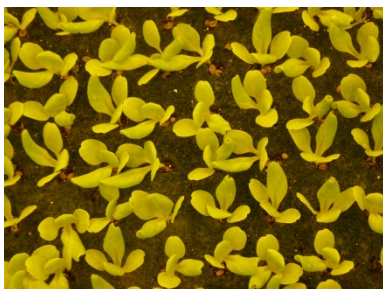
Day 7



Day 8



Day 9



Day 10



Day 11



At this time, the leaves are beginning to overlap. The roots of the seedlings have grown through the bottom of the plug tray. When transporting the plugs to the pond area, avoid damaging these exposed roots.



Day 11

This photo shows the plants just after transplanting into the floats.



## Transplanting

On Day 11, the seedlings are transported to the greenhouse and transplanted into the pond. Prior to transplanting, the seedlings are thoroughly sub-irrigated. Transplanting can be scheduled to follow normal sub-irrigation periods in order to prevent desiccation during transfer.

The seedling plugs float in the pond in Styrofoam floats. Each float is hand-drilled from 1” insulation. A wooden template placed over the Styrofoam board to be drilled hastens the drilling process. A drill press may be used if board geometry allows. Several holes can be drilled simultaneously if a clever drill press apparatus is created. A pneumatic drill may be used and will make a cleaner hole as it operates at a higher speed.

## Styrofoam Floats



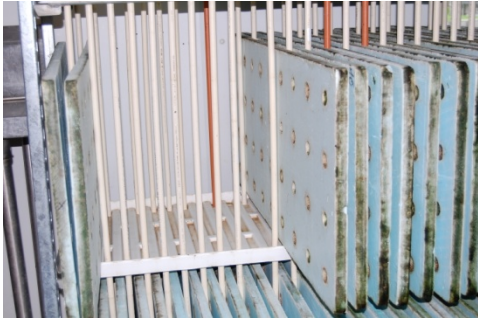
## Day 21 – Transplant



## Day 35 – Harvest



## Post-Harvest



Styrofoam floats are cleaned between each growing cycle with a weak bleach (2%) solution.

## **Chapter 5:** Packaging and Post-Harvest Storage

Packaging can be a significant cost depending on what materials customers demand. Often both a package for the product as well as a box to transport product in must be purchased.

Options:

In clamshell with or without roots

In lettuce bouquet with or without roots – clamshell or bag

Post-Harvest Storage

After being packaged, the lettuce should be stored at 40F.



## Chapter 6: Crop Health

### Disease

Maintaining a healthy crop is vital. Powdery mildew can be a problem during winter production of lettuce. A plan should be in place for the treatment of mildew and appropriate chemical controls should be obtained before the crop is planted.

The following are suggestions for maintaining a healthy greenhouse environment:

Keep the crop rapidly growing by providing adequate light, nutrients, and other environmental conditions at all times.

If root disease does occur, the ponds and solution tanks should be drained and the crop sacrificed. The ponds and tanks should be cleaned with a 2% bleach solution. Other sanitation products exist and are easily available such as Greenshield. It is possible the disease started in the Germination Area, and that area, including the benches and solution tanks, should be cleaned, as well.

Wash the Styrofoam floats, trays, and other equipment with a 2% bleach solution. The equipment should be washed between each use, to prevent the spread of disease.

Do not bring other plant material or soil into the greenhouse. This material may contain pests and pathogens likely to infect your crop. **Keep visitors to the greenhouse to a minimum** or allow them to view the production area from the outside of the greenhouse only.

Keep the solution tanks shaded in some manner. Algae flourish in wet, well-lit locations, and the solution tank is ideal for algal growth. Shading the tanks, input and output pipes, and other "wet" equipment will inhibit algal growth. The algae will not harm the crop directly, but may act to weaken the crop to potential disease.

### Pests

Pests in hydroponic lettuce production can be a problem though they are not generally a major problem. Insect pests that may be found coupled with hydroponic lettuce production include shore flies, fungus gnats, thrips, and aphids. Fast plant growth rates make pest population establishment difficult. With continuous crop production, pest populations may have the opportunity to establish themselves. Precautions can be taken to exclude pests from the facility, such as screening potential entry points (ventilation inlets). Keeping the grass and weeds mowed outside the greenhouse or removing all vegetation entirely can reduce pest pressure inside the greenhouse. Few pesticides have been labeled for use on greenhouse vegetables. Biological insect control is a viable but less used alternative. The CEA group tried nicotine as an aphid deterrent but not only did it not control aphids, but it also left a discernible taste on the lettuce.

## Chapter 7: References

AUTHOR(S): Albright, L.D. 1997.

TITLE: **Ventilation and shading for greenhouse cooling.**

WHERE: Proceedings of the International Seminar on Protected Cultivation in India, December 18-19, Bangalore, India. pp. 17-24.

AUTHOR(S): Albright, L.D. 1997.

TITLE: **Specifications, functioning and maintenance of equipment for forced cooling of greenhouses.**

WHERE: Proceedings of the International Seminar on Protected Cultivation in India, December 18-19, Bangalore, India. pp. 25-32.

AUTHOR(S): Albright, L.D. 1997.

TITLE: **Greenhouse thermal environment and light control.**

WHERE: In Plant Production in Closed Ecosystems, E. Goto et al. (eds.). Kluwer Academic Publishers, the Netherlands. pp. 33-47.

ABSTRACT: Greenhouse thermal environment results from the interactions among numerous factors: solar insolation; structural thermal characteristics; operation of heating, ventilation, and cooling systems; supplemental lighting; and properties of the greenhouse crop are among the most important. As greenhouse technology and sophistication evolve and environmental control becomes more complete, the importance of supplemental lighting increases. Luminaires contribute a sensible cooling load directly, and a latent cooling load indirectly by influencing transpiration. The objectives of this paper are to provide a general overview of greenhouse thermal environment, outline a methodology for greenhouse supplemental lighting control, and explore the interactions of supplemental lighting and the thermal environment. The approach used is based on modeling of greenhouse thermal processes, and simulations of supplemental lighting system control.

AUTHOR(S): Albright, L.D. 1996.

TITLE: **Controlled environment lettuce-production modules.**

WHERE: Proceedings of the 26th National Agricultural Plastics Congress and the American Greenhouse Growers Association Conference, June 14-18, Atlantic City, NJ. pp. 265-270.

AUTHOR(S): Albright, L.D. 1996.

TITLE: **The importance of design and control of light in high-productivity controlled environment agriculture (CEA).**

WHERE: Keynote paper, presented at the International Conference on Agricultural and Biological Environment (ICABE), August 15-19, Beijing, China. China Agricultural University Press, Beijing, China. 6 pp.

ABSTRACT: Of the numerous environmental parameters important for plant growth, light (PAR) is arguably the second most important (with the first being, thereby, temperature). Light is the basis for plant growth, timing and quality. If CEA facilities are to move to a higher level of sophistication and productivity, lighting systems must be designed as carefully as are heating systems and light must be controlled as carefully as is temperature. Commercial computer

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programs exist that can be used to design supplemental lighting systems to achieve uniformity of PPF. New algorithms are being developed that can control supplemental lights and movable shade mechanisms either by PPF level as a function of the stage of growth, or to achieve the same total integrated PPF each day. This presentation describes the importance of light control for consistent plant growth and recent work that shows the benefits of controlling light to a consistent daily integral. The report also describes computer programs that can be used for design and then control to achieve that goal. The technical details form the basis for a wider vision of the potential for Controlled Environment Agriculture.

AUTHOR(S): Albright, L.D., and H.I. Henderson, Jr. 1996.

**TITLE: Air conditioning greenhouses to increase effectiveness of carbon dioxide enrichment.**

WHERE: ASAE paper 964007. ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659. 15 pp.

