DEVELOPMENT OF CULTURAL PRACTICES AND ENVIRONMENTAL CONTROL STRATEGIES FOR THE PRODUCTION OF BASIL (*Ocimum basilicum* L.) IN A SEMI-ARID CLIMATE

By

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ABSTRACT

The objective of this study was to optimize the cultural and environmental conditions necessary to produce high quality basil in a semi-arid climate during summer. Basil grown in a retractable roof greenhouse (RRGH) and full sun over two years using production systems including rockwool, containers, raised beds, vertical towers, and soil was evaluated based on biomass accumulation, morphological characteristics and quality. Photosynthetic response of basil to temperature and light was tested in a growth chamber to determine the optimum conditions that enhance photosynthesis and increase productivity. Biomass accumulation and quality of basil were affected by environment and cultural practices, with the largest quantities of highest quality basil produced in rockwool or raised beds in the RRGH. The response of basil to light and temperature indicated that highest photosynthesis during summer occurred between temperatures of 25 to 35 °C at a light intensity of 1500 μmol m^{-1} s^{-1}.

1. INTRODUCTION

The mild winter climate in the low elevation desert regions of the Southwestern United States poses both advantageous and challenging environmental conditions for food production. The advantage of high solar radiation year round, with photosynthetic photon flux (PPF) averages of 50 mol d^{-1} in summer and 30 mol d^{-1} in winter (Kania and Giacomelli, 2002) is accompanied by supraoptimal air temperatures during summer months, with daily averages of 30 °C and maximum daily temperatures reaching 37 °C (AZMET, 1987 to 2001). The continental climate with little cloud cover throughout most of the year creates large diurnal fluctuations in temperature of 20 °C during summer months (AZMET, 1987 to 2001). Low annual precipitation of 30 cm per year creates an additional challenge for food production in this region of the United States. Despite these environmental challenges, various crops are produced throughout the year under field conditions. Controlled environment structures are currently gaining popularity in this region as they can take advantage of the high year round solar radiation, can moderate the fluctuations in air temperature, and potentially can reduce water use due to decreased evapotranspirational demands under cover.

Retractable roof greenhouses (RRGH) provide a unique opportunity to blend both full sun field and controlled environment greenhouse environmental conditions. The moveable roof and wall curtains permit structural manipulation, creating a dynamic structure with the capability of functioning between a full sun environment and a completely enclosed greenhouse. Although the RRGH can be used as a completely enclosed structure, and hence a completely controlled environment (with the addition of heating and cooling systems), attempting complete environmental control of this structure may not be economically feasible due to the porous curtain materials.

Retractable roof greenhouses in the United States have gained most of their popularity for nursery crop production in the Pacific Northwest. Other regions may benefit from these structures, but the method of controlling curtain movement, species selection and crop management will differ from region to region. Few research based studies to date have evaluated crop production in the RRGH in different climates using different strategies of manipulating the environment in the RRGH.

Culinary herbs are a crop that may benefit from retractable roof greenhouse production. Basil is a popular culinary herb with great niche market potential. Local year round production is a viable opportunity for basil production due to its short post-harvest shelf life. The potential advantage of RRGH production of basil is the possible increase in quality and length of production during unfavorable seasons compared to field production.

The first experiments evaluated the production potential of basil in two hydroponics systems under continuous shade in the RRGH with a field control. In subsequent experiments, additional production systems and roof curtain control of the RRGH were evaluated to maximize the production of basil under RRGH conditions during summer. Basil in full sun was grown in field soil the first year and in hydroponic systems the second year. The full sun trials allowed for comparison of yield and quality between the two retractable roof greenhouse environments and full sun. Field production in soil was initially used to compare production within the RRGH to standard field practices. During the second year of study, hydroponic systems were placed in all environments to compare the effect of the RRGH environment to full sun without the complication from different production systems.

Development of cultural practices and environmental conditions to optimize basil production included several production systems and roof control strategies. Hydroponic production systems chosen for the studies included rockwool culture, peat-based media in containers, raised beds with perlite, and stacked vertical pot systems. Roof control strategies evaluated in the second study included air temperature based control, solar radiation based control and globe thermometer based control. Air temperature was chosen as it is a popular method of control in the greenhouse industry. Solar radiation based control was chosen since curtain movement predominantly affects irradiance levels received by the crop canopy. Mean radiant temperature control using a globe thermometer was evaluated as a combination sensor that integrates several environmental variables including radiation, temperature and wind speed.

Photosynthesis of basil under different light and temperature conditions was evaluated to determine which combinations of these variables would lead to maximum rates of photosynthesis and subsequently to highest biomass production. Most experiments were carried out with ‘Genovese’ and ‘Purple Ruffles’, two cultivars that differ in morphology and growth rate of the more than twenty cultivars available in the trade.

The objectives of the thesis were:

1. Produce high quality basil during summer production in Arizona.

2. Improve yields and quality using a retractable roof greenhouse compared to full sun production.

3. Evaluate production systems and their effect on biomass and quality.

4. Evaluate retractable roof greenhouse curtain control strategies and the effect on yield and quality.

5. Determine the photosynthetic response of basil to temperature and light intensity in a growth chamber.

2. LITERATURE REVIEW

2.1. Retractable Roof Greenhouse Structures

Retractable roof greenhouses (RRGH) have been commercially available since the early 1990's (Vollebregt, 2002). Several styles of retractable roof greenhouses are available, and are chosen based on climate and specific crop needs. Retractable roof greenhouses are a type of open roof design. Many open roof greenhouses rotate the roof sections on a hinge either at the gutter or at the peak. Retractable roof greenhouses open the roof by retracting the covering material.

Two primary categories of retractable roof greenhouses are flat or peaked roof structures. Peaked roof greenhouses are used in climates that have snow loads. In climates without snow, flat roof structures are preferred as they are less expensive and more simple in design. The flat roof retractable roof greenhouses use water porous woven polyethylene films which expose crops grown within the structures to rain, whereas covers on peaked roof structures are impermeable to water and drainage is channeled to the gutters (Badgery-Parker, 1999).

Retractable roof greenhouses vary in cost per unit area depending upon the system components included. Flat roof-structures typically cost \$21.50 m^{-2} whereas the peaked roof structures are \$43.00 m^{-2} (Mathers, 2003). Additional curtains can be added, and variations in sidewall structure will increase the cost. Heat curtains, insect screens and additional shade curtains can be added in a layered system underneath the primary roof covering. Retractable wall curtains can be included in the structure. Some retractable sidewalls close at the ground, whereas others meet a polycarbonate sidewall one meter off the ground. To reduce cost, some growers install a single layer of polyethylene for a sidewall during the cold season, and upon removal leave the sides completely exposed during the remainder of the year.

2.2. Retractable Roof Greenhouses and the Nursery Industry

Retractable roof greenhouses have become most popular in the nursery industry. Advantages of using retractable roof greenhouses include labor savings, reduced energy use, reduced plant stress, improved plant quality and reduced time to finish the crop for sale (Svenson, 2000).

These benefits have been found where plants require outdoor as well as indoor environments. Oftentimes, quonset greenhouse structures and full sun field areas are used in combination during the life of the crop. Typical quonset structures are covered with white polyethylene and in many cases provide no additional environmental control. The advantage of the retractable roof greenhouse is that it can serve as both an outdoor and indoor environment. Schuch (2004) reported commercial RRGH environments were similar to shade houses with stationary covering materials and that they moderated root zone substrate and canopy temperatures better than in full sun in summer and fall. In winter, the RRGH was warmer at night than outdoors and root zones in containers were protected from freezing (Schuch, 2004).

Labor savings occur when an RRGH is used in place of the full sun and greenhouse combination because the crop does not need to be moved from outdoor to indoor environments during winter months. Labor savings can also be achieved because moveable sidewalls allow large equipment access to the structure (Svenson, 2000). Badgery-Parker (1999) stated that the real advantage of such structures is only realized in situations where there is a large labor component due to moving crops in and out of quonset greenhouses from full sun plots.

Retractable roof greenhouses also have reduced energy use compared to greenhouses with active environment control systems. The modification of environment within retractable roof greenhouses allows for passive cooling and heating and can provide sufficient environmental control to improve plant quality compared to outdoor environments without the associated costs of fully automated structures. If a crop only needs passive modification of ambient conditions, the adjustment of curtain positions can provide the shading and ventilation combinations for cooling during the day and the trapping of heat at night. Reduced water and fertilizer use has also been found in some cases compared to outdoor production due to reduced evapotranspirational demand (Svenson, 2000).

Several examples of reduced plant stress have been noted in retractable roof greenhouse structures. Compared to outdoor conditions, retractable roof greenhouses can offer a reduction in solar radiation and the associated radiative heat load which can limit plant growth during summer months. Exposing the crop to full sun in a RRGH has also been found to reduce stem elongation compared to quonset structures in low light conditions (Svenson, 1999).

Improved plant quality within retractable roof greenhouses include compact plants, plants acclimated to outdoor conditions and improved retail shelf life compared to plants grown under stationary cover through winter and full sun conditions during spring (Svenson, 2000).

2.3. Retractable Roof Greenhouse Advantages

The benefits of growing plants within retractable roof greenhouses in the nursery industry are due to the multiple environments that can be provided by a single structure compared to the combination of full sun and shade structures with stationary covering materials typically used. The ability for daily and seasonal change of the environment through curtain movement enables the grower to operate the structure as a full sun or shaded environment with many roof and wall position combinations.

Factors important for plant growth and quality that can be mediated by retractable roof greenhouses include winter and spring frost protection, root zone temperatures, crop hardiness, and time to finished product. These benefits have largely been found in container production in the nursery industry. The retractable roof greenhouse provides these benefits through curtain movement allowing for various combinations of shading, ventilation, heat trapping or cold trapping.

2.3.1. Frost Protection

Initially, retractable roof structures were used for frost protection of forest seedlings (Svenson et al., 2000). Both winter and spring frost protection are important features of retractable roof greenhouses used in the nursery industry. Container-grown nursery crops are typically grown in unheated quonset greenhouses during winter to prevent frost damage. During early spring higher temperatures in quonset greenhouses can cause premature shoot growth that may be damaged when shipped to retailers in colder climates. However, if the crop is moved outdoors it may be in danger of frost damage. It becomes labor intensive to continually cover and uncover the crops, or continuously move them in and out of quonset greenhouses. Retractable roof structures can protect crops during winter and spring from frost without causing premature shoot growth because the roof can be retracted during the daytime to maintain dormancy in plants (Svenson et al., 2000).

2.3.2. Root Zone Temperatures

In container production, retractable roof greenhouses have been used to reduce root zone temperatures in summer months, and to avoid freezing temperatures during winter and early spring months. Both supra-optimal and sub-optimal root zone temperatures can be damaging to the crop. In black containers, supra-optimal temperatures regularly occur during summer months when grown outdoors. Root injury resulting from high root zone temperatures can retard plant growth, decrease photosynthesis and cause shoot necrosis (Mathers, 2003). In winter months, above ground containers do not have the effect of soil to buffer low temperatures compared to plants grown in the ground. When the root zone in containers freezes, the shoots are more susceptible to desiccation (Mathers, 2003). Root zone temperature management has been a primary reason for the adoption of retractable roof greenhouses for nursery container production.

2.3.3. Timing and Quality of Finished Product

The timing to finish a product for delivery is critical to the marketing of specific crops. The improved control of timing of flowering, compactness and hardiness of the crop, and decreased production time have all been features achieved in container production in retractable roof greenhouses.

Cold-trapping is a procedure used for managing nursery crops in retractable roof greenhouses that traps cold night air in the structure to reduce daytime air temperatures. Cold-trapping can be used to prevent premature vegetative growth and flower bud development which decreases the quality of plants once shipped to colder regions. This procedure requires that the RRGH is open at night as long as minimum temperatures do not drop lower than the cold tolerance of the specific crop. Just before dawn, the structure is closed to trap the cold air inside as outside air temperatures increase. The structure is opened during the day once the inside air temperatures reach the outside air temperature, thus early growth is minimized by keeping the plants cool during warm days in early spring (Svenson et al., 1998).

Decreased disease incidence has also been noted in container grown nursery crops in retractable roof greenhouses compared to quonset structures (Svenson et al., 1998).

Studies involving schefflera have demonstrated the decreased time to finished product in retractable roof greenhouses compared to plants grown outdoors. Schefflera grew faster reaching a salable size sooner when compared to plants grown outdoors (Svenson et al., 1992). The crop was more uniform and larger in size when grown in a retractable roof greenhouse compared to outdoors or in shade structures with stationary curtains (Svenson and Johnston, 1991).

2.4. Retractable Roof Greenhouse Control Strategies

Retractable roof greenhouses have been most notably used to eliminate the need for the combination of full sun, shade house, and overwintering quonset greenhouse environments throughout the life cycle of a crop. Within the full sun, shade and overwintering structures, environmental control strategies are not employed. Rather the crop is moved throughout its development to the different locations. Retractable roof greenhouses provide the opportunity for one structure to serve as all three of those environments. However, when dealing with one structure versus three unique environments, control of the structure becomes an additional management requirement.

Control strategies for retractable roof greenhouses have been based on air temperature. From the air temperature, growers decide whether the roof and wall curtains should be re-positioned. Improved control strategies are needed that can integrate environmental parameters such as air temperature, solar radiation and wind speed to provide the microclimate that is best suited for the crop.

Air temperature based controllers are common in fully automated greenhouse structures. Within passive retractable roof structures that primarily manipulate exposure to solar radiation and ventilation, parameters other than air temperature may prove more useful.

Studies using mean radiant temperature based control for retractable roof greenhouses have been evaluated at the University of Arizona for the production of tomato and pepper (Suarez-Romero et al., 2004). This method of control successfully added radiation and wind speed to air temperature in the decision making process used for operating roof and wall curtains. Mean radiant temperature was a good indicator of plant fruit and leaf temperature and therefore the globe thermometer was evaluated as a potential controller for roof curtain position.

2.5. Basil Yields and Quality

Basil in the genus *Ocimum* is part of the Lamiaceae family. The *Ocimum* genus originated between the Tropic of Cancer and the Tropic of Capricorn throughout Africa, Southeast Asia and South America in warm regions from sea level to 1800 m, with the majority of species originating in the tropical rain forests of Africa (Sobti and Pushpangadan, 1977). Over 160 species of *Ocimum* exist and in the species *basilicum*, 20 cultivars are commonly grown; sweet basil being the most common in the United States. Basil is grown for many markets including the fresh and dried culinary markets, for its essential oils, and more recently as a component of preservatives. Production practices and subsequent yields vary according to the end product desired. Effects of nutrient concentrations, production practices, and shelf life studies are reported in the literature.

2.5.1. Essential Oils

The essential oils in basil are valuable for both culinary and essential oil markets. Essential oil quantities and specific types have been affected by nutrient concentrations and ratios, as well as by cultural practices manipulating the light quality received by the crop. The primary oils responsible for the characteristic flavor of basil include but are not limited to linalool, methyl chavicol, methyl cinnamate and eugenol (Sobti and Pushpangadan, 1977).

Increased oil production occurs under specific nutrient regimes. In terms of nitrogen form, essential oil content of basil was shown to decrease by 28% when fertilized with NH_4-N rather than NO_3-N, yet leaf dry weight was not affected by fertilizer source (Adler et al., 1989). Potassium and calcium ratios in the nutrient solution have also affected essential oil content. Ratios of K to Ca of 50-50 or 25-75 have shown greatest essential oil production (Takano, 1993). Suh and Park (1999) found the concentration of essential oils in sweet basil was increased when the concentration of the nutrient solution was greater, although there was a negative correlation between the concentration of essential oil and shoot fresh weight.

Essential oil content of basil has also been affected by light quality. Johnson et al. (1999) found that supplementing natural light in glasshouse grown basil with a UV-B treatment in the early morning enhanced the levels of essential oils in basil. Another study of field grown basil evaluated the effects of six colors of plastic mulches on basil leaf morphology and aroma content. Basil grown over both yellow and green plastic mulches produced higher concentrations of aroma compounds compared to plants grown over white or blue covers (Loughrin and Kasperbauer, 2001).

2.5.2. Production Systems

Basil has been grown in a wide range of conditions ranging from field cultivation to hydroponic systems in greenhouses. Substrate type, planting density and the associated yields and quality have been documented for some of the systems.

Basil has been successfully grown in containers, which has been of interest for growers who produce bedding plants (Gibson et al., 2000). Stem rot diseases including *Fusarium* species can occur in plug trays used in bedding plant production if plants are grown too crowded. Recommended cultural practices in container production from North Carolina State University include sowing 2 seeds per cell, with germination conditions of 21° C with the seed covered. Once transplanted, 2 to 3 weeks after seeding, the recommended growing temperatures are 17 to 18° C. Nitrogen fertilizer rates are recommended at 125 to 150 µmol mol^{-1} (Gibson et al., 2000).

Vertical hydroponic systems have been used to grow basil by the University of Florida. Basil cultivars ‘Genovese’, ‘Genovese Compact’, and ‘Purple Ruffles’ were grown in this system. Cultural practices associated with the vertical production in Florida included a tower of 8 pots, with 4 emitters at the top pot, and 2 emitters at the middle pot. In an observational study, yields found for basil harvested 12 times between September 24 and January 13 was as follows: 8.9 oz/plant for ‘Genovese’ (20 g/plant/harvest), 7.5 oz/plant for ‘Genovese Compact’ (18 g/plant/harvest), and 3.1 oz/plant for ‘Purple

Ruffles' (7 g/plant/harvest) (Hochmuth and Leon, 1999). In an additional study that evaluated different media types within the vertical production system, no differences were found between perlite alone or perlite mixed with vermiculite or coco coir (Hochmuth and Davis, 2004).

In a study by Smith et al. (1997), differences in yield of basil were found between different substrates and different planting densities. Increasing planting density from 2 to 16 plants per container (0.41 square section, 9.5 cm high) increased total container fresh weight of basil from 15 g/pot to 37 g/pot nine weeks after sowing (Smith et al., 1997). In the substrate trial, perlite increased basil yields compared to peat. Basil yields when grown in perlite were between 39 and 47 g/pot compared to 2 to 25 g/pot 12 weeks after sowing (Smith et al., 1997). Low yields in peat were due to plant death in many of the containers primarily from waterlogging which was attributed to the physical characteristics of peat.

Succop and Newman (2004) evaluated basil fresh weights in three substrates and two fertilizer sources over two years. Substrates types included rockwool, perlite and a commercial peat/perlite/compost media. Plants were spaced 23 cm within and between rows. Fertilizer included conventional or organic sources. Average fresh weight per plant per harvest under conventional fertilizer was 34 g for rockwool, 29 g for perlite and 35 g for the peat/perlite/compost media during the 1996 study where substrate type had no significant effect on yield. During the 1997 study, average fresh weight per plant per harvest using conventional fertilizer was 33 g for rockwool, 13 g for perlite and 30 g for the peat/perlite/compost media. Both rockwool and peat/perlite/compost medias improved yields compared to perlite.

2.5.3. Shelf Life

Basil has a short post-harvest shelf life and is further affected by its sensitivity to chilling injury. The leaves of basil become black and water-soaked within 3 to 4 days when stored below 5 °C which is a typical storage temperature for the majority of freshly harvested horticultural commodities (Lange, 1997). At 15 °C, the average shelf life of basil is 12 days (Lange and Cameron, 1994). Lange and Cameron (1997) found that pre and post harvest temperature conditioning could increase the shelf life of basil. Prior to harvest, plants chilled at 5 °C for 2 hours at the end of the light period and 2 hours at the beginning of the light period, had an increased shelf life of 3 days. After the harvest, they found that packaged basil stored for 1 day in darkness at 10 °C had an average shelf life that was increased by 5 days. Besides temperature conditioning, Lange and Cameron (1994) found that harvesting basil later in the day between 1800 and 2200 HR, compared to the morning hours of 0200 and 0600 HR increased the shelf life of basil by 100% when stored at temperatures greater than 10 °C but did not enhance resistance to chilling injury. The reason for increased shelf life due to harvest time was not determined in this study, but was possibly attributed to diurnal fluctuation affecting carbohydrate accumulation.

2.5.4. Preservative Effects

Antioxidants have been beneficial in both human health and in preservative effects in food and beverages (Juliani and Simon, 2002). Antioxidant components from phenolic-rich sources can be found in plant products. Basil contains many essential oils rich in phenolic compounds that have recently been investigated for their use in food preservation.

Two essential oils contributing to the flavor of basil include linalool and methyl chavicol and have been linked to the antimicrobial and antifungal properties of basil (Lachowicz et al., 1998). In a study performed by Lachowicz et al. (1998), essential oils from five varieties of basil were tested on a range of food-borne gram-positive bacteria, gram-negative bacteria, yeasts and molds, with results indicating that all varieties of basil tested showed antimicrobial activity against most of the organisms tested. The results of such investigations have prompted interest in incorporating essential oils from basil into food packaging materials (Suppakul et al., 2003).

3. 2003 EXPERIMENT: PRODUCTION OF ‘GENOVESE’ and ‘PURPLE RUFFLES’ BASIL IN THREE ENVIRONMENTS UNDER DIFFERENT CULTURAL PRACTICES

3.1. Introduction

The popularity of basil as a niche market crop has made local year-round production a viable alternative for growers. Basil has traditionally been produced in warm climates as a field crop, but has gained attractiveness for greenhouse growers due to the year-round demand and the high prices the product commands during winter when field produce is not available. In semi-arid climates such as Arizona, the potential of the retractable roof greenhouse (RRGH) to increase yield, quality and length of season for two cultivars of basil was evaluated.

This study served to quantify the biomass accumulation and quality of basil produced hydroponically within two RRGH environments compared to traditional field production in soil in full sun. Two cultural systems and two shade environments within the RRGH were evaluated. No roof or wall curtain control strategies in the RRGH were tested during this study in order to determine the response of basil within two permanent shade environments.

3.2. Materials and Methods

3.2.1. Cultural Practices

A RRGH (Cravo Equipment Ltd., Branford, Ontario, Canada) with the flat roof 3.65 m above the ground covered either with a clear woven glazing of 35% (RC98) or a white woven glazing of 50% (RAR-40) shade was used for this study. The RRGH was oriented north-south and the two adjacent middle bays were used for the study. Each bay was 18.3 m by 9.1 m with posts spaced 9.14 m apart from east to west, and 3.65 m apart from north to south. A detailed description of the structure has been given by Suarez-Romero et al. (2003).

The roof and wall curtains could be retracted (opened) to expose the plants within the structure to full sun light intensities, or could be deployed (closed) to shade the crop. The curtain position when closed was identified as 0% open, and when open was identified as 100% open.

For the duration of the experiment, the RRGH roof was closed during daytime except for small ventilation gaps of approximately 1.3 m every 9.1 m. Side walls were kept open during daytime. Only in cases of rains or high winds (above 30 km h^{-1}) were the roof and walls completely closed during the daytime. At night, the entire structure was closed. The roof was kept stationary throughout the experiment so that crop responses to the two shade environments could be evaluated before employing various roof and wall strategies.

A field plot in full sun was amended with compost that was incorporated to a depth of 20 cm. Drip tape (Drip Eze, Olson Irrigation, Santee, CA) was placed adjacent to transplants along the rows. Plants were spaced 0.3 m apart within rows, and rows were 0.8 m apart. Irrigation was applied for 15 minutes, between three and five times a day depending on environmental conditions. Fertilizer was applied weekly at the rate of 2.3 g N m^{-2} (Miracle Grow, Scotts Co., Marysville, OH).

Media in 18 L containers in the RRGH contained Sunshine Mix #1 (Sun Gro, Bellevue, WA) and perlite (3:1 vol.). Pots were spaced 0.7 m apart within rows and 1.0 m apart between rows. Three basil plants were grown in each pot. Pots were irrigated with a complete nutrient solution at a frequency controlled by a tensiometer set at -0.5 MPa.

Plants were also grown in rockwool slabs in the RRGH. Seedlings were sown in rockwool cubes (3.8 cm x 3.8 cm x 3.8 cm) and inserted into rockwool blocks (7.6 cm x 7.6 cm x 6.6 cm) once seedlings had developed the second to third set of true leaves. At the time of transplant to the RRGH, the rockwool blocks were set on top of the rockwool slabs (7.6 cm x 15.2 cm x 91.4 cm). Three plants, each in a rockwool block were grown on top of a rockwool slab. Plants were spaced 20 cm apart within rows, and 0.8 m between rows. Irrigation for each plant was provided by one 2 L hr^{-1} emitter controlled by a timer. All basil plants grown in rockwool were irrigated with a complete nutrient solution and frequency of irrigation was controlled by a timer to maintain 25% to 30% daily drainage. The fertigation solution had an EC of 1.8 dS m^{-1} and a pH of 6.3 throughout the experiment. The nutrient solution contained the following elements in mg L^{-1}: 150 NO_3-N, 50 P, 200 K, 150 Ca, 50 Mg, 3 Fe, 0.8 Mn, 0.4 Zn, 0.1 Cu, 0.3 B, and 0.05 Mo.

Two cultivars of basil (*Ocimum basilicum* L.), ‘Genovese’ and ‘Purple Ruffles’, were seeded into rockwool cubes in a mist house on June 14, 2003 (Johnny’s Selected Seeds, Winslow, ME). Basil was transplanted into the field and RRGH on July 14, 2003. Two weeks after transplant, from July 15 to July 30, basil was not harvested, and was allowed to acclimate before harvesting began. During this time plants were topped to encourage branching. From July 30 to August 14, two to four weeks after transplant, basil was harvested during the establishment phase of production to further encourage branching as the plants grew. From six weeks to fourteen weeks after transplant (harvests 4 to 12, August 28 to October 23), full production with weekly harvests was recorded, and from sixteen weeks to eighteen weeks after transplant (harvests 13 to 14, November 4 to November 18), fall production of basil was harvested bi-weekly. Harvested shoots generally consisted of two to five nodes. Plants were removed when low night temperatures damaged leaves in the RRGH and outside on November 24, 2003.

3.2.2. Data Collection, Experimental Design and Analysis

Biomass, environmental data and physiological parameters were recorded. Fresh weights for all harvests were recorded and dry weights at selected harvests were recorded. Leaf area, measured with a leaf area meter (LI-COR 3100, Li-Cor, Lincoln, NE) and internode length at selected harvests were recorded. Environmental parameters including instantaneous photosynthetically active radiation (Quantum sensor, Spectrum Technologies, Plainfield, IL), and air and media temperatures (HOBO H8 dataloggers, Pocassett, MO) were continuously monitored in all environments. Air temperatures were monitored at the plant canopy level. Substrate temperature sensors in the containers were placed approximately 10 cm interior to the edge of the container, approximately 5 cm deep. Substrate temperature sensors for the rockwool system were placed 5 cm deep inside the rockwool block above the rockwool slab, except during the last month of the experiment when both block and slab temperature was monitored. Stomatal conductance and transpiration were measured with a porometer (LI-COR 1600, Lincoln, NE) on October 8, 2003.

A split-split block design was used for the experiment with environment as a main plot, cultivation method as a split plot and cultivar as a sub-split plot. Each treatment was represented with 15 experimental units in three blocks each. For each basil cultivar, one experimental unit contained three plants, grown in either a container or a rockwool slab in the RRGH or three consecutive plants in the field. Each experimental unit of three plants was harvested and an average weight per plant was calculated. In total, each treatment contained 45 plants.

Data were analyzed using SAS and JMP IN (SAS Institute Inc., Cary, NC). Means were analyzed using ANOVA and mean separations were calculated by Tukey's HSD.

3.3. Results and Discussion

3.3.1. Biomass Accumulation

Basil fresh weight production was significantly affected by environment, cultural conditions, and cultivar in a three-way interaction. 'Genovese' produced greatest biomass in rockwool under either shade followed by plants growing in containers under the clear woven and white woven roof, respectively (Table 3.3.1.1, Figure 3.3.1.1). 'Purple Ruffles' produced greatest biomass in rockwool under either shade and approximately 30% less biomass in pots under either shade (Table 3.3.1.1, Figure

3.3.1.2). When averaged over all treatments, ‘Genovese’ produced 91% more biomass than ‘Purple Ruffles’ throughout the study. Greater yield of ‘Genovese’ compared to ‘Purple Ruffles’ basil or in general of green-leaf versus purple-leaf basil cultivars has been reported before (Hochmuth and Leon, 1999).

Field production was up to 50% lower for each cultivar when compared to the highest production for each cultivar in rockwool (Table 3.3.1.1). For the ‘Genovese’ basil, plants grown in rockwool produced 45% more biomass than plants in containers and 106% more biomass than plants grown in soil in full sun. ‘Genovese’ basil in containers produced 42% more biomass than in full sun. For the ‘Purple Ruffles’ basil, plants grown in rockwool produced 44% more biomass than plants in containers and 160% more biomass than plants in soil in full sun.

Field yields may be low due to transplant shock as basil was not direct seeded. The high solar radiation and air temperatures during Arizona summers as well as monsoon season occurring during the study may have reduced field production, which illustrates the need for protected cultivation in this area. Field production may also benefit from colored plastic mulches which have been found to increase the fresh weight and leaf area of basil (Loughrin and Kasperbauer, 2001).

The differences in yield between the rockwool and container production systems are due to a variety of factors. The high water holding capacity of the peat-based media in containers lead to less frequent irrigation and hence nutrient delivery as compared to the rockwool. The high water holding capacity of the peat-based media may have resulted in lower dissolved oxygen concentrations which can reduce shoot growth

(Gibson et al., 2000). Well-draining substrates like rockwool are more favorable for basil growth, as peat in particular has been shown to reduce the growth of basil compared to other well-draining substrates like perlite (Smith et al., 1997). Succop and Newman (2004) reported basil grown in rockwool had similar biomass accumulation to peat/perlite media, where plants grown in rockwool produced 33 g/plant/week, plants grown in peat/perlite mixes produced 30 g/plant/week during the 1997 trial. The reported weekly yields are much lower than the rockwool and container yields from within the RRGH most likely due to the lower solar radiation in Colorado compared to Arizona.

Table 3.3.1.1. Total fresh weight yield (kg) of 15 experimental units grown in different environments and cultural conditions for 16 weeks. Each experimental unit is the mean of three plants.

	Full Sun	Clear Woven		White Woven	
Cultivar	Soil	Rockwool	Containers	Rockwool	Containers
Genovese	9.3 d*	18.8 a	14.4 b	19.4 a	11.9 c
Purple Ruffles	3.9 f	10.0 d	7.2 e	10.5 cd	7.0 e

*Means within this table followed by a different letter are significantly different at $p<0.05$.