ABSTRACT: Greenhouse lettuce, and other crops, can benefit from supplemental lighting to enhance growth on dark days. When carbon dioxide is added during lighted hours, growth may be enhanced further. Unfortunately, heat added by lights may initiate venting and waste carbon dioxide. This paper presents a simulation model that suggests a modest degree of air conditioning may be economically beneficial in permitting carbon dioxide enrichment without venting to substitute for supplemental lighting to enhance growth. The simulations suggest the savings of lighting costs may compensate for operating a simple air conditioning system during days of moderate cooling load and limited solar input.

AUTHOR(S): Albright, L.D. 1995.

**TITLE: Controlling greenhouse ventilation inlets by pressure difference.**

WHERE: HortTechnology 5(3):260-264.

ABSTRACT: Computerized control of the greenhouse climate has increased the importance of air distribution and mixing. This report reviews the fluid mechanics of air flow through ventilation inlets and external pressures imposed by winds and applies the analyses to suggest methods of inlet control that improve traditional greenhouse ventilation. The suggested improved control has been implemented in a five-section research greenhouse on the Cornell University campus and has improved climate control significantly during ventilation. Potential pitfalls in implementing the improved control methods are discussed.

AUTHOR(S): Albright, L.D. 1995.

**TITLE: Greenhouse lighting control to a daily PPF integral, with energy and cost consequences.**

WHERE: ASAE paper 954487. ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659. 22 pp.

ABSTRACT: A methodology is described and, from it, an accompanying computer model has been developed to calculate the yearly operating cost of a supplemental lighting system for commercial greenhouses based on reaching a prescribed daily integral of PPF. The model is sensitive to time-of-day rates (including application of those rates to weekends and holidays), weather, greenhouse characteristics, luminaire characteristics, and greenhouse location.

AUTHOR(S): Albright, L.D. 1994.

**TITLE: Predicting greenhouse ventilating fan duty factors and operating costs.**

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WHERE: ASAE paper 944576. ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659. 20 pp.  
ABSTRACT: A methodology is described and, from it, an accompanying computer model has been developed to calculate the yearly operating cost of a mechanical ventilation system for commercial greenhouses having no installed evaporative (or other) cooling system. The model is sensitive to time-of-day rates (including application of those rates to weekends and holidays), thermal parameters, fan characteristics, environmental control set points, and weather.

AUTHOR(S): Albright, L.D. 1994.

**TITLE: Fan operating costs for controlled environment agriculture.**

WHERE: Proceedings of the 5th annual CAEP Agricultural Demand-Side Management Conference. Albany, NY. May 3-5, 1994. A Northeast Regional Agricultural Engineering Service Publication. Riley-Robb Hall, Cornell University, Ithaca, NY 14853. pp. 51-60.

AUTHOR(S): Albright, L.D., and A.J. Both 1994.

**TITLE: Comparison of luminaires: efficacies and system design.**

WHERE: Proceedings of the International Lighting for Plants in Controlled Environments Workshop. University of Wisconsin, WI. March 27-30, 1994. NASA Conference Publication CP-3309. pp.281-297.

ABSTRACT: The trust of this report suggests supplemental lighting design processes that might be used to achieve desired PAR levels and adequate uniformity over a lighted space. Measured PAR distribution patterns from eight commercially available 400 W HPS luminaires are used in three design examples, implemented through a commercially-available lighting design computer program. Results suggest that PAR uniformity within  $\pm 10\%$  is achievable at intensities of 200 and 300 micromol/sq. m/s in greenhouses and plant growth chambers. When PAR intensity is significantly lower (e.g., 50 micromol/sq. m/s), uniformity is more difficult to achieve. This study suggests the desirability of developing computer data file standards for PAR, rather than vision lighting, for commercial luminaires, and obtaining a consensus data base of surface reflectance values for materials used in plant growth chambers and greenhouses. Results also suggest that luminaire selection can have a significant effect on lighting energy use and operating cost because of different numbers of various models of luminaires required to meet a design goal, not just luminaire-to-luminaire efficacy differences.

AUTHOR(S): Both, A.J., S.S. Scholl, L.D. Albright, and R.W. Langhans. 1998.

**TITLE: Comparing continuous lettuce production in nutrient film technique and floating hydroponics.**

WHERE: Proceedings of the 15th International Lettuce Conference and Leafy Vegetable Crops Workshop. September 23-26, 1998. Atlantic City, NJ. pp. 16-17.

AUTHOR(S): Both, A.J., L.D. Albright, and R.W. Langhans. 1998.

**TITLE: Coordinated management of daily PAR integral and carbon dioxide for hydroponic lettuce production.**

WHERE: Acta Horticulturae 456:45-51.

ABSTRACT: The interaction between daily integrated photosynthetically active radiation (PAR) and elevated aerial CO<sub>2</sub> concentration was studied during plant growth experiments with leaf lettuce (*Lactuca sativa* L., cv. Vivaldi) in a controlled environment agriculture facility

(greenhouse) using the nutrient film technique. Accurate control of all environment parameters (except relative humidity) and four identical greenhouse sections constituted the experimental setup. Supplemental lighting (high pressure sodium lamps) was used to provide additional PAR to the lettuce on days when too little sunlight was available to reach the required daily light integral. Two experiments with four treatments each were performed to investigate six integrated PAR/CO<sub>2</sub> concentration combinations:-- 11/1500; 12/1250; 13/1000; 14/750, 15/530, and 16/400 (mol per sq. m per d/ppm). Lettuce plants were grown for 24 days under these conditions after being grown in a growth room under optimum conditions for 11 days. Periodic harvests during the greenhouse growing phase provided shoot dry mass data. Shoot fresh mass and number of leaves per plant were determined at the final harvest: 35 days after seeding. Plant growth under the six different treatments was virtually identical and resulted in an average shoot fresh mass of 190 g with a dry matter percent-age of 3.7%. The results of the described experiments show a flexible management strategy regarding daily integrated PAR level and aerial CO<sub>2</sub> concentration can be employed for the most economical lettuce production.

AUTHOR(S): Both, A.J., C.A. Chou, L.D. Albright, and R.W. Langhans. 1997.

TITLE: **A microwave powered light source for plant irradiation.**

WHERE: Acta Horticulturae 418:189-194.

ABSTRACT: A new high intensity electrodeless light source, powered by two microwave generating units, was evaluated and compared with fluorescent and air- and water- cooled high pressure sodium (HPS) lamps. Radiation measurements were taken in the following wavebands: 400-700 nm (photosynthetically active radiation or PAR), 700-800 nm (far red), 800-2,800 nm (near infrared) and 2,800-50,000 nm (far infrared), for all four light sources. The distribution of the radiation output of the microwave lamp over the various wavebands closely resembled the output of a water-cooled HPS lamp, although the microwave lamp was capable of delivering much higher light intensities. The relatively small amount of radiation emitted in the infrared waveband makes the microwave lamp a promising light source for plant irradiation in growth rooms (phytotrons).

AUTHOR(S): Both, A.J., L.D. Albright, R.W. Langhans, B.G. Vinzant, and P.N. Walker. 1997.

TITLE: Electric energy consumption and PPFi output of nine 400 watt high pressure sodium luminaires and a greenhouse application of the results.

WHERE: Acta Horticulturae 418:195-202.

ABSTRACT: The PPFi (instantaneous photosynthetic photon flux, in micromol/sq. m/s) output and electric energy consumption of nine different 400 watt high pressure sodium (HPS) luminaires were measured at six mounting heights from 0.5 to 3.0 m in 0.5 m increments. Differences in luminaire efficacy and PPFi distribution patterns were found, but too few luminaires were tested to reach statistically valid conclusions. The most efficient luminaire proved 25% more energy efficient than the least efficient luminaire. PPFi data from one of the luminaires tested was used to design a research greenhouse which required uniform PPFi distribution patterns at various PPFi levels.