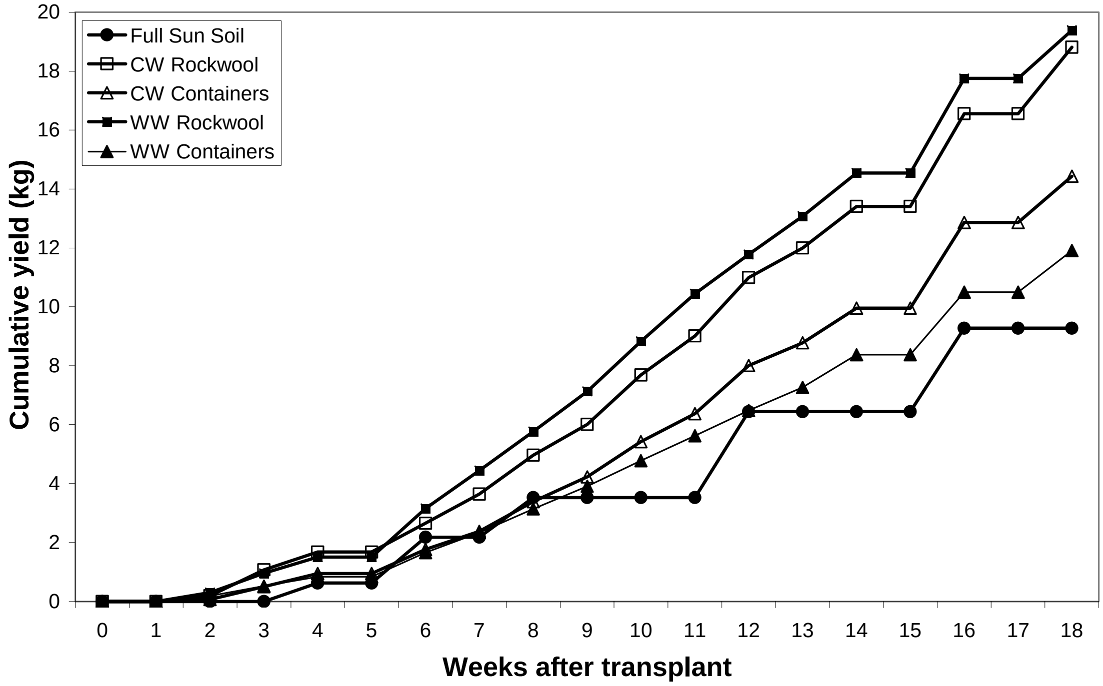

Figure 3.3.1.1. Cumulative ‘Genovese’ basil yields. Each data point represents the total cumulative yield for 15 experimental units. Each experimental unit is the mean of three plants. (CW = clear woven roof, WW = white woven roof).

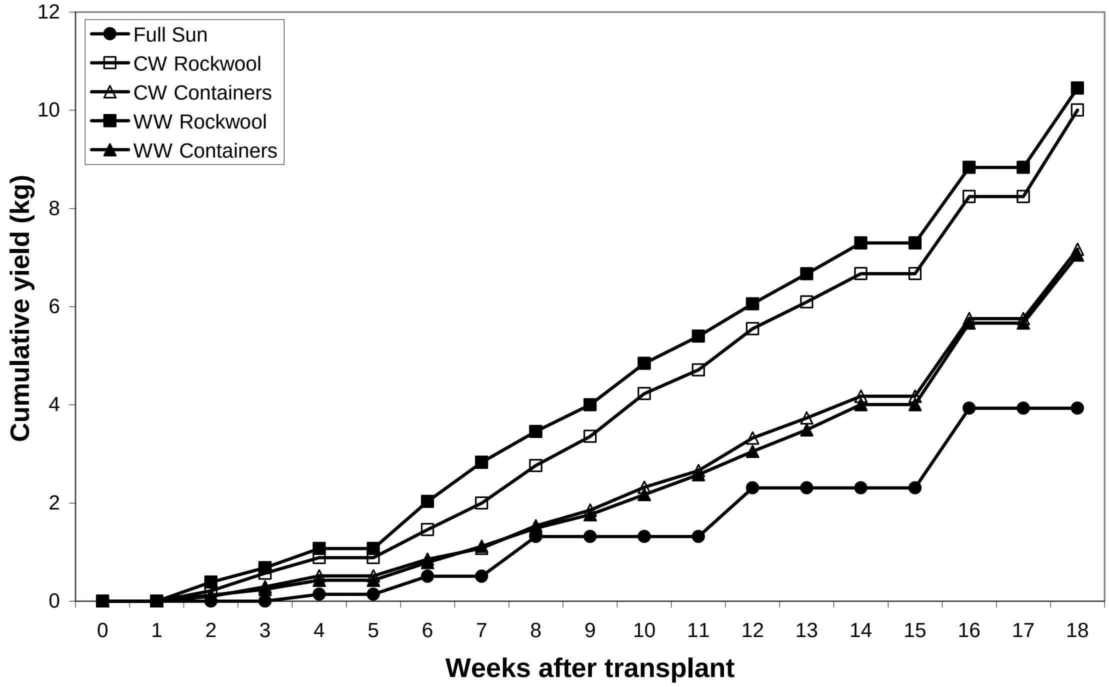

Figure 3.3.1.2. Cumulative ‘Purple Ruffles’ basil yields. Each data point represents the total cumulative yield for the treatment with 15 experimental units. (CW = clear woven roof, WW = white woven roof).

The initial harvests provided little salable material and served primarily to encourage branching. If the first three harvests are not taken into consideration, weekly production estimates are as follows: ‘Genovese’ basil produced 90 g plant^{-1} week^{-1} in rockwool, 63 g/plant/week in containers and 44 g/plant/week in soil in full sun. ‘Purple Ruffles’ produced 47 g/plant/week when grown in rockwool, 34 g/plant/week in containers and 19 g/plant/week in soil in full sun. In estimating production on a per area scale, it is assumed that for each production system within the RRGH, there was a density of 3 plants m^{-2} (either in a container or a rockwool slab), and in the field there was a density of 1.7 plants m^{-2}. In a typical field situation, a density of 9 plants m^{-2} would be expected with plants spaced 0.3 m apart within and between rows. In a research situation, with the need to collect data from within the plot area, densities were much reduced. Including all harvests over a four month period, biomass for the different production systems and cultivars under the experimental conditions described above were as follows: ‘Genovese’ produced 4.3 kg m^{-2} under rockwool culture, 3.0 kg m^{-2} in containers and 1.2 kg m^{-2} in soil in full sun. ‘Purple Ruffles’ produced 2.3 kg m^{-2} under rockwool culture, 1.6 kg m^{-2} in containers and 0.5 kg m^{-2} in soil over a four month production period. These production estimates are for a summer season crop and do not include the time from seed to first harvest.

Overall, ‘Genovese’ is a higher yielding cultivar compared to ‘Purple Ruffles’ in all environments and production systems. ‘Genovese’ basil produced the greatest amount of salable biomass when grown in rockwool under either shade environment of the retractable roof greenhouse.

3.3.2. Morphological and Physiological Measurements

Average dry weight to fresh weight ratios are listed in Table 3.3.2.1 for both basil cultivars. Dry matter accounted for 10 to 14% of the total fresh weight. For both cultivars, greater dry matter accumulation occurred for basil grown in full sun in soil. Dry matter accumulation has been previously correlated to increased interception of radiation (Lawlor, 2001). For fresh market purposes, the increase in dry matter is not necessary or an indicator of quality. For dried herb packaging, the increase may not be significant due to the overall greater production in the RRGH, producing more dry matter per unit area compared to full sun. As a cultivar, ‘Genovese’ accumulated 9% more dry matter than ‘Purple Ruffles’ ($p<0.001$, Table 3.3.2.1). Basil grown in full sun in soil accumulated 13% more dry matter than plants grown in the RRGH in either production system ($p<0.001$, Table 3.3.2.1).

Table 3.3.2.1. Mean dry weight to fresh weight ratio of two basil cultivars grown in different environments and cultural conditions.

Cultivar	Dry weight: fresh weight ratio
Genovese	0.12 a*
Purple Ruffles	0.11 b
Environment	
Full Sun	0.13 a
Clear Woven	0.11 b
White Woven	0.12 b
System	
Soil	0.13 a
Rockwool	0.12 b
Containers	0.11 b

*Means within a treatment followed by a different letter are significantly different at $p<0.05$.

Transpiration of basil was affected by environment ($p<0.0001$) and production system ($p<0.0001$), but not by cultivar ($p=0.5587$, Table 3.3.2.2). Basil grown under the clear woven roof in the RRGH had transpiration rates 148% greater than in full sun. Basil grown in rockwool had transpiration rates 19% greater than basil grown in containers and 146% greater than in soil. Rockwool is a well draining substrate that was irrigated frequently to maintain 20% drainage and remained more fully hydrated compared to the containers throughout the day which were controlled by the tensiometer. Basil grown in full sun in soil was well watered at the time of measurement, but high incident radiation on the crop caused partial stomatal closure (Table 3.3.2.2), resulting in a reduction in transpiration.

Stomatal resistance of basil was affected by environment ($p<0.0001$) and production system ($p<0.0001$), but not by cultivar ($p=0.7395$, Table 3.3.2.2). Stomatal resistance of basil under full sun in soil was 325% greater than either RRGH environment in both production systems. Increased stomatal resistance in full sun may have resulted from several factors including wind speed, high solar radiation in full sun and possible water stress. The increased stomatal resistance reduced transpiration in this environment which may have resulted in the higher leaf temperatures recorded in full sun (34 °C ± 0.16) compared to the RRGH (30 °C ± 0.11) on this day. The increased stomatal resistance in full sun and the subsequent reduction in transpiration could contribute to a decrease in nutrient uptake and possible reduction in plant growth.

Table 3.3.2.2. Transpiration (µg cm^{-2} s^{-1}) and stomatal resistance (s cm^{-1}) of two cultivars of basil grown in the RRGH under two production systems and in full sun in soil.

Environment	Transpiration	Stomatal Resistance
Full Sun	9.5 c*	3.4 a*
Clear Woven	23.6 a	0.6 b
White Woven	19.4 b	1.0 b
Production System		
Soil	9.5 c	3.4 a
Rockwool	23.4 a	0.7 b
Containers	19.6 b	0.9 b

*Means within a treatment and column followed by a different letter are significantly different at $p<0.05$.

Leaf area of basil was significantly affected by shade, but not by the production systems in the RRGH. Both cultivars produced leaves with the greatest leaf area under clear woven shade, followed by white woven shade, and leaves with the smallest leaf area in full sun in the field (Table 3.3.2.3). The reduction in leaf area under field conditions compared to the clear woven shade environment was greater for ‘Genovese’ than ‘Purple Ruffles’, indicating that ‘Genovese’ plants may be more sensitive to changes in light intensity in a production environment than ‘Purple Ruffles’. The large differences in leaf area between basil grown under the clear woven roof compared to those grown under full sun are to be expected, but the smaller difference between those grown under the white woven roof compared to the field may be due to decreased photosynthesis under white woven shade therefore inhibiting further increase in leaf area compared to clear woven shade. The increased leaf area under cover enhances the marketability of the crop and may also partly compensate for the reduced solar radiation due to shading (Gimenez et al., 2002).

Table 3.3.2.3. Leaf area per leaf (cm^2) of basil grown in three environments.

Cultivar	Full Sun	Clear Woven	White Woven
‘Genovese’	9.0 c*	19.6 a	16.1 b
‘Purple Ruffles’	13.7 c	20.2 a	18.0 b

*Means within a row followed by a different letter are significantly different at $p<0.05$.

Internode lengths also differed between the three light environments ($p<0.0001$) for ‘Genovese’ basil, but were not significantly affected by production system (Table 3.3.2.4). The internode lengths of the ‘Purple Ruffles’ basil were not affected by either light environment or production system. For the 'Genovese' basil, the internode length under clear woven shade was 20% greater than under white woven shade and 65% greater than under full sun in the field. The internode lengths under white woven shade were 37% greater than those under full sun in the field. These differences follow the trends of the leaf area differences. Differences in leaf area and internode lengths resulted in an overall morphology characterized by compact plants with smaller leaves for plants grown in soil in full sun. For the fresh culinary market, the plants in the RRGH which had larger leaf areas irrespective of shade or production system were preferable.

Table 3.3.2.4. Internode length (cm) of basil grown in three environments.

Cultivar	Full Sun	Clear Woven	White Woven
'Genovese'	4.3 c*	7.1 a	5.9 b
'Purple Ruffles'	3.1 a	4.0 a	4.0 a

*Means within a row followed by a different letter are significantly different at $p<0.05$.

Quality of basil was superior in both RRGH environments when grown in rockwool or containers compared to soil in full sun. By visual observation, the plants in full sun were of lesser quality due to increased flowering, poor color development in 'Purple Ruffles', and required washing to clean the product.

3.3.3. Environmental Monitoring

Instantaneous photosynthetic photon flux (PPF) was measured above the basil canopy using a quantum meter (Quantum sensor, Spectrum Technologies, Plainfield, IL) on August 24, 2003, five times throughout the day: 0600, 0900, 1200, 1500, and 1800

HR. Light intensity under the clear woven roof and white woven roof was approximately 35% and 50%, respectively, of the intensity under full sun (Figure 3.3.3.1).

The air temperature differences between the clear woven and white woven shade in the RRGH were negligible, and were therefore combined. During the summer (July 14 to September 21, 2003), the minimum and maximum air temperatures outside ranged between 20 ºC and 45 ºC respectively. In the RRGH during the summer, temperatures were approximately 2 ºC cooler than air temperatures outside, with the roof closed and the walls open, and 2 to 5 ºC warmer at night, with the entire structure closed (Figure 3.3.3.2). Representative diurnal air temperatures during summer are presented in Figure 3.3.3.3. Outdoor air temperatures show greater diurnal fluctuations, but overall are similar to the RRGH air temperatures during the day when the structure is open. Air temperature differences under the clear woven and white woven shade were negligible. If leaf temperatures were monitored, differences between these environments would likely become more apparent, due to differences in radiation heat load on the plants not reflected in air temperature due to high ventilation rates. The rate of change in air temperature in all three environments was similar.

During late fall, the structure was kept closed with 20% ventilation gaps and during this period the air temperatures within the RRGH were 2 to 5 ºC warmer at night (Figure 3.3.3.4). Similar trends have been noted previously where cooler temperatures were found under cover during warmer parts of the season, and warmer temperatures were found under cover during cooler parts of the season (Gimenez et al., 2002). Air temperatures during winter nights in a RRGH have been reported to maintain temperatures 4 °C above outdoor air temperatures (Schuch, 2004). Although night temperatures in the RRGH were slightly warmer than outdoors, once outdoor air temperatures decreased to -5 ºC at the end of November 2003, air temperatures reached 0 °C inside the RRGH (Figure 3.3.3.5). At this time, the entire canopy of plants in the field was damaged and the upper portions of the canopy were damaged in the RRGH. The upper portions of the canopy are the youngest portion of the plant, and the most sensitive to chilling injury (Lange and Cameron, 1997). Although the temperatures did not completely damage the RRGH plants like those in the field, the upper portions of the canopy are the portions that are harvested for a salable product, therefore the RRGH was not able to extend the production season through late fall and winter for a warm weather crop like basil without supplemental heat in Arizona.

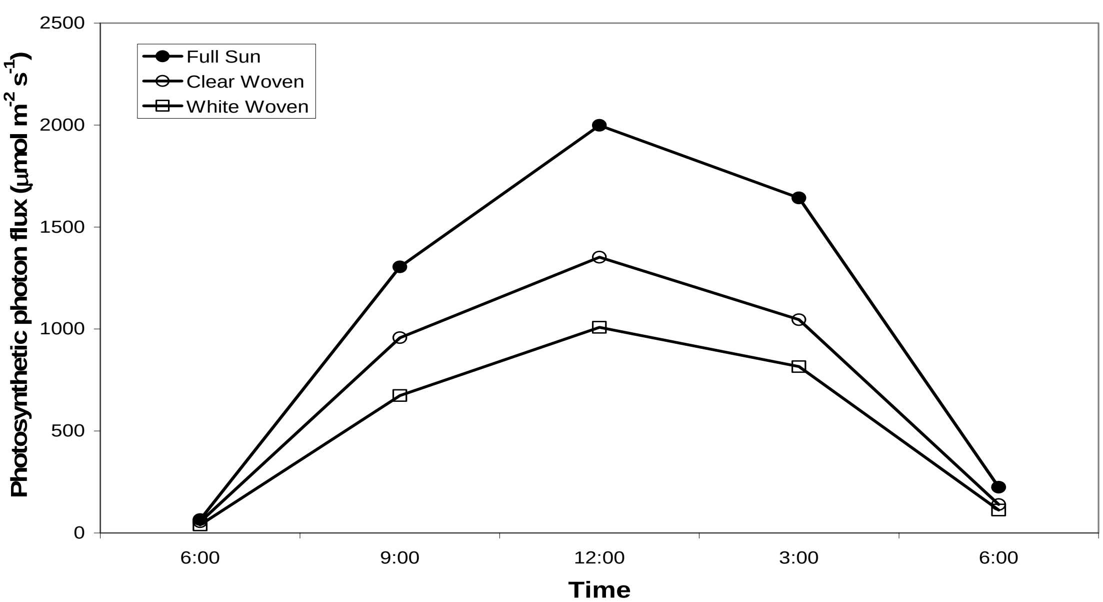

Figure 3.3.3.1. Instantaneous photosynthetic photon flux under three environments on August 24, 2003.