AUTHOR(S): Both, A.J., L.D. Albright, R.W. Langhans, R.A. Reiser, and B.G. Vinzant. 1997.

TITLE: Hydroponic lettuce production influenced by integrated supplemental light levels in a controlled environment agriculture facility: Experimental results.

WHERE: Acta Horticulturae 418:45-51.

ABSTRACT: Bibb lettuce (*Lactuca sativa* L., cv. *Ostinata*) was grown in peat-vermiculite plugs placed in a recirculating hydroponic (NFT) system. Supplemental lighting was used to reach different PPFTarget levels in each of 35 treatments. A second order exponential polynomial was developed to predict DW accumulation for PPFTarget levels between 8 and 22 mol m<sup>-2</sup> d<sup>-1</sup>. Little difference in DW production was noted between lettuce grown under daytime and nighttime lighting. Tipburn was prevented using a fan blowing greenhouse air vertically down onto the lettuce plants. Marketable (150 g FW) lettuce heads were produced in 24 days after transplant while receiving an average PPFTintegral of 17 mol/sq. m/d.

AUTHOR(S): Both, A.J., A.R. Leed, E. Goto, L.D. Albright, and R.W. Langhans. 1996.

TITLE: **Greenhouse spinach production in a NFT system.**

WHERE: Acta Horticulturae 440:187-192

ABSTRACT: Primed spinach (*Spinacia oleracea* L., cv. *Nordic*) seed was started in rockwool slabs in a growth room for eight days before the seedlings were transplanted into a controlled environment greenhouse equipped with five identical, but separate, NFT systems. The day and night temperatures in the greenhouse were maintained at 24 and 18°C, respectively, with the daytime starting at 06:00 and ending at 22:00 hr. A photoperiod of 16 hrs was maintained, to prevent early bolting, and different target daily integrated light levels (PPF, in mol/sq. m/d) were studied to observe dry weight production. HPS lamps were used as the supplemental light source. Thirty-three days after seeding a final harvest was performed. Using the expolinear growth equation, dry weight production can be predicted based solely on target daily integrated light levels. Total chlorine residuals in the nutrient solution higher than 1 ppm were observed to be toxic. Root disease (rot) in the plant crown was found to be caused by *Fusarium*. Several remedies, including three biofungicides and potassium silicate, were tried but none proved to be consistently successful.

AUTHOR(S): Both, A.J.; 1995.

TITLE: **Dynamic simulation of supplemental lighting for greenhouse hydroponic lettuce production.**

WHERE: PHD Dissertation, Cornell University Libraries, Ithaca, NY 14853. 172 pp.

ABSTRACT: 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/sq. m/d. 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 deg 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/sq. m/d 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.

AUTHOR(S): Both, A.J. 1994.

TITLE: **HID Lighting in Horticulture: a short review.**

WHERE: Greenhouse Systems, Automation, Culture and Environment. International Conference. Hyatt Regency Hotel, New Brunswick, NJ. July 20-22, 1994. Northeast Regional Agricultural Engineering Service, Publication 72. Riley-Robb Hall, Cornell University, Ithaca, NY 14853. pp. 208-222.

AUTHOR(S): Both, A.J., L.D. Albright, R.W. Langhans, B.G. Vinzant, and P.N. Walker. 1992.

TITLE: **Research on energy consumption of HID Lighting.**

WHERE: Proceedings of the 4th National CAEP Agricultural Demand-Side Management Conference. Syracuse, NY. October 20-22, 1992. Northeast Regional Agricultural Engineering Service, Publication 65. Riley-Robb Hall, Cornell University, Ithaca, NY 14853. pp. 125-134.

AUTHOR(S): Chiu, A.J. 1996.

TITLE: **Computer control of shade and supplemental lights for greenhouse hydroponic lettuce production.**

WHERE: MEng Report. Department of Agricultural and Biological Engineering, Cornell University, Ithaca, NY 14853. 44 pp.

ABSTRACT: The purpose of this project was to design and test a computer-controlled shade and supplemental lighting system for hydroponic lettuce production. The code was based on a Pascal algorithm, written by Dr. Louis D. Albright, whose work was a computer simulation study of this study. The goal was to determine how well theoretical and actual computations agree, and to control a physical system to achieve prescribed daily light integrals. The system consisted of a PS/2 computer, interfaced to high pressure sodium lamps, a horizontal shade curtain, and a Li-Cor quantum light sensor. A limited number of experiments were completed to test the algorithm's performance. The first set of experiments involved the use of an event recorder and theoretical events. The second set of experiments, however, tested the actual operation of the luminaires and the shade cloth. Difficulties were encountered in tuning the system for accurate light control, because some code parameters and constants needed to be altered by empirical means. The daily integrated photosynthetically active radiation (PAR) was achieved by supplementing the solar PAR with that from 400 Watt high pressure sodium (HPS) lamps, and by deploying the shade cloth to limit solar PAR on bright days. Both the operation of the lights and shade were used to try to achieve the target PAR goal of 17 mols per square meter per day.



Lettuce crops were not grown in the greenhouse area, since extensive studies have shown that an accumulation goal of 17 mols per square meter per day is the optimum light level for quality Ostinata lettuce production. Therefore, it was assumed that if the system was able to maintain this desired daily PAR, then lettuce crops can be grown with this shade and lighting system. The control system was reliable for short-term experimentation, but long-term reliability has yet to be tested. Testing occurred during several days in the month of April. However, testing during the summer months, the period of greatest light insolation, still needs to be performed.

AUTHOR(S): Ciolkosz, D.E., L.D. Albright, and J.C. Sager. 1998.

TITLE: **Microwave lamp characterization.**

WHERE: Journal of Life Support and Biosphere Science Vol. 5:00-00. 18 pp. In Press.

ABSTRACT: The operating properties of the SAA microwave lamp, developed by Fusion Lighting Inc., were determined with reference to its usefulness in Bioregenerative Life Support Systems (BLSS). Lamp flux density in several wavelength ranges, spectral output, and temperature response (-10 to +40 deg C) were determined by mounting the lamp and sensors in a controlled environment chamber. Lamp intensity distribution was also measured using a swing arm apparatus with a 1m radius. A model was developed to characterize the intensity distribution of the lamp as a function of lamp geometry and output properties. The lamp was found to produce a spectral output similar to that of earlier models, but with a higher photosynthetic output per lumen and per input watt. Radiant energy output was measured to be 0.399 radiant watts per micromol/s PAR compared with 0.56 radiant watts per micromol/s PAR for high pressure sodium lamps. Total lamp output dropped approximately 0.4% for every degree C rise in ambient temperature, with little change in light quality. The intensity distribution of the lamp was found to produce a fairly uniform flux density (+/- 22%) in a 40 degree cone from lamp nadir. the advantages and drawbacks of this light source for use in BLSS are discussed.

AUTHOR(S): Ciolkosz, D.E. and J.C. Sager. 1998.

TITLE: **Imaging of LED array flux densities.**

WHERE: Journal of Life Support and Biosphere Science Vol. 5:00-00. 15 pp. In Press.

ABSTRACT: Arrays of light emitting diodes (LEDs) are being used in life science plant flight experiments and show promise for use in Bioregenerative Life Support Systems (BLSS). However, the small volume and short distances from the LED array necessary in these applications create several unique problems. The discrete LEDs are small and the spatial non-uniformity of the lamps near the array results in significant irradiance variation on surfaces near the array. These irradiance variations make it difficult to use traditional hand held sensors to measure the light levels under the array accurately. The usefulness of rear projection video camera imaging is investigated for the analysis of uniformity of irradiance from an LED array. Irradiance measurements were taken at a high mounting height from the array using both a 400-700 nm quantum sensor and a video camera. Additionally, video images were recorded at different mounting heights from the array. The rear projection imaging technique was suitable for analyzing the irradiance from LED arrays. Comparison of the readings from the video image and the sensor suggests that there is a non linear relationship between video image reading and sensor value ( $R^2 = 0.884$ ). These data also show that the average photosynthetically active radiation level (PAR) does not change as mounting height varies, but that the spatial uniformity

of the PAR does increase as mounting height increases. These results are consistent with geometrical analyses of the system.

AUTHOR(S): Ciolkosz, D.E., and L.D. Albright. 1997.

TITLE: **Evaluation of whole plant transpiration as affected by greenhouse air movement.**

WHERE: ASAE paper No. 974029. ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659, USA. 18 pp.

ABSTRACT: Investigations were conducted to determine the degree to which evaporation of reverse osmosis treated water from petri dishes can be used to predict evapotranspiration in hydroponic greenhouses and, in turn, to evaluate airflow systems for their ability to induce evapotranspiration. The relationship between crop evapotranspiration and dish evaporation was found to be linear, with an R sq. (adj) of 0.592. Adding CO<sub>2</sub> concentration to the relationship improved the R sq. (adj) to 0.895. Severity of tipburn also evinced a relationship with dish evaporation rate, but as a step function. Dish evaporation rates greater than 2 cm per day resulted in the least tipburn on the crops. The crop coefficient, K<sub>c</sub>, varied in a manner consistent to that of field crops, except for a sharp drop at the time of plant respacing. The pan coefficient, K<sub>c</sub>, showed no noticeable trends with respect to time, and had an average of 0.215. Side by side comparisons of different air distribution systems suggested that air distribution has a large effect on dish evaporation (and, hence, plant evapotranspiration) and that unit heaters placed in a collision flow or shear flow configuration can achieve a greater level of uniformity of evaporation than use of overhead turbulator fans. The application of this information to the design of air distribution systems for greenhouses is discussed.

AUTHOR(S): Ciolkosz, D.E., L.D. Albright, and A.J. Both. 1998.

TITLE: **Characterizing evapotranspiration in a greenhouse lettuce crop.**

WHERE: Acta Horticulturae 456:255-261.

ABSTRACT: Tipburn, a physiological disorder of lettuce, has been linked to insufficient evapotranspiration (ET). Better understanding of ET in greenhouse lettuce crops may be useful as a management tool to control tipburn. A regression model is presented to characterize ET from greenhouse lettuce (*Lactuca sativa* L., cv. "Vivaldi") based on data from twelve crops grown in a nutrient film technique (NFT) system. Several CO<sub>2</sub> concentrations and daily light integrals were applied to the lettuce crops and the resulting daily ET integrals were measured. A regression model was derived for daily ET as a function of growth rate and the resulting daily and cumulative ET values were calculated and compared to measured values. ET rate was found to vary linearly with growth rate (R sq. (adj) = 0.63) but higher CO<sub>2</sub> levels were associated with lesser values of the slope of the relationship. Modeled and measured data were in good agreement even though relative humidity was not included in the model. An equation is presented that may be useful to calculate daily ET targets that must be achieved to prevent tipburn in hydroponic lettuce.

AUTHOR(S): Controlled Environment Agriculture Program. 1996.

TITLE: **Controlled environment agriculture scoping study.**

WHERE: Electric Power Research Institute Publication CR-107152. EPRI, 3412 Hillview Avenue, Palo Alto, CA 94304. 70 pp.

AUTHOR(S): Dalrymple, K. D. 1998.

TITLE: Study of the water-jacketed high pressure sodium lamp: bare lamp flux density experiments, reflector design, and placement within a growth chamber.

WHERE: MEng Report. Department of Agricultural and Biological Engineering, Cornell University, Ithaca, NY 14853. 120 pp.

ABSTRACT: Horticultural lighting systems are used in growth chambers to produce high flux density, uniform lighting conditions for plant growth. However, infrared radiation (heat) generated by these lighting systems must be removed from the growth chamber for temperature control. Heat rejection via mechanically cooling growth chamber air can be costly. In water-jacketed lamps, water is circulated around the lamp as a mechanism for heat removal from the lamps. A water-jacketed high-pressure sodium (HPS) lamp made by Bhalla Lighting, Inc. was tested for light output. A photosynthetically active radiation (PAR) sensor was used to record flux density readings at varying angles from 0 to 90 degrees along a path 1.0 m from the lamp. Readings were taken along the front, sides, and back of the lamp. The inverse square law was used to convert the flux density data into lamp PAR intensity distributions. The light intensity distribution of the water-jacketed HPS lamp was compared to light intensity distributions of two non-water-jacketed HPS lamps. Tests were also conducted to determine if lamp efficiency was temperature dependent. Wattage through the ballast was measured for non-water-jacketed and water-jacketed lamp situations. Light output and wattage of the water-jacketed lamp were less than those of the non-water-jacketed lamps. Lamp intensity distributions were used to create a luminaire data file for use in Photopia, a reflector design software package created by Lighting Technologies, Inc. Water-jacketed HPS lamp and reflector designs were created using AutoCAD R13 and then tested in Photopia. The most suitable luminaire (lamp and reflector combination) was then used in Lumen Micro, another lighting program developed by Lighting Technologies, Inc., to generate a lighting plan for a plant growth room at the Cornell University CEA Demonstration Greenhouse Facility. The lighting grid was designed to deliver maximum light uniformity at the plant growth surface. The advantages and disadvantages of water-jacketed HPS lamps are discussed. Recommendations for further development of water-jacketed HPS lamps are made. Useful practical advice is given on the use of the water-jacketed lamp in the Cornell University CEA Demonstration Greenhouse Facility.

AUTHOR(S): Danish, W.E. 1994.

TITLE: **A growers' guide to lettuce crop production using nutrient film technique in controlled environment agriculture facilities.**

WHERE: MPS Project Report. Cornell University Libraries, Ithaca, NY 14853. 68 pp.

ABSTRACT: The purpose of this project is to provide a summary of the present level of technology in the production of lettuce in Controlled Environment Agriculture (CEA) and a step-by-step practical growers' guide to greenhouse lettuce crop production using nutrient film technique. The CEA research program began several years ago at Cornell to develop and demonstrate new technologies and cultural methods aimed at improving the profitability of horticultural crop production in controlled environments. CEA is not a completely new idea, but an optimization of all know elements affecting plant growth. When the usual environmental factors for crop production are optimized, temperature, water, and nutrients, the limiting factor to plant growth is light. Plants need light to grow, and in the North East growers must rely on supplemental lighting during the winter months to produce a finished crop in a reasonable time.

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Now, the cost of electricity is the largest component of variable costs. This guide leads growers through lettuce crop production using nutrient film technique. In order for CEA to be successful, the grower must be vigilant in adherence to the recommended principles shown here. Without the buffering advantage of a crop grown in soil, any mistake, however small, can be fatal to the lettuce crop. For all this trouble, the rewards can be great. The lettuce can grow from seed to a marketable 5 ounce head in just 35 days by following directions.

AUTHOR(S): de Villiers, D.S. 1997.

**TITLE: Vegetable cultivar evaluation and crop selection for controlled environment agriculture and advanced life support systems.**

WHERE: MSc Thesis. Cornell University Libraries, Ithaca, NY 14853. 176 pp.