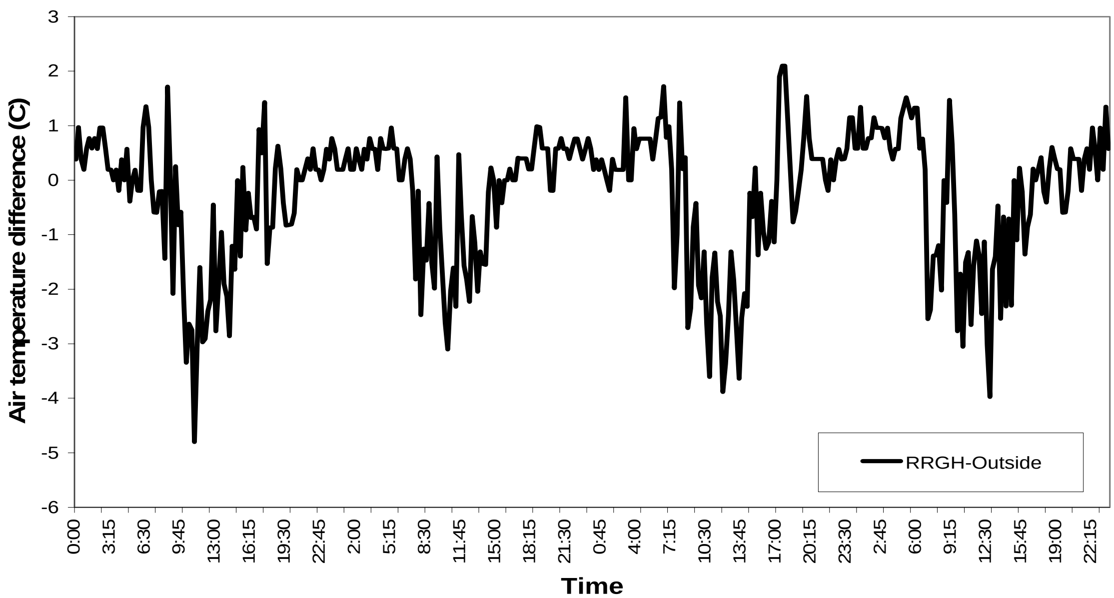

Figure 3.3.3.2. Air temperature differences between the RRGH and full sun from July 27 to 30, 2003.

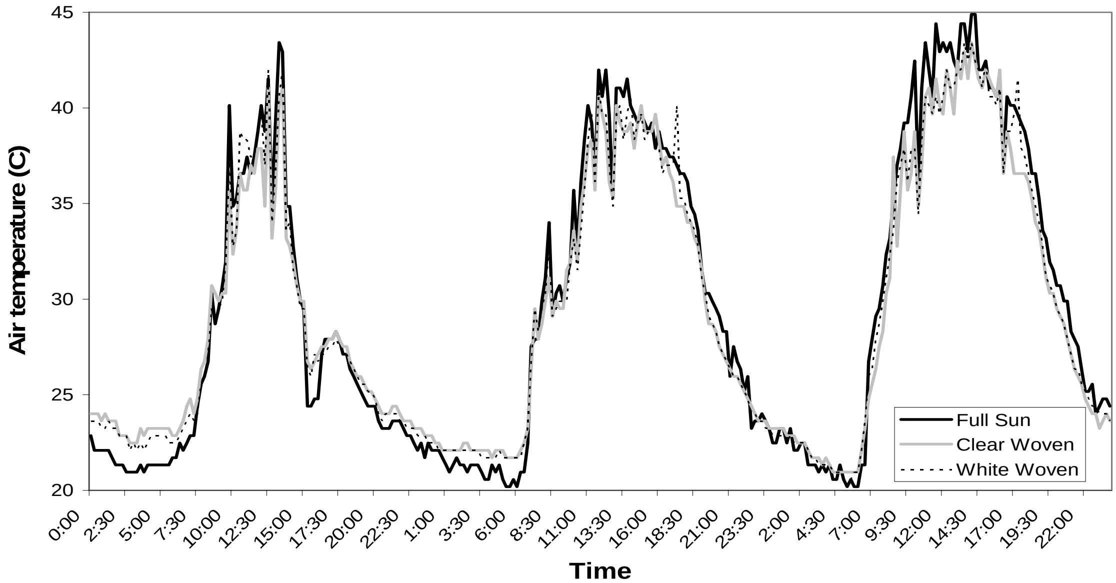

Figure 3.3.3.3. Summer air temperatures in three environments from August 1 to 3, 2003.

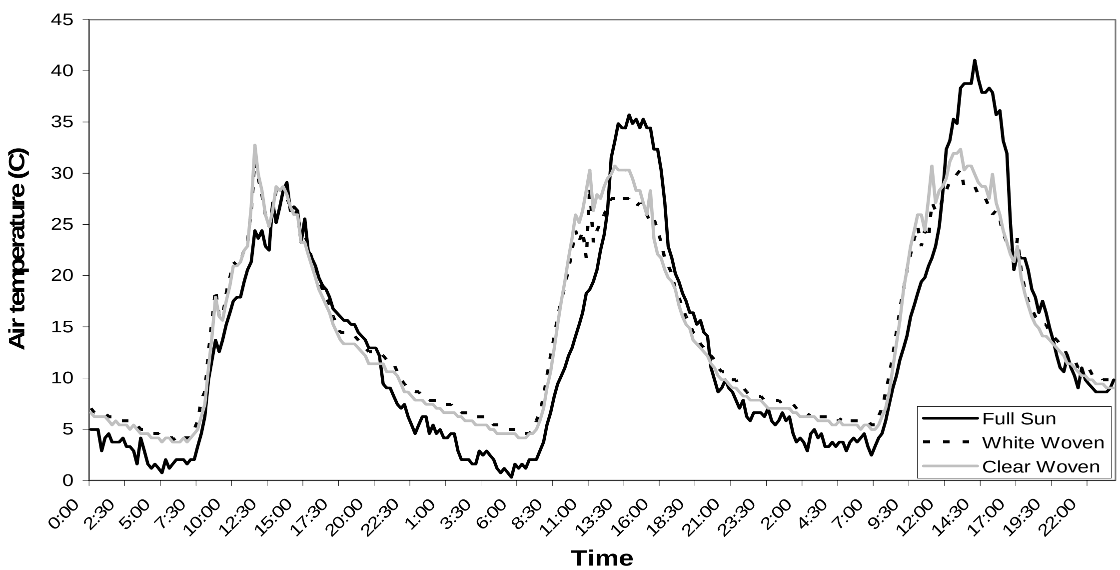

Figure 3.3.3.4. Fall air temperatures in three environments from November 7 to 9, 2003.

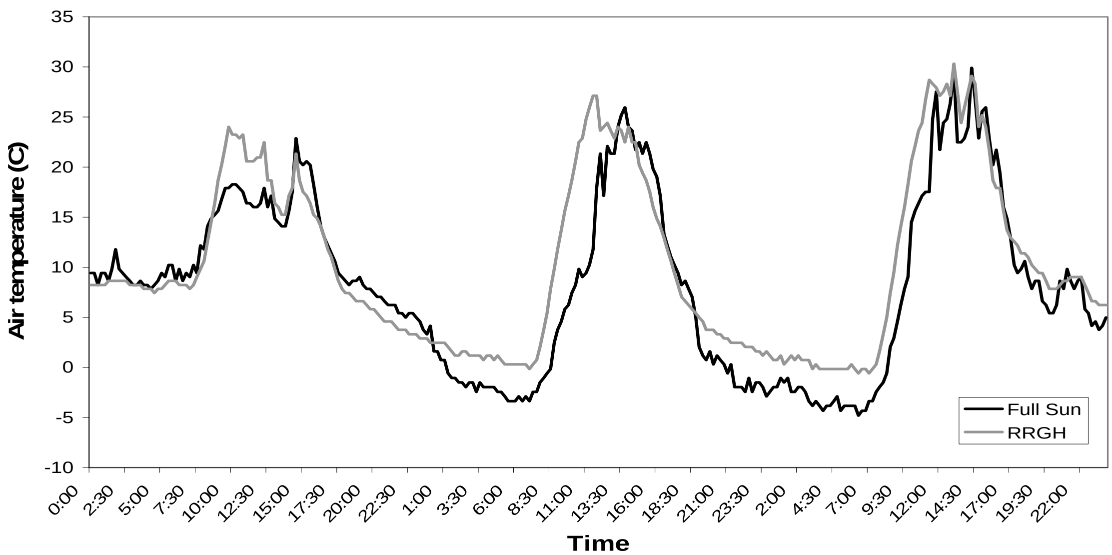

Figure 3.3.3.5. Air temperature at time of frost in three environments on November 22 to 24, 2003.

Substrate temperatures in the RRGH were not different between shade environments and have been combined for the RRGH per production system. Throughout the summer months, temperatures in rockwool closely followed air temperatures. It is important to note that the rockwool temperature sensor was located in the rockwool block at this time and not in the rockwool slab, which likely affected results. In the future, it would be more accurate to measure slab temperature which more accurately represents the root zone of the mature crop.

Rockwool block temperatures were regularly up to 10 ºC warmer than the field soil during the day, and up to 8 ºC warmer than containers (Figure 3.3.3.6). Containers regularly reached temperatures up to 12 ºC warmer than the field soil during the day (Figure 3.3.3.6), with a delay time in heating as well as cooling. Containers were warmer than rockwool in the evening and through the night (Figure 3.3.3.6). Field soil temperatures also showed a delay in heating and cooling when compared to air temperatures, but never reached maximum air temperatures as did the other substrates.

Summer substrate temperatures in the field and containers (Figure 3.3.3.7) had a lag time as they warmed up during the day and cooled at night compared to the more rapid rates of increase and decrease in rockwool blocks. The temperature in the rockwool slab had a lesser rate of increase and decrease in diurnal temperature change, more similar to the trends seen in containers (Figure 3.3.3.8). Therefore the rockwool slabs may not have shown the same temperature trends as the rockwool blocks, but slabs were not measured during summer. Field soil temperatures fluctuated about 10 °C per day, and were 10 °C or more cooler than air temperatures at that time of year.

During the fall, when outdoor air temperatures still regularly reached 35 °C and above, substrate temperatures in the containers and in the field rarely exceeded 20 °C (Figure 3.3.3.9). The rockwool temperatures were greater than both the containers and field soil possibly due to location of the temperature sensor in the rockwool block. During this time of year, the rockwool temperatures were similar to air temperatures in terms of the rate of increase and decrease throughout the day, without reaching maximum air temperatures as seen in summer. Substrate temperatures in the RRGH at the time of frost were similar to the field at the end of November, but tended to be warmer than field soil temperatures during the day (Figure 3.3.3.8). Productivity of basil in rockwool and containers indicated that root zone temperatures up to 45 ºC were not detrimental to yield of both basil cultivars, although root zone temperature above 37.8 °C have been reported to reduce shoot growth and can cause plant death (Mathers, 2003).

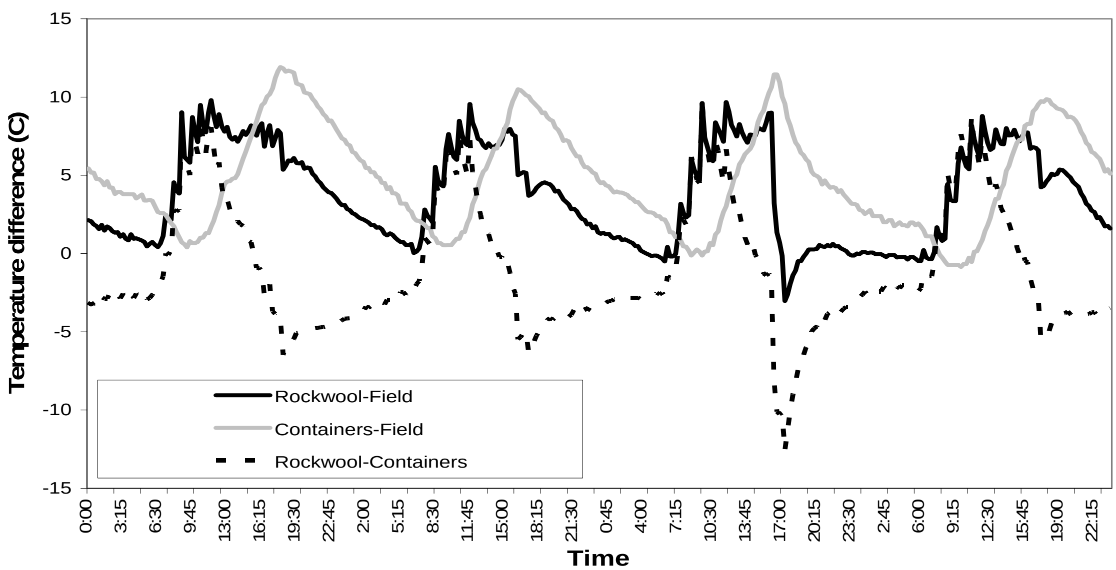

Figure 3.3.3.6. Substrate temperature differences (°C) between three environments from July 27 to 30, 2003.

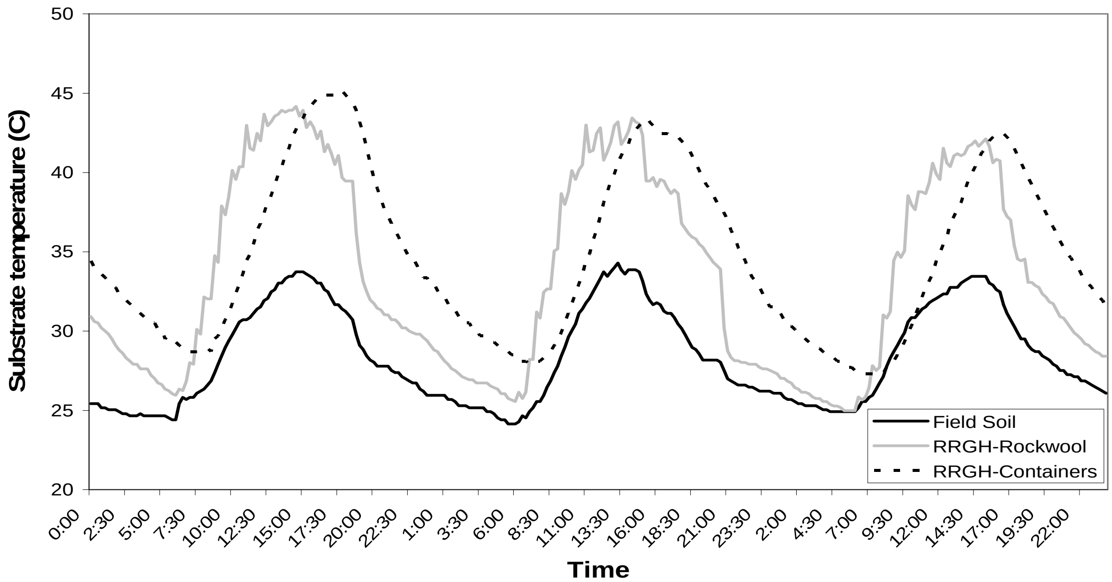

Figure 3.3.3.7. Summer substrate temperatures from July 24 to 26, 2003.

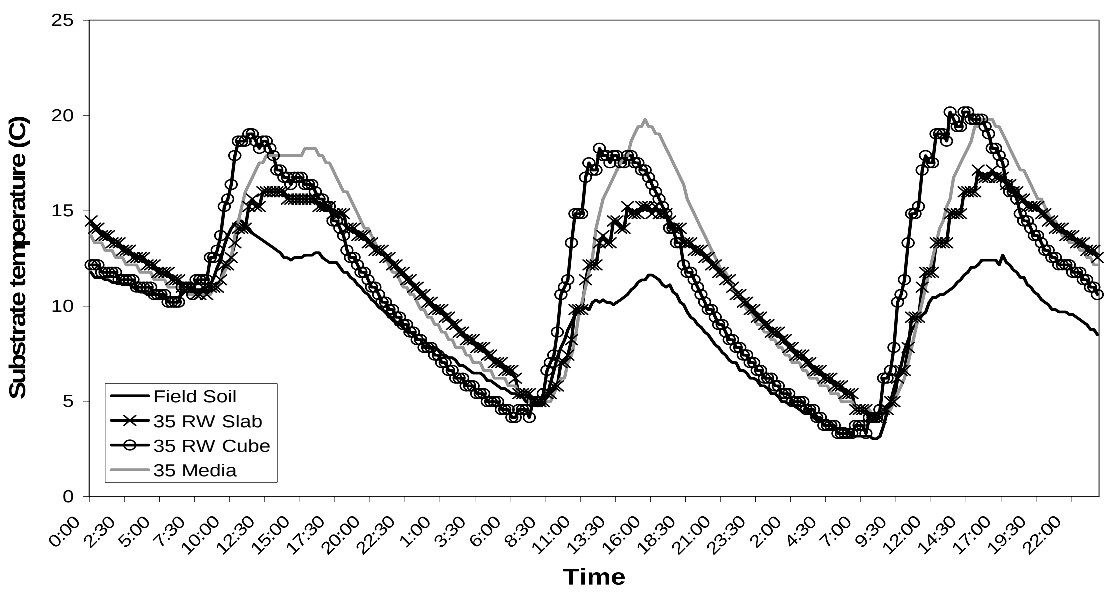

Figure 3.3.3.8. Substrate temperatures at time of frost: November 22-24, 2003.

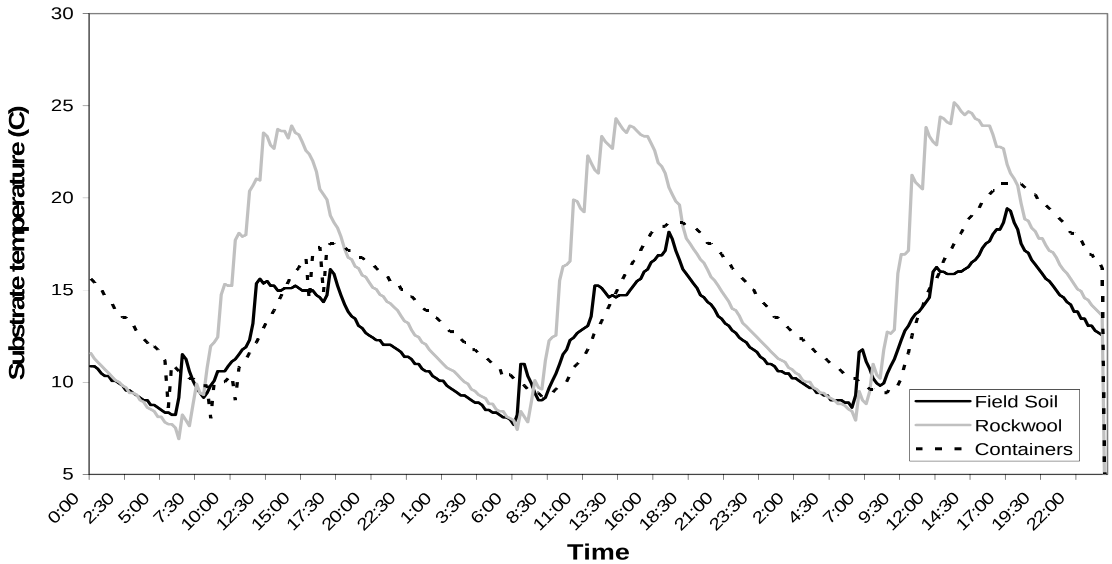

Figure 3.3.3.9. Fall substrate temperatures from November 7 to 9, 2003.

3.4. Conclusions

Fresh weight data indicated that all RRGH treatments produced significantly more biomass of higher quality than plants grown in the field. Within the RRGH, biomass production of both basil cultivars was primarily affected by production system and little by shade. Within the RRGH, rockwool was superior for basil production, most likely due to the properties of the substrate which resulted in more fertigation events and therefore greater nutrient and oxygen availability. Overall, the retractable roof greenhouse produced high quality basil for the fresh culinary market. For year-round production of basil, supplemental heating would be necessary once outdoor temperatures reach close to 0 °C. Further research needs to evaluate roof and wall strategies, the economic feasibility of producing basil in a retractable roof greenhouse in rockwool culture and the feasibility of supplemental heating for year-round production of this warm weather herb.

4. 2004 BASIL TRIAL: HYDROPONIC BASIL PRODUCTION IN TWO PRODUCTION SYSTEMS AND THREE ENVIRONMENTS

4.1. Introduction

Results from the 2003 basil trial indicated the potential for greater production of high quality basil in the retractable roof greenhouse (RRGH) during the summer compared to full sun production in soil. However, production in both environments was limited by low temperatures in late fall. These results led to a refinement of the experimental procedures in 2004 to further test the role of cultural practices and environmental conditions for basil production.

Raised beds and a vertical stacked pot production system were tested in the 2004 trial within the RRGH and in full sun. Both systems represent commercial cultural practices and are less expensive than the rockwool system over time as the systems can be re-used. Perlite was also used in all environments and systems so that production system results were not complicated by differences in substrate type.

After evaluating the response of basil to the two stationary shade environments of the RRGH in the 2003 basil trial, the focus shifted to an evaluation of roof curtain control strategies to take advantage of the changeable environments of the RRGH. Three roof curtain control strategies were evaluated in the 2004 trial based on control by air temperature, solar radiation or mean radiant temperature of a globe thermometer.

4.2. Materials and Methods

4.2.1. Cultural Practices

Basil (*Ocimum basilicum* L.), 'Genovese Compact' was seeded on May 4, 2004 (Johnny's Selected Seeds, Winslow, ME). Cell trays (128 cells per tray) were filled with Sunshine Mix #1 (Sun Gro, Bellevue, WA) and perlite (Therm-O-Rock, Chandler, AZ) (1:1 vol.), and 2 seeds were planted per cell. Trays were placed on benches in a greenhouse with mist applied for 15 seconds every hour during the day. Basil was thinned to one plant per cell once the first set of true leaves had developed. Once thinned, a half strength nutrient solution (recipe in Section 3.1) was applied daily. In order to harden off plants before moving them from the environmentally controlled greenhouse to full sun or the RRGH, mist was turned off and plants were fertigated through sub-irrigation. On June 21, 2004, 48 days after seeding plants were transplanted into three different environments: full sun outdoors, and two retractable roof greenhouse environments. Within the RRGH, basil was transplanted under either a clear woven polyethylene roof providing approximately 35% shade, or under a white woven polyethylene roof providing approximately 50% shade.

In all three environments basil was transplanted into two production systems, either a raised bed or a vertical growing system. Each raised bed was constructed of wood boards (2.5 cm x 15.2 cm), 3.1 m in length and 0.9 m in width set directly on the ground, over a black ground cover in full sun and over a white ground cover in the RRGH. Each bed was lined with a 0.15 mm polyethylene liner with drainage slits in the bottom. Each raised bed was filled with medium grade perlite (Therm-O-Rock West Inc., Chandler, AZ) to a depth of 15 cm. Beds were covered with white netting to prevent the perlite from being blown by strong winds. Plants were placed into three rows within each raised bed, 10 plants per row. Plants were spaced 30 cm apart within and between rows. The 8 middle plants of each row were considered one experimental unit. Including 30 cm around the perimeter of each raised bed, the density of plants in the raised beds was 7.3 plants m^{-2}.

The vertical system used in the experiment was Verti-Gro™ (Verti-Gro, Summerfield, FL) which consisted of 6 square shaped pots with a volume of 5 L per pot stacked on edge to create a tower. Towers were supported by reinforced bar, conduit (1.27 cm diameter) and PVC pipe (1.9 cm diameter). Reinforced bar, 90 cm in length, was driven into the ground to 45 cm. Conduit, 1.5 m in length was slipped over the above ground portion of rebar. PVC pipe of the same length was placed over the conduit to keep the nutrient solution from coming in contact with the conduit and to fit the holes in the pots of the vertical system containers. Drainage holes in the bottom of each pot allowed the fertigation solution to percolate through the entire system. One plant was placed in each of the four corners of each pot, with the entire tower holding 24 plants. The vertical system had a density of 16 plants m^{-2}. Each tower occupied an area of 1.5 m^2, which provided adequate space for access around each tower.

Plants were fertigated through an injection system (A12 Advantage, Dosmatic, Carrollton, TX) that supplied nutrients with each irrigation. The nutrient solution used was the same as described in Section 3.1. An EC of 1.8 dS m^{-1} and a pH of 6.3 were maintained throughout the experiment. Fertigation was applied through 1.25 cm white on black polyethylene tubing (Toro, Bloomington, MN). White on black tubing was used to possibly reduce excessive temperatures in the irrigation lines. Each vertical tower had two 18.9 L h^{-1} emitters (PC-05 10-32, Rain Bird, Tucson, AZ) attached to the white on black poly tubing and spaghetti tubing staked into the top pot. In each raised bed, the white poly tubing was attached to Ro-Drip (Roberts Irrigation Products Inc., San Marcos, CA), which applied 68.5 L h^{-1}.

Fertigation events were controlled by the Argus computer control system (Argus, White Rock, British Columbia, Canada) using the quantum sensors (LI-190 Quantum sensor, Li-Cor, Lincoln, NE) located in the RRGH environments, and the pyranometer (LI-200 Pyranometer, Lincoln, NE) in full sun. In each environment, plants in either a vertical tower or a raised bed were irrigated for five minutes based on accumulated light. Accumulated light by the Argus was calculated by dividing the instantaneous light intensity by 3600 seconds and adding the values every second. Once the accumulated reading reached the threshold setting of 400 W m^{-2} in full sun, or 800 µmol m^{-2} s^{-1} in the RRGH, an irrigation event was triggered. Irrigation based on accumulated light provided consistency between the three environments, and accounted for changes in weather. Initially, immature plants were fertigated for a three minute duration until the first harvest after which the five minute duration was maintained throughout the rest of the study.

4.2.2. Experimental Design and Analysis

Basil plants in two production systems were arranged in a split block design in each of the three environments (Figure 4.2.2.1). Each environment contained three raised beds and three vertical towers, with one block represented by one raised bed or one tower. Within each block were three experimental units, consisting of 8 plants each. The experimental units in the towers were set up to detect possible differences within the tower due to light and nutrient distribution. Raised beds and towers were blocked west to east in all environments in order to detect any differences due light distribution that may have been caused by the 20% roof opening used for ventilation when the roof was in the closed position. Data was analyzed using JMP IN (SAS Institute, Inc., Cary, NC). Means were analyzed using ANOVA and mean separations were calculated by Tukey's HSD.

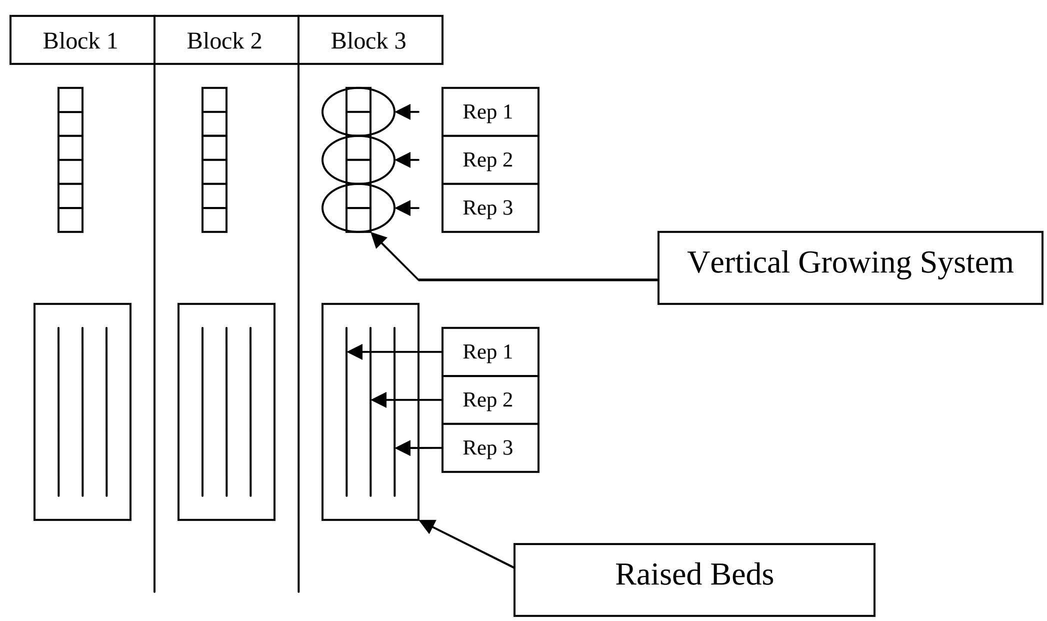

Figure 4.2.2.1. Layout of production systems in each of the three environments.

4.2.3. Environmental Monitoring

The environmental data collected within the three environments included the following: PPF (in the RRGH), solar radiation (in full sun), air temperature, substrate temperature, irrigation volume, leaf temperature, globe temperature, and roof and wall position throughout the day. Data were recorded by the Argus computer control system and were recorded continually by a computer. The quantum sensors used in each environment of the RRGH were located on a cross bar, directly below the roof curtain. They were located in the west side of each bay, so that when the roof was closed except for the 20% ventilation gap on the east side of each bay, the sensor would monitor the shade that the majority of the crop experienced. The full sun pyranometer was located on a weather station directly above the roof curtain at a height of 4 m above the ground on the east side of the retractable roof greenhouse. All environmental data recorded were saved in 15 minute averages.

Air temperature sensors for all three environments were thermistors in aspirated chambers with aspiration rates of 3 m s^{-1} (Argus, White Rock, British Columbia, Canada). One air temperature sensor was located in each of the retractable roof greenhouse environments at 2.5 m above the ground. The full sun temperature sensor was located on the east side of the greenhouse as part of the weather station 4 m above the ground.

Substrate temperature sensors were thermistors that recorded 15 minute averages. Two substrate temperature readings were taken per production system per environment. Substrate temperature sensors were located within the root zone at an approximate depth of 5 cm, approximately 5 cm from the base of the basil plant. Within the towers, sensors were located in the second pot from the top of the tower and the second pot from the bottom of the tower at a depth of 5 cm.

Leaf temperature sensors were constructed from thermocouples. A Campbell data logger (CR 10x datalogger, Campbell Scientific, Inc., Logan, UT) was used to record leaf temperature sensors, as the Argus computer control system is not compatible with thermocouples. Fifteen minute averages were used to record leaf temperatures. Thermocouple wire (18-gauge) was connected to the Campbell datalogger and connected to 30 gauge fine wire thermocouple using Type T thermocouple connectors (Omega, Stamford, CT). The tips of the fine wire thermocouple were stripped and twisted together. The tip of the twisted portion was cut so that there was only one connection point between the copper and constantine which were then soldered together. Then all exposed copper and constantine was painted with nail polish. The tip of the 30-gauge fine wire thermocouple tip was taped to the underside of a sun-lit leaf with duct tape. One leaf temperature sensor was located on the underside of a sunlit leaf in each production system in each environment.