**ABSTRACT:** Cultivar evaluation for controlled environments is a lengthy and multifaceted activity. The chapters of this thesis cover eight steps preparatory to yield trials, and the final step of cultivar selection after data are collected. The steps are as follows: (1) Examination of the literature on the crop cultivars to assess the state of knowledge. (2) Selection of standard cultivars with which to explore crop response to major growth factors and determine set points for screening and, later, production. (3) Determination of practical growing techniques for the crop in controlled environments. (4) Design of experiments for determination of crop responses to the major growth factors, with particular emphasis on photoperiod, daily light integral and air temperature. (5) Developing a way of measuring yield appropriate to the crop type by sampling through the harvest period and calculating a productivity function. (6) Narrowing down the pool of cultivars and breeding lines according to a set of criteria and breeding history. (7) Determination of environmental set points for cultivar evaluation through calculating production cost as a function of set points and size of target facility. (8) Design of screening and yield trial experiments emphasizing efficient use of space. (9) Final evaluation of cultivars after data collection, in terms of production cost and value to the consumer. For each of the steps, relevant issues are addressed. In selecting standards to determine set points for screening, set points that optimize cost of production for the standards may not be applicable to all cultivars. Production of uniform and equivalent-sized seedlings is considered as a means of countering possible differences in seed vigor. Issues of spacing and re-spacing are also discussed. In mapping crop response to growth factors, it is proposed that a first set of experiments examine daylength sensitivity and light intensity effects by holding daily light integral constant while varying photoperiod and light intensity. A second set of experiments would vary daily light integral at a fixed photoperiod appropriate to the crop to explore limits on productivity. Temperature would be varied in both sets of experiments. For most vegetable crops, comparison of cultivars of different maturity date requires discovery of the yield function over the harvest period, from which can be ascertained when productivity is maximum. At least three harvests timed to bracket the peak in productivity are advised. Arguments are presented that the most likely and feasible source of superior materials for controlled environments will be from breeding lines currently under evaluation. Fast screening procedures are proposed to ascertain plant characteristics other than yield performance when information is lacking. Set points for yield trials need to be those for production; appropriate set points cannot be determined without economic analysis of facility cost, labor cost, and cost of supplying inputs. To economize on space needed for yield trials, I have proposed use of opaque, reflective side walls between cultivars and sample harvest units to replace guard rows and accommodate staggered harvests. The cost of production index (COPI) is

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the single most important criterion for cultivar evaluation. For commercial CEA, final selection of cultivars requires market analysis additionally because the cheapest cultivar to produce may not be the best seller. For space life support, post-harvest processing costs need to be included with production costs. The value of superior quality and palatability in fostering well-being of colonists needs to be weighed against additional cost in providing it. Crop selection for space colonies is addressed in the introductory and penultimate chapters. It is argued that crop selection should be guided from menu in addition to nutritional goals and minimization of cost.

AUTHOR(S): Goto, E., A.J. Both, L.D. Albright, R.W. Langhans, and A.R. Leed. 1996.

TITLE: **Effect of dissolved oxygen concentration on lettuce growth in floating hydroponics.**

WHERE: Acta Horticulturae 440:205-210.

ABSTRACT: Lettuce (*Lactuca sativa* L., cv. *Ostinata*) growth experiments were carried out to study the effect of dissolved oxygen (DO) concentration on plant growth in a floating hydroponic system. Pure O<sub>2</sub> and N<sub>2</sub> gas were supplied to the hydroponic system for precise DO control. The system allowed for DO concentrations above the maximum possible saturation concentration attainable when using compressed air. Eleven day old lettuce seedlings were grown for 24 days under various DO concentrations: sub-saturated, saturated, and super-saturated. There was no significant difference in fresh weight, shoot and root dry weight among the following DO concentrations: 2.1 (25% of saturated at 24°C), 4.2 (50%), 8.4 (saturated), and 16.8 (200%) mg/L. The critical DO concentration for vigorous lettuce growth was considered to be lower than 2.1 mg/L. Neither root damage nor delay of shoot growth was observed at any of the studied DO concentrations.

AUTHOR(S): Goto, E.; Albright, L.D.; Langhans, R.W.; Leed, A.R. 1994.

TITLE: **Plant spacing management in hydroponic lettuce production.**

WHERE: ASAE paper 944574. ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659. 13 pp.

ABSTRACT: Three different spacing options were tested in a hydroponic lettuce production system. Two kinds of productivity and a growing area utilization efficiency factor were introduced to compare practical spacing management with idealized spacing management for individual days during a production period, and over the entire production.

AUTHOR(S): Langhans, R.W. 1994.

TITLE: **Fluorescent and high intensity discharge lamp use in chambers and greenhouses.**

WHERE: Proceedings of the International Lighting for Plants in Controlled Environments Workshop. University of Wisconsin, Madison, WI. March 27 - 30, 1994. NASA Conference Publication CP-3309. pp. 211-215.

AUTHOR(S): Lin, S.Y. 1995.

TITLE: **Effects of seed hydration treatments, media moisture content, and inhibitors on spinach (*Spinacia oleracea* L.) seed germination.**

WHERE: MSc Thesis. Cornell University Libraries, Ithaca, NY 14853. 66 pp.

ABSTRACT: The pericarp of spinach (*Spinacia oleracea* L.) seed plays a major role in germination. Excess water and inhibitors in the pericarp both may cause poor germination of seeds. This research focused on optimal seed hydration treatments, the optimum range of media moisture content, and temperatures on germination of spinach (cv. 'Nordic') seeds. The bio-

effects of inhibitors leached from the seeds were also investigated. Data were logarithmically transformed and analyzed by analysis of variance and trend analysis. The spinach seeds were primed under dark conditions in 30% polyethylene glycol (PEG) solutions at 15 deg C for 1 to 4 days, and germinated again under dark conditions at 15, 20, and 25 deg C for 7 days. Germination performance was evaluated by final germination percentages, rate (T50), and uniformity (T[90-10]). Interactions between PEG soak duration and germination temperature did not reveal consistent trends. One day priming, which resulted in rapid germination and high germination percentage, is recommended because less PEG is used and less time is consumed in priming. In an alternative approach, spinach seeds were hydrated in reverse osmosis (RO) water at 10 or 15 deg C for 24, 36, and 48 hours. The shortest hydration time of 24 hours was recommended based on the improvement in uniformity of germination. Hydration treatments in water were superior or equal to priming with respect to rate of germination. Spinach seeds were sensitive to moisture during the germination stage, more seriously in wet conditions than dry conditions. The range of blotter moisture was adjusted between 11 ml and 21 ml RO water per container in the first study, but results indicated that amounts over 15 ml were too great for the spinach seeds to germinate well. Therefore, the range of blotter moisture was between 6 ml and 15 ml in the second study, and the results demonstrated 6 ml was still enough for good germination even though the blotters appeared dry. Seed germination performance indicated that the addition of 9 to 12 ml RO water was the most effective for good germination. Seven bioassay experiments were designed to investigate the effects of inhibitors in the spinach seeds. The seeds were soaked in RO water at 5 to 25 deg C for varied times--6 hours, one, and two days. After the seeds were soaked a certain time, the solutions were used to moisten broccoli ('Pirate'), and lettuce ('Ostinata', 'Summertime', and 'Empire') seeds. The effects of the leachate were evaluated by the final germination percentage and radicle growth of the broccoli or lettuce seeds. The results of these experiments do not show a clear relationship between soaking temperature and inhibitor removal. Overall, inhibitors leached from spinach seeds have a negligible or inconsistent effect on germination or root growth of lettuce or broccoli.

AUTHOR(S): Mathieu, J.J., L.D. Albright, K. Kurata, and E. Goto. 1998.

TITLE: Whole crop simulation model of water and nutrient uptake within a recirculating hydroponic system: a literature review. 2 pp.

AUTHOR(S): Reinhardt, W.W. 1994.

TITLE: **Net energy analysis of vegetable crops.**

WHERE: Presented at the 5th Annual CAEP Conference, May 3-5, Albany, NY. A Northeast Regional Agricultural Engineering Service Publication. Riley-Robb Hall, Cornell University, Ithaca, NY 14853. pp. 61-68.

ABSTRACT: This paper will define controlled environment agriculture (CEA) for the year-round production of fresh vegetables in New York State. The New York State Energy Research and Development Authority (Energy Authority) is supporting CEA development because it is a growing industry that will cause significant impacts on energy use and agricultural employment, while avoiding the environmental emissions associated with conventional vegetable production. CEA research at Cornell University (Ithaca, NY) is supported by the Energy Authority and the State's electric utilities. Researchers are investigating energy management opportunities in the operation of CEA facilities to minimize operating energy costs for growers and peak load growth

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for electric utility systems. Finally, this paper will evaluate and compare energy requirements to grow fresh vegetables in New York, using CEA techniques like those being developed at Cornell, with existing alternatives of field crops and greenhouse production grown off-season in the South and West, or greenhouse production grown in Europe.

AUTHOR(S): Rerras, N. 1996.

TITLE: **Neural network modeling of the greenhouse aerial environment.**

WHERE: MSc Thesis. Cornell University Libraries, Ithaca, NY 14853. 89 pp.

ABSTRACT: Use of neural networks to model multi-input multi-output processes is becoming a popular technique in modern control applications. In this thesis neural networks are considered for modeling the short term response of the greenhouse aerial environment. Different neural network architectures are considered such as multilayer feedforward networks and Elman recurrent networks. Their performance is compared using data from a greenhouse simulation model as well as actual greenhouse operational data. The methods are also compared to more conventional modeling methods such as autoregressive moving average exogenous (ARMAX) models. Suitable methods for implementation, training and testing are considered. Feedforward neural networks proved more suitable for greenhouse environment modeling than Elman networks. Feedforward networks also achieved better predictions than ARMAX models at the expense of longer training. Elman networks provided fairly good predictions but needed significantly longer training than feedforward networks. Neural network application in a commercial greenhouse environment is hindered by their need for computing resources. ARMAX models still present the most cost-effective alternative for modeling the greenhouse environment, due to their modest demands in computing resources. Neural networks are feasible, perform better, and will eventually become more attractive as advanced computing platforms become more affordable.

AUTHOR(S): Setiawan, A. 1998.

TITLE: **Applying pseudo-derivative-feedback algorithm to greenhouse temperature control.**

WHERE: MSc Thesis. Cornell University Libraries, Ithaca, NY 14853. 169 pp.

ABSTRACT: The Pseudo-Derivative-Feedback (PDF) control algorithm is applied to control greenhouse air temperature. A forced-air hot water heating system and a pad and fan cooling system are controlled by the PDF algorithm. Performance of the PDF control is compared to Proportional-Integral (PI) control through simulation with an approximated dynamic system model of the greenhouse air. The difficulties of time delays in a control system are discussed. The importance of recognizing the effects of time delays on control system performance for both PDF and PI control is demonstrated with a comparison between control systems with and without the time delay. Additional experiments with PDF, PDF cascade, and PI control are performed to compare the performance of each control scheme. The PDF cascade system controls both heating-system water temperature and greenhouse air temperature. Results of simulation and real-world experimentation show that PDF control has a better load handling capability than PI control. Changes in a final-control-element, FCE (e.g., variation in the temperature of the hot-water supply, or nonlinearity in the heating system valve), were best handled by the PDF cascade control system.

AUTHOR(S): Setiawan, A., L.D. Albright, and R.M. Phelan. 1998.

TITLE: **Simulation of greenhouse air temperature control using PI and PDF algorithms.**

WHERE: Proceedings of the first IFAC Workshop on Control Applications and Ergonomics in Agriculture, Athens, Greece. June 15-17, 1998. pp. 111-116.

ABSTRACT: Pseudo-Derivative-Feedback (PDF) control is compared to PI control through simulation using an approximated dynamic system thermal model of the greenhouse and through experiment results. The effects of time delays on control system performance for both PDF and PI control are demonstrated. Results showed PDF control to have a better load handling capability than PI control. PDF control was exceptionally better than PI for systems without time delay and significantly better for systems with time delay.

AUTHOR(S): Spinu, V.C., L.D. Albright, and R.W. Langhans. 1998.

TITLE: **Electrochemical pH control in hydroponic systems.**

WHERE: Acta Horticulturae 456:275-282.

ABSTRACT: This paper reports an innovative method based on electrochemistry to adjust the pH in nutrient solutions used in hydroponics. The required quantity of H<sup>+</sup> or OH<sup>-</sup> ions is produced in-situ through electrolytic water decomposition. Because the direction and rate of electrochemical reactions can be easily manipulated by controlling the polarity and voltage applied between electrodes, the most important advantage of this method in comparison to traditional pH control using chemicals is the possibility to accomplish accurate and reliable pH control to within a narrow, preset pH range. Moreover, additional positive effects of improving the quality of added raw water such as alkalinity control, reducing the concentration of sodium, and water disinfection can be accomplished in the same electrolytic unit. Electrochemical technology offers possibilities to eliminate the risk of pH control failures due to overdoses and excludes the necessity of having reagent (acid and base) storage tanks and of handling these hazardous materials. Important savings of reagents, dosage and mixing equipment, storage tanks and improved environment and safety objectives can be realized. Available greenhouse space can be used more efficiently.

AUTHOR(S): Spinu, V.C., and L.D. Albright. 1998.

TITLE: **Electrotechnology for water conditioning: A simulation model.**

WHERE: Acta Horticulturae 456:283-290.

ABSTRACT: This paper relates some aspects of an innovative electrotechnological approach focused on improving water quality for horticultural use. Principal processes to condition water for plant growth (related to alkalinity; mineralization; sodium; pH and disinfection) are accomplished in a simple, low-cost, electrolytic unit, which can be affordable for individual growers. Installing such a water conditioning unit directly in a greenhouse achieves additional positive effects. One which makes this technology particularly useful in a greenhouse is the evolution of pure CO<sub>2</sub> as a result of bicarbonate ion decomposition. A simulation model has been developed using MS EXCEL worksheets to predict the dynamics of all important processes related to water treatment in the electrotechnological unit. This computer model establishes the relationships among (1) design parameters such as the type, number and geometry of electrodes, type of membrane, voltage level applied between electrodes, water flow rate through the treatment chamber; (2) raw water quality parameters such as: total dissolved solids (TDS), concentrations of principal ionic species (Na<sup>+</sup>, Ca<sup>2+</sup>, Mg<sup>2+</sup>, HCO<sub>3</sub><sup>-</sup>, SO<sub>4</sub><sup>2-</sup>, Cl<sup>-</sup>), alkalinity,

hardness, pH, EC, temperature; (3) the same parameters for water after treatment; (4) regime and efficiency parameters (electrical current applied, electricity and energy consumed per cubic meter of treated water, current efficiency for TDS removal; and (5) quantities of by-products derived from the processes accompanying operation of an electrolytic water conditioning unit (O<sub>2</sub>, CO<sub>2</sub>, base solution). An analysis of the applicability and efficiency of this electrotechnological approach for improving water quality from the main natural water sources of Moldova was completed using this simulation model. The electrotechnology can contribute efficiently to the successful development of intensive horticulture in Moldova and other regions of the world.

AUTHOR(S): Stevenson, C.L. 1993.

TITLE: **Consumer Preferences for Greenhouse Grown Bibb Lettuce: an Application of Conjoint Analysis.**

WHERE: MSc Thesis. Cornell University Libraries, Ithaca, NY 14853. 89 pp.