Two mean radiant temperature black globe sensors were constructed (Figure 4.2.3.1). One was located above the roof curtain on the east side of the retractable roof greenhouse in full sun at the weather station. The second black globe thermometer was located under the clear woven polyethylene roof cover. Black globes were constructed from 10 cm diameter copper hemispheres cut in half (Standard Type A Toilet Tank Copper Float, Ace Hardware, Tucson, AZ) that were spray painted with a black matte paint (Painter's Touch Flat Black, Rust-Oleum, Vernon Hills, IL). Inside the hemisphere, a copper coil was soldered into the center to hold the thermistor. The thermistor was placed into the copper coil. The hemisphere was filled with insulation foam (GreatStuff, Dow Chemical Company, Marietta, GA). The finished black globe thermometer was then mounted on a wood board and placed into the two environments. Data was collected as 15 minute averages by the Argus system. The outdoor globe on the weather station was used for roof control of the retractable roof greenhouse. The indoor globe was used to record the conditions inside the RRGH.

Figure 4.2.3.1. Construction of globe thermometer. Internal view of copper coil for insertion of thermistor (left) (prior to addition of thermistor and insulation foam) and view of completed globe thermometer (right).

The RRGH roof was controlled throughout the study using each of the three control strategies. Roof and wall movements were monitored and recorded by the Argus system.

For irrigation control, a separate solenoid was used for each production system in each environment and was controlled and recorded by the Argus. Irrigation volumes were calculated on a daily basis based on the length of time solenoids were activated.

4.2.4. Basil Data Collection

Plant data recorded throughout the study included fresh weight, shoot dry weight, root dry weight, leaf area, internode length, photosynthesis, percent flowering, stomatal density and plant survival.

Fresh weight was recorded weekly from July 13, 2004 to September 28, 2004. Basil plants were harvested early in the morning to prevent any wilting during harvesting. The first harvest was recorded five weeks after transplant once canopies had fully developed. Basil plants were cut back to a height of 20 cm at each harvest to ensure uniformity. Harvested shoots typically consisted of 3 to 5 leaf pairs. Weekly harvests prevented basil plants from flowering under summer conditions.

Leaf area of basil shoots were recorded bi-weekly from July 20, 2004 to September 28, 2004. For each leaf area measurement, a representative shoot was chosen from each experimental unit in all environments and production systems. Mature leaves longer than 4 cm were measured using a Li-Cor Leaf Area Meter (LI-3100 C Area Meter, Li-Cor, Lincoln, NE).

Shoot dry weights were recorded once throughout the study. Shoots from each replication in all environments and production systems were measured. Fresh weights for the selected shoots were recorded on August 10, 2004. Shoots were placed in paper bags and dried at 60 °C for 72 hours. Dry weights were recorded, and fresh weight to dry weight ratios were calculated.

Root dry weights were recorded once at the end of the study, on November 1, 2004. Root weight was recorded for the raised beds, and two root masses per block per environment were measured. After completion of the experiment, all plants were cut at the base and removed. Roots were collected by cutting a 30 cm by 30 cm section around the base of each plant. All stem matter was removed. Roots were separated from the perlite substrate by washing them through a screen. After isolating the roots, they were placed in brown paper bags and dried for 72 hours at 60 °C. Any remaining perlite that became visible after drying was removed, and root dry weights were recorded.

Percent flowering was recorded for all replications in all production systems and environments weekly beginning at the sixth harvest, once mature plants began to flower regularly.

Internode lengths of all experimental units under all production systems and environments were recorded bi-weekly. Internode lengths were measured on the internode below the most recently fully expanded leaves at the top of the canopy.

Photosynthesis measurements were recorded twice during the study on clear sky days August 26, 2004 and September 23, 2004. Photosynthesis measurements were recorded only on basil plants grown in raised beds. On August 26, 2004, five measurements were taken per environment, and on September 23, 2004, ten measurements were taken per environment. Photosynthesis measurements were recorded using a Ciras-2 photosynthesis meter (PP Systems, Amesbury, MA). Sunlit leaves at the top of the canopy were measured under ambient light conditions. On both days of measurement, photosynthesis readings were recorded at 0900, 1200 and 1500 HR. In the RRGH, the roof was closed at all times of measurement on August 26. On September 23, the roof was open for the 0900 HR measurement and closed for the 1200 HR and 1500 HR measurements. The Ciras-2 was set to a stomatal ratio of 50/50 on the abaxial/adaxial leaf surfaces. Carbon dioxide was supplied through the cuvette at a flow rate of 400 $\mu mol\ mol^{-1}$.

Stomatal densities were recorded once after completion of the experiment on September 28, 2004. Five shoots from basil grown in raised beds in each environment served as the representative shoots and fully expanded sunlit leaves from each environment were measured. Stomates on both the abaxial and adaxial surfaces were counted. Both surfaces of the leaf, avoiding leaf veins were painted with nail polish and left to thoroughly dry. Once dry, the nail polish was peeled off the leaf and the side of the nail polish that faced the leaf was placed face up on the slide. For each of the five leaves per environment, three sections of 1 mm^2 each were counted for stomates, providing 15 replications per environment. In order to accurately count all stomates, microscope images were projected on a computer screen using a camera attached to the microscope. An image 1 mm^2 in size was projected on to the computer screen with a transparency taped over the screen. Stomates were marked on the transparency as the focus zoomed up and down in order to bring all stomates into view. Transparency marks were then counted to provide the total number of stomates per replication.

4.2.5. Retractable Roof Greenhouse Control Strategies

Recommended control strategies for RRGH suggest exposing the crop to full sun solar radiation in the early morning and late afternoon hours (Vollebregt, 2002). Additionally, air temperature was a poor indicator and therefore insufficient method of controlling plant temperature which is critical for manipulating physiological processes in tomato and pepper (Suarez-Romero et al., 2004).

Three control strategies were used to control the movement of the roof curtains of the retractable roof greenhouse. Full sun conditions had no control strategy and were representative of ambient conditions. In the RRGH, the three strategies were controlled using sensor inputs into the Argus computer control system which then controlled the motors to position the roof and wall curtains.

The three strategies were repeated four times each throughout the study, and each strategy repetition lasted one week. Each weekly harvest represented the previous week of plant growth as affected by the environmental conditions due to roof curtain control strategy. Control strategies began one week prior to the first harvest on July 6, 2004. The three strategies included air temperature based control (Strategy I), solar radiation based control (Strategy II), and outdoor black globe thermometer based control (Strategy III) (Table 4.2.5.1). Each strategy was repeated two consecutive weeks, and then an additional two consecutive weeks later in the season to create a total of four repetitions. The harvests for Strategy I were measured on July 13, July 20, August 24, and August 31, 2004. The harvests for Strategy II were measured on July 27, August 3, September 7, and September 14, 2004. The harvests for Strategy III were measured on August 10, August 17, September 21, and September 28, 2004.

Table 4.2.5.1. RRGH control strategies; roof closure setpoints and harvest dates.

Strategy	Roof closure setpoint	Harvest dates
I: Air Temperature	> 20 °C	July 13, July 20, Aug 24, Aug 31
II: Solar Radiation	> 700 W m^{-2}	July 27, Aug 3, Sep 7, Sep 14
III: Globe Thermometer	> 35 °C	Aug 10, Aug 17, Sep 21, Sep 28

Each of the three strategies used outdoor sensors for control. Since opening and closing the roof curtains is dependent upon whether ambient conditions are desirable for the basil crop, outdoor sensors need to be used to determine when to open the roof and wall curtains. The air temperature sensor, pyranometer, and black globe thermometer used for control were all located on the weather station above the roof curtain on the east side of the retractable roof greenhouse.

Although the three strategies used throughout the experiment manipulated the roof curtain position, the wall curtains remained on air temperature control throughout the study. Overrides for the roof and wall curtains also remained the same independent of the different roof curtain control strategies. The clear woven and white woven roof curtains were controlled the same despite the different shade environments they provided.

The wall curtains of the retractable roof greenhouse were controlled by the air temperature sensor on the weather station. Since light intensity and temperatures were high throughout the duration of the study, the objective was to maximize ventilation. Therefore, the walls were set to open 100% when the air temperature reading was greater than or equal to 20 °C, and to close when air temperature reading were below 20 °C, except for the ventilation gap.

Overrides for the system included rains, high winds and nighttime hours. The entire structure, independent of setpoints and strategies was set to completely close between 2300 and 0400 HR. This strategy was followed for safety as well as to control for light in cases where a bright moon or nearby construction at night could trigger the roof to open under strategy II. The entire structure was also set to close during rains, and/or when wind speeds exceeded 30 km h^{-1}. The computer was also programmed for a 10 minute delay before opening or closing a curtain based on a setpoint to minimize constant opening and closing cycles which cause unnecessary wear on the structure.

Strategy I, air temperature control for roof curtain position used the outdoor aspirated air temperature sensor located on the weather station. The air temperature based roof control strategy used the same set points that the walls used throughout the duration of the study. When the outdoor temperature was less than 20 °C, the roof was open 100%. When the outdoor temperature sensor was greater than 20 °C, the roof was closed, except for a ventilation opening of 20%.

Strategy II, light based control used a setpoint for the outdoor pyranomter to control roof movement. As soon as light reached the sensor, the roof opened 100%. Once the light intensity was greater than 700 W m^{-2}, the roof was closed except for a ventilation opening of 20%. After midday, once the light level dropped below 700 W m^{-2} the roof was 100% open for the remainder of the day until sunset. Once the pyranometer could not detect any more light, the roof was completely closed until sunrise.

Strategy III used a black globe thermometer mounted on the outdoor weather station to control roof curtain position. When the globe temperature was less than 35 °C, the roof was 100% open. When the globe temperature was greater than 35 °C, the roof was closed except for the 20% ventilation gap. This strategy was based upon the ability of the globe thermometer to represent leaf temperature. The threshold of 35 °C was determined based on preliminary correlations between globe and leaf temperatures in order to prevent leaf temperatures in excess of 30 °C, which would possibly inhibit photosynthesis of basil.

4.3. Results and Discussion

4.3.1. Fresh Weight Production in Three Environments and Two Production Systems

Overall, basil biomass accumulation under three environments and two production systems, and three roof control strategies was affected by production system ($p<0.001$). Basil grown in raised beds produced almost double the fresh weight as basil grown in the vertical growing system on a per plant basis in all three environments (Table 4.3.1.1). Due to the large differences in productivity of basil within the two production systems, the systems were treated separate for further analysis. In addition, the RRGH environments have also been separated from the full sun environment to quantify the effects of roof control strategy on biomass accumulation, as no roof control treatments were applied to the full sun environment. Analysis of fresh weight has been evaluated between the early season (July 6 to August 16, 2004) during the first rotation of control strategies compared to the late season (August 17 to September 27, 2004) during the second rotation of control strategies.

In comparing fresh weight production of basil throughout the study in the three environments for each production system, basil grown in raised beds was not affected by environment (p=0.7653), whereas basil grown in the vertical growing system was influenced by environment (p=0.0038). These overall means include differences due to roof control strategy (Table 4.3.1.2).

Table 4.3.1.1. Weekly fresh weight per plant of basil grown in two production systems in three environments.

Production System	Fresh Weight (g)
Raised Beds	89.5 a*
Vertical Growing System	45.2 b

*Means within the table followed by a different letter are significantly different at p<0.05.

Table 4.3.1.2. Weekly fresh weight (g) per plant of basil grown in two production systems in three environments.

Environment	Raised Beds	Vertical Growing System
Full Sun	88.9 a*	47.8 a
Clear Woven	88.0 a	40.4 b
White Woven	91.5 a	47.5 a

*Means within a column followed by a different letter are significantly different at p<0.05.

Basil production under different treatment conditions was additionally affected by season, maturity, and potential transplant shock in full sun. Separating the production period between early and late season resulted in differences in biomass accumulation. The environmental conditions during the early and late season were very similar, making maturity a more likely cause of different trends between early and late season. Figure 4.3.1.1 illustrates the initial maturity effect in full sun, whereas the delay in maturity in the RRGH was less pronounced during the first four weeks of production. Transplant shock under full sun conditions appears more likely as the cause of the seasonal differences. Low fresh weight at the second harvest in the RRGH was due to over harvesting at the first harvest.

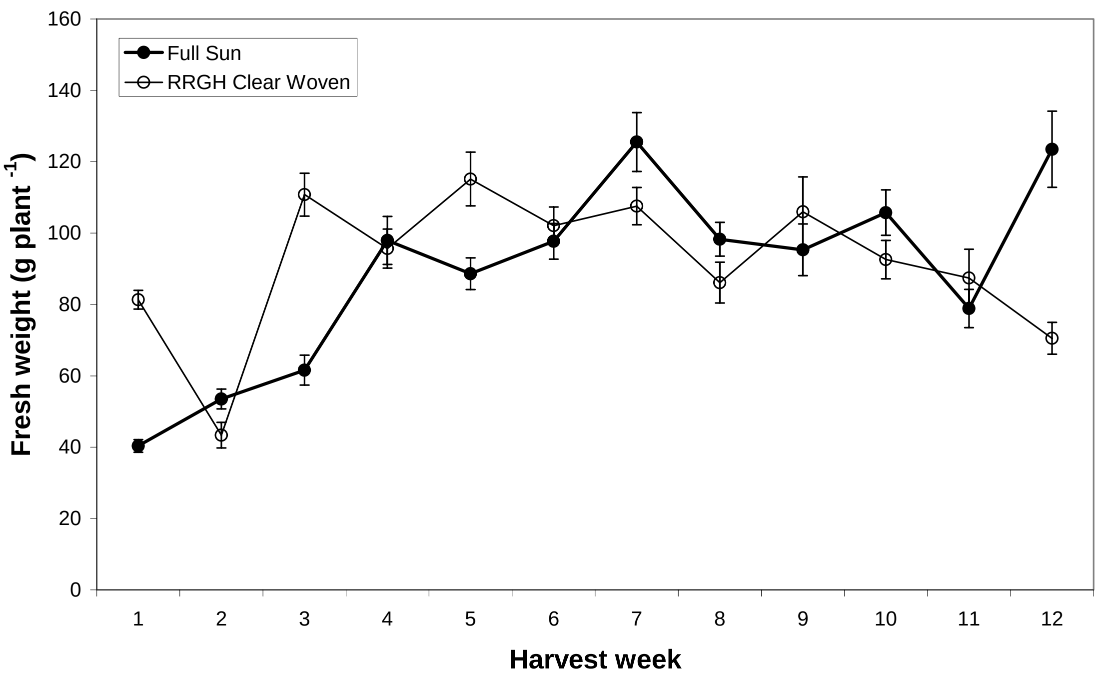

Figure 4.3.1.1. Weekly fresh weight of basil grown in raised beds or in a retractable roof greenhouse.

4.3.2. Fresh Weight of Basil Grown in Raised Beds in the RRGH under Three Roof Control Strategies Compared to Full Sun

Biomass accumulation of basil grown in raised beds in the RRGH was affected by roof control strategy (p=0.0003) and not by RRGH environment or by seasonal differences. Under both RRGH environments, roof control based on solar radiation or globe thermometer increased basil biomass production by 30% compared to roof control based on air temperature (Table 4.3.2.1). Roof control based on both solar radiation and the globe thermometer opened the roof for longer periods of the day than control based on air temperature and therefore provided more light to the canopy.

Biomass accumulation of basil grown in raised beds in full sun was affected by seasonal differences (p<0.0001). Basil produced 43% more biomass in late season compared to early season (Table 4.3.2.2). Plants grown in full sun were exposed to high solar irradiance and air temperature during the early season possibly causing transplant shock which slowed their establishment and maturity in the beginning of the season.

Table 4.3.2.1. Weekly fresh weight per plant of basil grown in raised beds in the RRGH using three roof control strategies.

Strategy	Fresh Weight (g)
I: Air Temperature	74.8 b*
II: Solar Radiation	95.0 a
III: Globe Thermometer	99.4 a

*Means within the table followed by a different letter are significantly different at p<0.05.

Table 4.3.2.2. Weekly fresh weight per plant of basil grown in raised beds in full sun during two seasons.

Season	Fresh Weight (g)
Early Season (July 6 to August 16, 2004)	73.3 b*
Late Season (August 17 to September 27, 2004)	104.5 a

*Means within the table followed by a different letter are significantly different at $p<0.05$.

4.3.3. Fresh Weight of Basil Grown in a Vertical Growing System in the RRGH under Three Roof Control Strategies Compared to Full Sun

In the RRGH, basil biomass production in the vertical growing system was affected by the three RRGH roof control strategies ($p=0.0065$), the two RRGH environments ($p<0.0001$), and by seasonal differences ($p<0.0001$). Roof control strategy based on solar radiation and the globe thermometer increased basil biomass accumulation by 14% compared to roof control based on air temperature (Table 4.3.3.1). Basil grown under the clear woven roof produced 18% more biomass than under the white woven roof (Table 4.3.3.1). Late season productivity was also 25% greater than early season (Table 4.3.3.1). Plants in the high density vertical growing system were predominantly affected by solar radiation. Biomass accumulation in the RRGH increased under the clear woven roof, and also increased by roof control strategies that provided more light to the canopy throughout the day. Early and late season differences in the RRGH are possibly due to maturity of the crop.

Table 4.3.3.1. Weekly fresh weight (g) per plant of basil grown in a vertical growing system in the RRGH using three RRGH roof control strategies, two RRGH environments, during early and late season. Significant main effect fresh weights are presented.

Strategy	Fresh Weight (g/plant/week)
I: Air Temperature	40.3 b*
II: Solar Radiation	46.2 a
III: Globe Thermometer	45.8 a
Environment	
Clear Woven	47.7 a
White Woven	40.4 b
Season	
Early	39.1 b
Late	49.0 a

*Means within a main effect followed by a different letter are significantly different at $p<0.05$.

Basil grown in vertical towers in full sun was affected by seasonal differences in productivity ($p<0.0001$). Productivity in the vertical growing system was 78% greater in late season compared to early season (Table 4.3.3.2). The low early season yields were accompanied by immature plants and the higher late season yields were accompanied by mature plants with more room to develop due to low survival rates of basil in the vertical system in full sun.

Table 4.3.3.2. Weekly fresh weight per plant of basil grown in a vertical growing system in full sun during two seasons.

Season	Fresh Weight (g)
Early (July 6 to August 16, 2004)	34.4 b*
Late (August 17 to September 27, 2004)	61.3 a

*Means within this table followed by a different letter are significantly different at $p<0.05$.

Biomass accumulation in the vertical growing system was lower on a per plant basis compared to the raised beds, but the advantage of the vertical system is the increased productivity per unit area. 'Genovese Compact' yields were 2.6 kg/m^2/month in raised beds and 2.9 kg/m^2/month in the vertical system. The 12% increase in productivity in the vertical system is important for commercial applications despite the decreased per plant productivity due to the characteristics of the vertical system.

4.3.3.1. Basil fresh weight within the vertical growing system affected by pot position within the tower

Within the RRGH, pot position in the vertical system significantly affected biomass accumulation ($p<0.0001$) with the top pots yielding 23% more compared to the middle and bottom pots (Table 4.3.3.1.1). In full sun, pot position affected biomass accumulation ($p<0.0001$) with top pots producing 58% more than plants in the middle and bottom pots.

Table 4.3.3.1.1. Weekly fresh weight (g) per pot position of basil plants grown in the vertical growing system in the RRGH and in full sun.

Pot position	RRGH	Full Sun
Top	50.1 a*	63.4 a
Middle	41.9 b	43.6 b
Bottom	39.5 b	36.4 b

*Means within a column followed by a different letter are significantly different at $p<0.05$.

The effects of pot position remained the same regardless of roof control strategy, or environment within the RRGH, and by season for the RRGH and full sun. Middle and bottom pot positions had reduced yields compared to top pot positions most likely due to reduced light availability at lower levels in the vertical column. The larger difference between full sun and the RRGH was due to low plant survival of plants in the top pot positions in full sun. In full sun, plants in the top pots had greater light availability as well as more room to grow due to lower plant density after survival rates dropped.

4.3.4. Comparison of Basil Yields

Little information is available on typical fresh weight yields of basil cultivars. Commercial production estimates under ideal growing conditions and cultural practices for greenhouse hydroponic growers are 4.8 kg/m^2/month (1 lb/ft^2/month) (Morgan, 2001). The highest yields obtained in the present research study were 2.9 kg/m^2/month in the vertical system and 2.6 kg/m^2/month in raised beds. Lower planting density, lower nitrogen in the fertigation solution, and lower yields of ‘Genovese Compact’ compared to ‘Genovese’ may all have contributed to the lower yields found in the present study compared to commercial estimates.

Research based studies generally report yields lower than optimal commercial yields. Nelkin and Schuch (2003) reported production rates for ‘Genovese’ basil of 89 g/plant/week when grown in rockwool and 63 g/plant/week when grown in containers with a peat/perlite mixture under either 35% or 50% shade. Production rates of basil in the RRGH grown in raised beds were equal to rates of basil grown in rockwool, and basil grown in the vertical growing system produced 29% less than basil grown in containers on a per plant basis. The advantage of the vertical system relies on increased yields on a per area basis rather than per plant basis.

The Verti-Gro™ system has been evaluated at the North Florida Research and Education Center at Suwannee Valley. ‘Genovese Compact’ basil grown in a greenhouse in the vertical system over 15 weeks produced on average 14.2 g/plant/week (Hochmuth and Leon, 1999). In the RRGH in Arizona, ‘Genovese Compact’ in the vertical system produced more than double the reported yields from Florida. Differences are likely a result of the high light intensities in Arizona during the summer production period compared to winter production in Florida although neither light intensities nor integrated PPF values for the Florida production were reported. Daytime/nighttime temperatures in the Florida greenhouse were 35/15 °C, which showed similar diurnal fluctuation compared to the Arizona RRGH through most of the production period, therefore assuming lower light intensity as a more probable reason for the differences in production.

Succop and Newman (2004) reported yields of basil grown in perlite as 29 g/plant/week during the 1996 trial and 13 g/plant/week during the 1997 trial. Basil grown in perlite produced similar biomass compared to rockwool or peat based media with either conventional or organic nutrient solution over 18 weeks of harvesting in a greenhouse in Colorado during the 1996 study, but significantly less during the 1997 study. Basil grown in the present study within the RRGH in perlite produced almost six times more than the 1997 trial yields of Succop and Newman when grown in raised beds and two and a half times more when grown in the vertical system. Lower light intensities in Colorado may have contributed to the low yields in their trials, but the further reduction of yield in perlite during the 1997 trial was not discussed. Daytime/nighttime temperatures in the Colorado greenhouse were 29/20 °C.

Tesi et al. (1995), reported yields of 15 g/plant for ‘Genovese’ basil in a heated greenhouse in Italy. In a planting density trial, Smith et al. (1997) reported basil yield up to 37 g/pot at a density of 16 plants per pot (pot size reported as 0.41 square section 9.5 cm high pots) 5 weeks after sowing. In a substrate trial, Smith et al. (1997) reported the highest basil yields in perlite compared to peat and coir, with yields of 47 g/pot, averaging all planting densities in the trial from 2 to 16 plants per pot.

4.3.5. Morphological, Physiological, Flowering and Survival Results

Leaf area of basil was affected by environment ($p<0.001$, Table 4.3.5.1). Leaf area of basil grown in the RRGH was 33% greater than in full sun. The increased light in full sun decreased leaf area for both production systems compared to the shaded environment in the RRGH which promotes leaf area expansion. Leaf area under cover compared to full sun has been shown to increase for many species (Boardman, 1977), and increase the marketable quality of leaf crops due to thinner, more tender leaves (Gimenez et al., 2002).

Internode lengths of basil were affected by environment ($p<0.001$, Table 4.3.5.1), and followed the same trend as leaf area. Internode lengths were 19% more elongated in both RRGH environments compared to full sun. Internode lengths became elongated similar to leaf area expansion due to increased shade.

Table 4.3.5.1. Leaf area (cm^2) and internode length (cm) of basil grown in three environments.

Environment	Leaf Area	Internode Length
Full Sun	16.3 b*	3.4 b
Clear Woven	21.4 a	4.0 a
White Woven	22.0 a	4.1 a

*Means within a column followed by a different letter are significantly different at $p<0.05$.

Percent of flowering shoots were recorded as an indicator of quality, as flowers create a bitter flavor in the leaves. The percentage of flowering shoots at each harvest indicated that basil was affected by environment in raised beds ($p<0.0001$) and in the vertical growing system ($p<0.0001$). Basil grown in full sun or under the clear woven roof material had 275% more flowers each week than basil grown under the white woven roof material (Table 4.3.5.2). Basil grown in the vertical system had 100% more flowering in full sun compared to the clear woven roof and 430% more compared to the white woven roof (Table 4.3.5.2). The high percentage of flowering shoots throughout the study in full sun decreased the marketability of those shoots.

Table 4.3.5.2. Percent flowering of basil grown in two production systems in three environments.

Environment	Raised Beds	Vertical System
Full Sun	19 a*	32 a
Clear Woven	11 a	16 b
White Woven	4 b	6 c

*Means within a column followed by a different letter are significantly different at $p<0.05$.

The survival of basil plants was affected by environment in raised beds (p=0.0127) and in the vertical system (p=0.0001). The vertical growing system was particularly affected in full sun as the column structure exposed all of the plants to the environment and heavy winds that occurred during monsoon season. The losses in the vertical system in full sun compared to the RRGH were much greater, with only 64% of the crop surviving in full sun (Table 4.3.5.3). The protection of the crop and equipment is a significant advantage of the RRGH structure. Plants grown in the raised beds were not as vulnerable to weather conditions in full sun as the structure of the canopy in this system provides buffering from heavy winds. The low survival rates of plants within the vertical system in full sun also affected the differences in fresh weight due to pot position, as the plants in full sun had more space and light availability compared to those in the RRGH.

Table 4.3.5.3. Percent survival of basil plants in two production systems and three environments.

Environment	Raised Beds	Vertical System
Full Sun	93 b*	64 b
Clear Woven	100 a	99 a
White Woven	100 a	100 a

*Means within a column followed by a different letter are significantly different at p<0.05.

Dry matter content of basil grown in raised beds was affected by environment (p=0.0123) as was the dry matter content of basil grown in the vertical system (p=0.0035). Dry matter of basil grown in raised beds was 44% greater in full sun compared to either RRGH environment, although when grown in the vertical system, dry matter was 22% greater under the white woven roof of the RRGH compared to either of the other two environments (Table 4.3.5.4). In raised beds, the greater dry matter accumulation in full sun compared to the RRGH is similar to the results found in the first study. Studies have illustrated that increased dry matter is closely related to the amount of radiation intercepted by the crop (Lawlor, 2001). The increase in dry matter content of basil grown in raised beds follows the experimental evidence. Basil grown in the vertical system showed the opposite trend and may be a combined result of the decrease in intercepted radiation due to the structural orientation of the towers compared to the horizontal distribution of plants in the raised beds as well as the low plant survival in towers in full sun.

Table 4.3.5.4. Dry matter content of basil (%) grown in two production systems in three environments.

Environment	Raised Beds	Vertical System
Full Sun	13 a*	9 b
Clear Woven	9 b	9 b
White Woven	9 b	11 a

*Means within this table followed by a different letter are significantly different at $p<0.05$.

Photosynthesis (Pn) was affected by an interaction between environment and time of day on August 26 ($p=0.0172$) and September 23 ($p=0.0082$). On August 26, the roof of the RRGH was closed at all measurement times while on September 23, the roof was open at the time of the 0900 HR measurement. The August 26 measurements show a diurnal pattern where photosynthesis increases from morning to noon and again decreases after noon in all three environments (Figure 4.3.5.1). Maximum Pn occurred at noon in full sun and under the clear woven roof and both were 120% greater than the lowest Pn rates found at 1500 HR under both RRGH environments. Pn rates of basil plants grown in the RRGH were the same at all times of day, while in full sun, rates increased at noon to 67% above rates found at 0900 and 1500 HR.

On September 23, the roof was open at 0900 HR in the RRGH. Pn rates at 0900 HR are similar to those found on August 26, but at noon on September 23, the rates in the RRGH dropped compared to full sun when the roof was closed. On both dates, at 1200 and 1500 HR, rates are lower in the RRGH compared to full sun. Roof control strategies which opened the roof for longer periods of the day have the potential to maintain photosynthetic rates at full sun levels. On September 23, the highest Pn rates were found under all three environments at 0900 HR when all three environments had the same light intensity. The highest rates at the time of the 0900 HR measurements are 127% greater than the lowest rates found under the white woven roof at 1200 and 1500 HR. The diurnal pattern of increasing then decreasing photosynthesis is not found on September 23, 2004.

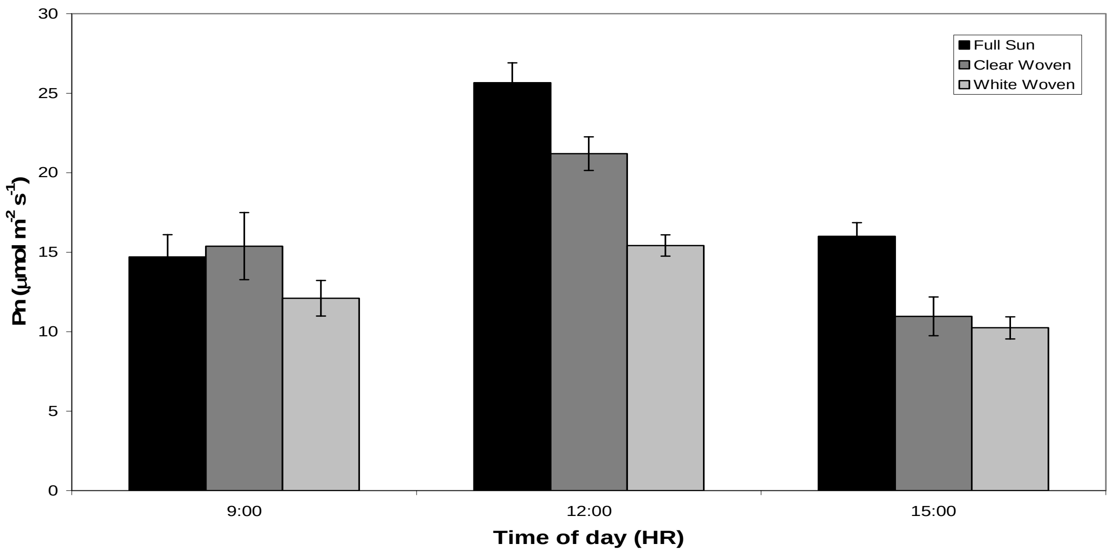

Figure 4.3.5.1. Photosynthesis of basil leaf grown in raised beds in three environments during August 26, 2004.