ABSTRACT: The purpose of this study is to analyze consumers' preferences for greenhouse grown bibb lettuce. Consumers' preferences are elicited using a decompositional method of preference structure measurement known as conjoint analysis. The research design includes the product attributes packaging, price, and pesticide-free. Results are analyzed at the individual as well as the market level. At the individual level, a main effects plus two-way interaction model is estimated for each individual. At the market level, a main effects model is used to determine whether purchase frequency of greenhouse grown bibb lettuce is related to consumers' preferences for the products' attributes. At the individual level, the results indicate packaging has a significant effect for 75% of the respondents; pesticide-free has a significant effect for 35% of the respondents, and price has a significant effect for 23% of the respondents. There is a large amount of heterogeneity in consumers' preferences for packaging at the individual level. However, the majority of consumers prefer the plastic bag and dislike the crisper. Consumers are split on their preferences for no packaging. More respondents have a significant interaction between packaging and pesticide-free than between packaging and price or between pesticide-free and price. With the exception of the interaction between pesticide-free and the plastic bag, there is a large amount of heterogeneity in the direction of the interaction effects. The interaction between pesticide-free and plastic bag is positive for 72% of the respondents for whom this is a significant interaction. At the market level, respondents in the frequent and moderate purchase frequency groups have the same preferences for the attributes used in the design. Respondents in the infrequent purchase frequency group are more price sensitive than the market average and have a greater than average preference for the pesticide-free attribute. Respondents who never purchase greenhouse grown bibb lettuce have a greater than average preference for no packaging and a greater than average disutility for the crisper. Based on these results, the product, as it is presently marketed in Binghamton and Vestal, is only the fifth most preferred product profile for the frequent and moderate purchase frequency groups and the fourth and sixth most preferred product profile for the infrequent and never purchase frequency groups. The product profile packaged in the plastic bag with the lower price level and the pesticide-free label is the most preferred profile for all purchase frequency groups. therefore, the results indicate the utility of the product may be increased by changing the packaging type.

AUTHOR(S): Thompson, H.C. 1997.

**TITLE: Air and root temperature effects on growth of lettuce, *Lactuca sativa*, in deep-flow hydroponic systems.**

WHERE: MSc Thesis. Cornell University Libraries, Ithaca, NY 14853. 89 pp.

ABSTRACT: Lettuce production is often limited geographically by boundaries where air temperature is outside the range possible for sufficient vegetative growth. This study, in particular, addresses air temperature ranges above the normal growing temperature for butterhead lettuce (*Lactuca sativa* L., cv. 'Ostinata'). The question of interest is whether lettuce can be produced in warm air environments by cooling the root zone. Conversely, we examine if cool air temperatures can be compensated for by increasing root zone temperatures. The mechanism examined is control of temperature at the growing point. By creating a gradient of temperatures between air and root environment, we examine how the temperature at the growing point is affected, and, in turn, how the growth rate of that particular treatment is affected by the temperature gradient, and the temperature at the growing point. Lettuce seedlings were germinated in growth chambers and transplanted after eleven days into three hydroponic ponds in a greenhouse. The crop grew in the ponds until final harvest 35 days after seeding. Each greenhouse crop was grown at a constant air temperature. Daytime temperature set points were centered on 24 deg C, the optimum temperature for lettuce growth. Air temperature set points were 17 deg C (62.6 deg F), 24 deg C (75.2 deg F), and 31 deg C (87.8 deg F), and dropped 5 deg C during the night. Each of the three pond's nutrient solution was set to one of these daytime set point temperatures (17, 24, and 31 deg C) for each crop. After a crop's final harvest, a new crop was brought into a different greenhouse air temperature, and with the same three water temperatures randomized among ponds. The study consisted of six experiments. The first three experiments used each of the three air temperature set points, and the second three experiments were replicates of the first set. Harvests were taken on days 14, 21, 28, and 35 and dry weights measured. Temperatures at the growing point and at 1 and 2 cm depth in the soil plug were measured with thermocouples and an infrared thermometer. Analysis was done using a split-plot design with air temperature as the main treatment, pond water temperature as a sub-treatment, and harvest day as a sub-sub-treatment. Dry weight was used as response variable. Air temperature had a significant effect on the growth curves. Each air temperature produced a significantly different rate of growth regardless of water temperature. The main effect of water temperature on dry weight was significant. There was no statistical interaction between air and water temperature. The optimal temperature for lettuce dry weight production was 24 deg C air and 24 deg C water. The temperature at the growing point was not affected by the air/water temperature gradient for most of the growth cycle. We found control of growth rate through growing point temperature not possible, yet growth rate was influenced by air/water temperature gradient. Root temperature greatly contributed to final dry weight and quality of the crop. Growth curves were analyzed to find the date of harvest when differences among ponds within one air temperature treatment became significant. All curves showed that differences were notable by day 21 and significant in all treatments by day 28. A simple computer model was written to calculate final dry weight from air and water temperature set points.

AUTHOR(S): Thompson, H.C., R.W. Langhans, A.J. Both, and L.D. Albright. 1998.

**TITLE: Shoot and root temperature effects on growth of lettuce, *Lactuca sativa*, in a floating hydroponic system.**

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WHERE: Journal of the American Society for Horticultural Science 123(3):361-364.

ABSTRACT: Butterhead lettuce (*Lactuca sativa* L., cv. *Ostinata*) was used to study lettuce production at varied shoot (air) and root (pond) temperatures. A floating hydroponic system was used to study the influence of pond temperature on lettuce growth for 35 days. Pond water temperature set points of 17, 24 and 31 deg C were used at air temperatures of 17/12, 24/19, and 31/26 deg C (day/night). Pond temperature affected plant dry mass, and air temperature significantly affected growth over time. Maximum dry mass was produced at the 24/24 deg C (air/pond temperature) treatment. Final dry mass at the 31/24 deg C treatment did not differ significantly from the 24/24 deg C treatment. The 24 deg C pond treatment maintained market quality lettuce head production in 31 deg C air. Using optimal pond temperature, lettuce production was deemed acceptable at a variety of air temperatures outside the normal range, and particularly at high air temperatures.

AUTHOR(S): Wheeler, E.F., L.D. Albright, R.M. Spanswick, L.P. Walker, and R.W. Langhans. 1998.

TITLE: **Nitrate uptake kinetics in lettuce as influenced by light and nitrate nutrition.**

WHERE: Transactions of the ASAE 41(3):859-867.

ABSTRACT: A mathematical relationship was developed which shows environmental influences of light and nitrate nutrition on growth and nitrate uptake kinetics. Growth chamber experiments provided data for model development and validation. Ion-specific macro-electrodes determined nitrate depletion from circulating solutions in short-term kinetic tests. Lettuce (*Lactuca sativa* L., cv. *Ostinata*) was grown under three light levels and three nutrient solution nitrate contents which represented a range of adequate and inadequate environments. Larger, faster-growing plants should have a larger demand for nitrate and hence larger uptake rates than smaller, environmentally stressed plants. Results showed higher sustained levels of nitrate uptake by larger plants. Neither the severity of stress under which a plant was grown nor the plant size were the sole determinants of maximum potential uptake behavior, however. Increased light level was related to an increased ability to transport nitrate on a short-term basis. Increased light level was associated with increased maximum nitrate uptake rates ( $V_{max}$ ) as described by the Michaelis-Menten relationship. The effects of environmental light and nitrate levels on nitrate uptake was incorporated into a power relationship where the maximum uptake velocity was determined in relation to the shoot growth rate.

AUTHOR(S): Wheeler, E.F., and L.D. Albright. 1995.

TITLE: **Quantification of lettuce growth in relation to environmental stress.**

WHERE: ASAE paper No. 954461. ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659, USA. 25 pp.

ABSTRACT: The objective of this research was to determine how age, nitrate nutrition and light level influenced growth and associated nitrate uptake rates over the commercial production period of hydroponically grown lettuce. Three N levels were combined with three light zones for nine treatments of lettuce in one growth chamber. Light level was varied from 135 to 375 micromol/sq. m/s and nitrate-nitrogen level was supplied at 0.04, 0.4 or 4.0 mM. Plants do not respond linearly to light and nitrogen levels and these two environmental factors interact in ways difficult to interpret. Treatments were compared to each other through an Environmental Growth Factor (EGF). Shoot growth rate EGF ranked plants logically into more or less stressful

environments. Low-light/low-nitrogen plants had the lowest EGF with values around 0.2, meaning their growth rates were about 20% of the high-light/ high-nitrogen treatment growth rates. Dry weight increase was best represented by an exponential polynomial having three empirical parameters. When coefficient values were graphed and differentiated by light and nitrogen levels, a relationship among the nine treatment parameters emerged. From the relationships, growth curves can be constructed by interpolation for lettuce grown between the specific light and nitrogen levels of this experiment. Biomass was partitioned to leaves and roots differently, depending on environmental conditions to which the plant was exposed. Root masses of low nitrogen-grown lettuce were particularly large, with root:shoot ratios approaching 1.0 under low light conditions. Root dry weight was influenced almost exclusively by the nitrogen level in which the plants grew. Shoot dry weights were more indicative of plant responses to the EGF.

AUTHOR(S): Wheeler, E.F. 1995.

TITLE: **Nitrate uptake and plant growth as influenced by light and nitrate nutrition.**

WHERE: PhD Dissertation. Cornell University Libraries, Ithaca, NY 14853. 340 pp.

ABSTRACT: Evaluation of the kinetics of nitrate uptake over a plant lifecycle, as influenced by environmental factors, would fill a gap in our current understanding of nutrient assimilation and assist in crop management. Many plant nutrient uptake models are purely empirical evaluations based on Michaelis-Menten enzyme kinetics, which appear to fit the observed kinetic data but do not accommodate the physiological mechanisms of nutrient uptake. Michaelis-Menten does show the strong dependence of uptake rates on the nutrient content of the solution surrounding plant roots. Since environmental conditions influence plant growth, and growth creates a demand for nutrients, nitrate uptake should be related to environmental conditions. This research resulted in the development of a Michaelis-Menten-based mathematical relationship which shows environmental influences of light and nitrate nutrition on lettuce growth and N uptake. A growth chamber was outfitted with three nutrient solutions where the major variable was nitrate content: Low N, 0.04 mM; Medium N, 0.4 mM; High N, 4.0 mM. The chamber had lighting zones representing High (350 micromol/sq. m/s), Medium (250 micromol/sq. m/s) and Low (150 micromol/sq. m/s). Each of the three N levels was present in each of the three light zones so that nine environmental treatments were positioned in the chamber. Environmental conditions are best related to a plant growth response. An Environmental Stress Factor (ESF) was proposed as a means to quantify how stressful a combination of environmental factors was compared to adequate or optimal conditions. Uptake rate was quantified into a predictive relationship for lettuce grown under a range of light- and N-level environments. Environmental conditions were incorporated into the  $V_{max}$  term of the Michaelis-Menten kinetic equation. A power curve relationship predicted the maximum uptake rate,  $V_{max}$ , once environmental conditions were specified. Lettuce maximum uptake rates ( $V_{max}$ ) were fairly consistent across the majority of light- and N-level treatments. For Low N grown plants, the availability of adequate light allowed the plants to at least double their maximum uptake rates.

AUTHOR(S): Wheeler, E.F., J. Kossowski, E. Goto, R.W. Langhans, G. White, L.D. Albright, and D. Wilcox. 1995.

TITLE: **Consideration in selecting crops for the human-rated life support system: a linear programming model.**

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WHERE: Adv. Space Res. 18(1/2):233-236.

ABSTRACT: A Linear Programming model has been constructed which aids in selecting appropriate crops for CELLS (Controlled Ecological Life Support System) food production. A team of Controlled Environment Agriculture (CEA) faculty, staff, graduate students and invited experts representing more than a dozen disciplines, provided a wide range of expertise in developing the model and the crop production program. The model incorporates nutritional content and controlled-environment based production yields of carefully chosen crops into a framework where a crop mix can be constructed to suit the astronauts' needs. The crew's nutritional requirements can be adequately satisfied with only a few crops (assuming vitamin mineral supplements are provided) but this will not be not satisfactory from a culinary standpoint. This model is flexible enough that taste and variety driven food choices can be build into the model.

AUTHOR(S): Wheeler, E.F., L.D. Albright, L.P. Walker, R.M. Spanswick, and R.W. Langhans. 1994.

TITLE: **Plant growth and nitrogen uptake Part 1: Beyond the Michaelis-Menten relationship.**

WHERE: ASAE paper No. 947506. ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659, USA. 15 pp.

AUTHOR(S): Wheeler, E.F., L.D. Albright, L.P. Walker, R.M. Spanswick, and R.W. Langhans. 1994.

TITLE: **Plant growth and nitrogen uptake Part 2: Effects of light level and nitrate nutrition.**

WHERE: ASAE paper No. 947505. ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659, USA. 14 pp



## Appendix

### Stock Solutions

Two stock solutions are prepared which will be added separately to RO water and will supply nutrients to the lettuce plants while in the pond area. Two separate stock solutions are prepared to prevent certain chemical reactions. These chemical reactions will cause some of the chemicals to form a precipitate and become inactive. The precipitates will not form if mixed one after another with a large volume of RO water.

STOCK A	
These chemicals are added to 300 L of RO water	
Calcium Nitrate	29160.0 g
Potassium Nitrate	6132.0 g
Ammonium Nitrate	840.0 g
Sprint 330 Iron - DTPA (10% Iron)	562.0 g

STOCK B	
These chemicals are added to 300L of RO water	
Potassium Nitrate	20378.0 g
Monopotassium Phosphate	8160.0 g
Potassium Sulfate	655.0 g
Magnesium Sulfate	7380.0 g
Manganese Sulfate*H <sub>2</sub> O (25% Mn)	25.6 g
Zinc Sulfate*H <sub>2</sub> O (35% Zn)	34.4 g
Boric Acid (17.5% B)	55.8 g
Copper Sulfate*5H <sub>2</sub> O (25% Cu)	5.6 g
Sodium Molybdate*2H <sub>2</sub> O (39% Mo)	3.6 g

### Final Fertilizer Solution Concentrations

Macro-nutrients:			Micro-nutrients:		
N	8.9 millimol l <sup>-1</sup>	(125 ppm)	Fe	16.8 micromol l <sup>-1</sup>	(0.94 ppm)
P	1.0 millimol l <sup>-1</sup>	( 31 ppm)	Mn	2.5 micromol l <sup>-1</sup>	(0.14 ppm)
K	5.5 millimol l <sup>-1</sup>	(215 ppm)	B	15.0 micromol l <sup>-1</sup>	(0.16 ppm)

Ca	2.1 millimol l <sup>-1</sup>	( 84 ppm)	Cu	0.4 micromol l <sup>-1</sup>	(0.03 ppm)
Mg	1.0 millimol l <sup>-1</sup>	( 24 ppm)	Zn	2.0 micromol l <sup>-1</sup>	(0.13 ppm)
S	1.1 millimol l <sup>-1</sup>	( 35 ppm)	Mo	0.3 micromol l <sup>-1</sup>	(0.03 ppm)