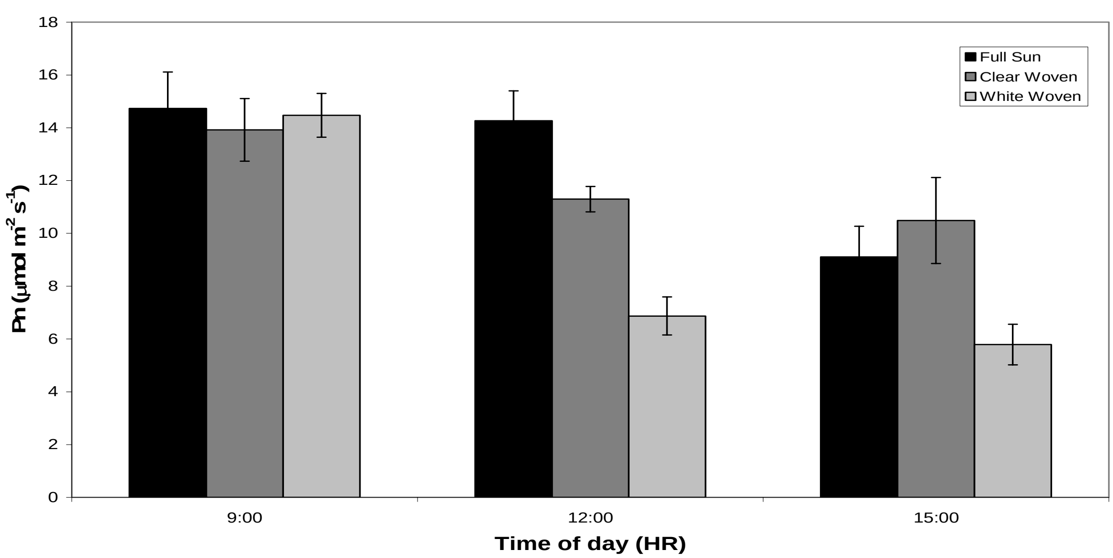

Figure 4.3.5.2. Photosynthesis of basil leaf grown in raised beds in three environments during September 23, 2004.

Table 4.3.5.5. Leaf temperature (°C) of basil in raised beds in three environments, three times of day during two days. Leaf temperatures are followed by standard errors (SE).

August 26, 2004	Full Sun	Clear Woven	White Woven
0900 HR	29.3 (0.34)	30.3 (0.24)	29.1 (0.52)
1200 HR	34.9 (0.29)	33.0 (0.31)	31.8 (0.21)
1500 HR	35.0 (0.70)	31.2 (0.46)	32.2 (0.28)
September 23, 2004			
0900 HR	26.2 (0.20)	28.5 (0.27)	27.7 (0.41)
1200 HR	33.5 (0.35)	32.1 (0.22)	31.1 (0.33)
1500 HR	33.4 (0.36)	31.4 (0.37)	32.1 (0.21)

Table 4.3.5.6. Mean instantaneous PPF (µmol m^{-2} s^{-1}) measured by Ciras-2 quantum sensor at time of measurement in three environments. Instantaneous PPF is followed by standard errors (SE).

August 26, 2004	Full Sun	Clear Woven	White Woven
0900 HR	768 (89)	634 (77)	546 (96)
1200 HR	1763 (58)	1047 (55)	616 (9)
1500 HR	1085 (276)	506 (80)	403 (18)
September 23, 2004			
0900 HR	855 (112)	1090 (57)	1213 (63)
1200 HR	1727 (83)	949 (33)	530 (5)
1500 HR	1045 (98)	560 (72)	345 (24)

Higher photosynthetic rates within the RRGH compared to full sun were anticipated due to the modification of the microclimate. Lower leaf temperatures in the afternoon under shade in the RRGH (Table 4.3.5.5) accompanied by high summer solar radiation (Table 4.3.5.6) was expected to promote photosynthesis of basil. Incident mean PPF values vary depending on the angle the Ciras-2 was held at the time of measurement. Photosynthesis rates were highest in full sun, and higher at all times of day compared to basil grown within the RRGH. Photosynthesis rates were greater in August compared to September. In August, maximum photosynthesis reached 25 µmol m^{-2} s^{-1}, but in September the highest reading was 15 µmol m^{-2} s^{-1}. Higher photosynthesis rates were expected to correlate with greater fresh weights, yet environments were very similar overall in biomass accumulation. The greater carbon fixation in full sun, which did not contribute to an increased yield compared to the RRGH, may have been due to photosynthates being allocated to increased root biomass, or due to anatomical differences in stomatal density between plants grown in full sun versus the RRGH. If leaves grown in full sun had higher stomatal densities, photosynthesis rates would appear higher than in the RRGH, although leaves grown in the RRGH had greater leaf areas.

In analyzing factors that may have explained the increased photosynthesis in full sun, root dry weight and stomatal density were evaluated. Root dry weights were not different between environments (p=0.7065) with an overall mean of 10.8 g per 30 cm by 30 cm section. Stomatal density was affected by an interaction between environment and surface of leaf (p=0.0009). Greatest differences in stomatal density were due to surface of the leaf. The abaxial surface had 55% more stomates per mm^2 than the adaxial surface (Table 4.3.5.7). Differences between environment were not large enough to assume stomatal density affected the accuracy Ciras-2 readings.

Table 4.3.5.7. Number of stomates per mm^2 in three environments on two leaf surfaces.

Environment	Adaxial Surface	Abaxial Surface
Full Sun	89 bcd*	146 a
Clear Woven	88 bcd	109 bc
White Woven	79 cd	140 a

*Means within this table followed by a different letter are significantly different at $p<0.05$.

4.3.6. Environmental Data Common to the Raised Bed and Vertical Production Systems.

Roof control strategy primarily manipulated the solar radiation received by the crop within the RRGH, which affected leaf and substrate temperatures, but had little effect on air temperatures. Solar radiation received by the canopy differed based on control strategy due to roof position. Differences in environment based on strategy are a result of the strategy within the confines of the specified setpoints. Different setpoints within the specific strategies would result in differences in environmental conditions. In addition to the effects of strategy on solar radiation and temperatures, water application was also affected by strategy because control of irrigation events was based on accumulated light.

Under Strategy I, air temperature control, the roof remained closed throughout the day in both RRGH environments, therefore the crop within each RRGH environment was not exposed to full sun light intensities at any time of day (Figure 4.3.6.1). Air and leaf temperatures were similar between the RRGH and full sun under Strategy I, although the substrate temperature was lower in the RRGH compared to full sun (Figure 4.3.6.2). Greater leaf temperatures in full sun compared to the RRGH would be expected for all RRGH roof control strategies, but the similar leaf temperatures found in Strategy I are unexpected. In the 2003 experiment, in which the roof remained in the same closed position as Strategy I throughout the duration of the study, leaf temperatures were 4 °C lower in the RRGH compared to full sun.

The roof remained closed throughout this strategy because outdoor air temperatures were always greater than 20 °C during the day (Figure 4.3.6.3). This control strategy resulted in reduced fresh weight yields and was associated with greater leaf areas and internode lengths.

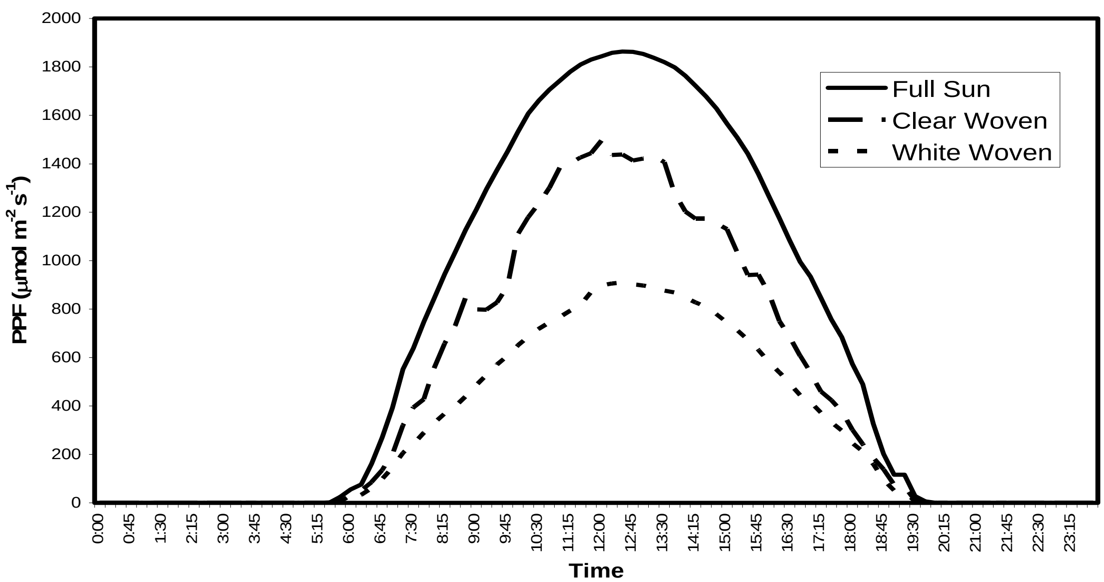

Figure 4.3.6.1. Daily PPF in three environments using strategy I: air temperature in the two RRGH environments on July 11, 2004.

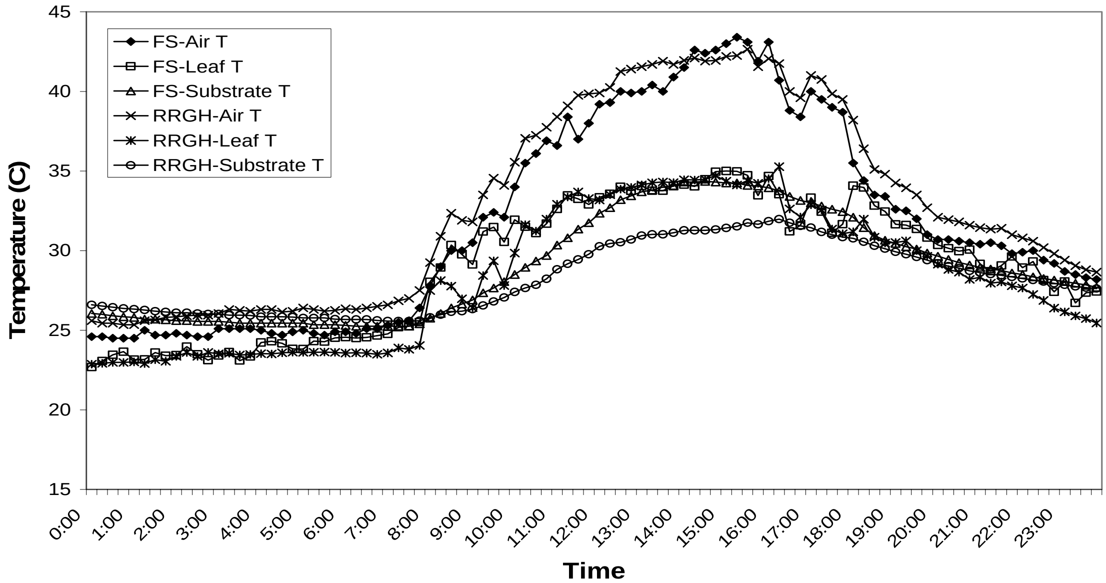

Figure 4.3.6.2. Temperatures in RRGH and full sun using Strategy I on July 18, 2004.

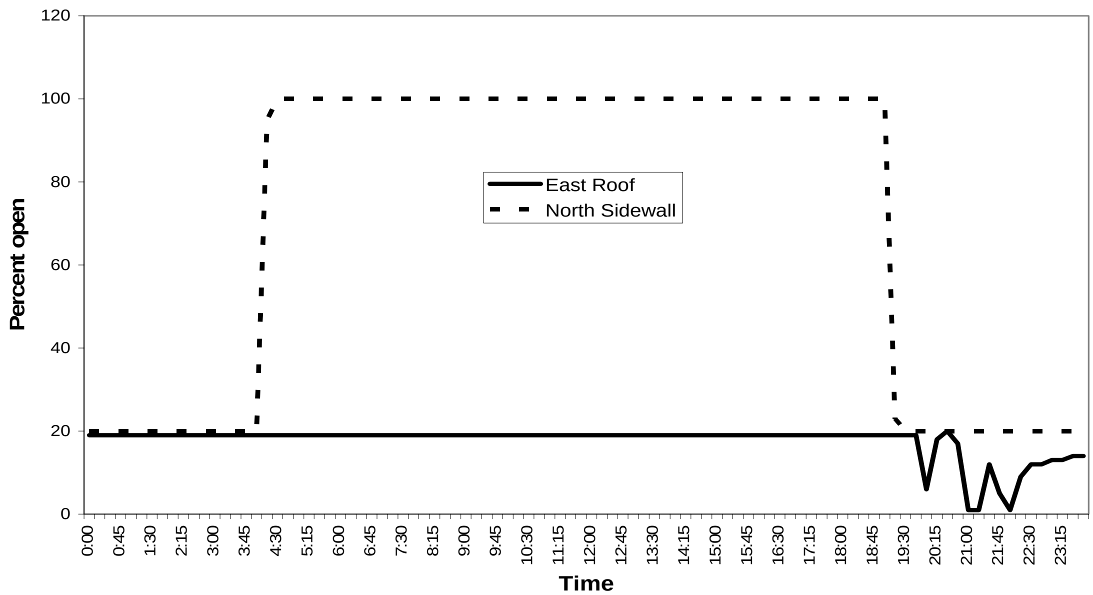

Figure 4.3.6.3. RRGH roof and wall curtain movement using Strategy I: air temperature control on July 17, 2004. (Percent open: 0 – closed, 100 – open).

Plants grown in the RRGH under Strategy II, solar radiation control, received additional integrated daily PPF from exposure to full sun light intensities early and late in the day (Figure 4.3.6.4). In Strategy II, air temperatures were similar in all environments, but leaf and substrate temperatures were lower in the RRGH compared to full sun (Figure 4.3.6.5). The roof opened early and late in the day when the outdoor light intensity was below 700 W m^{-2} (Figure 4.3.6.6).

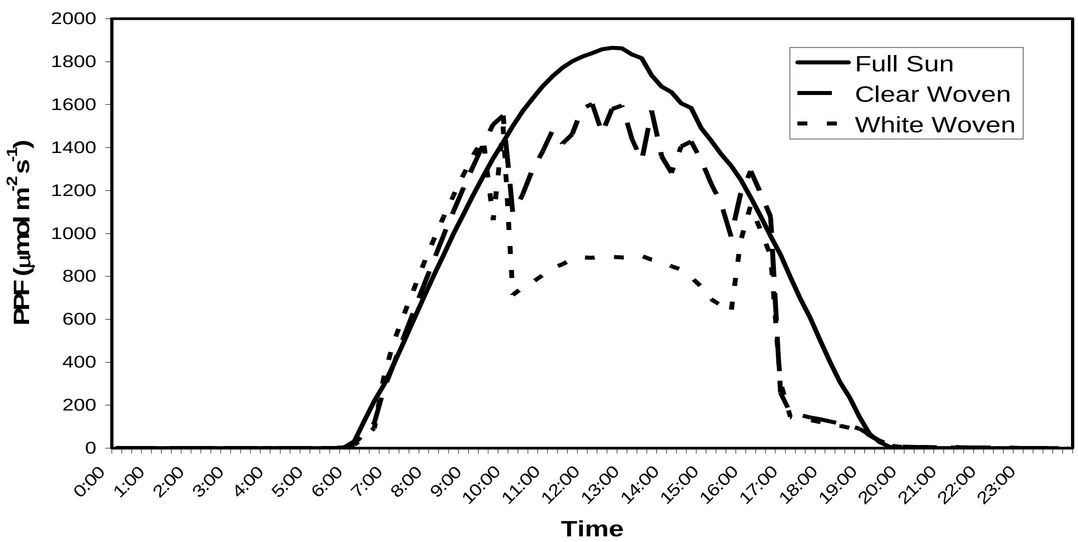

Figure 4.3.6.4. Daily PAR in three environments using strategy II: solar radiation in the two RRGH environments on July 29, 2004.

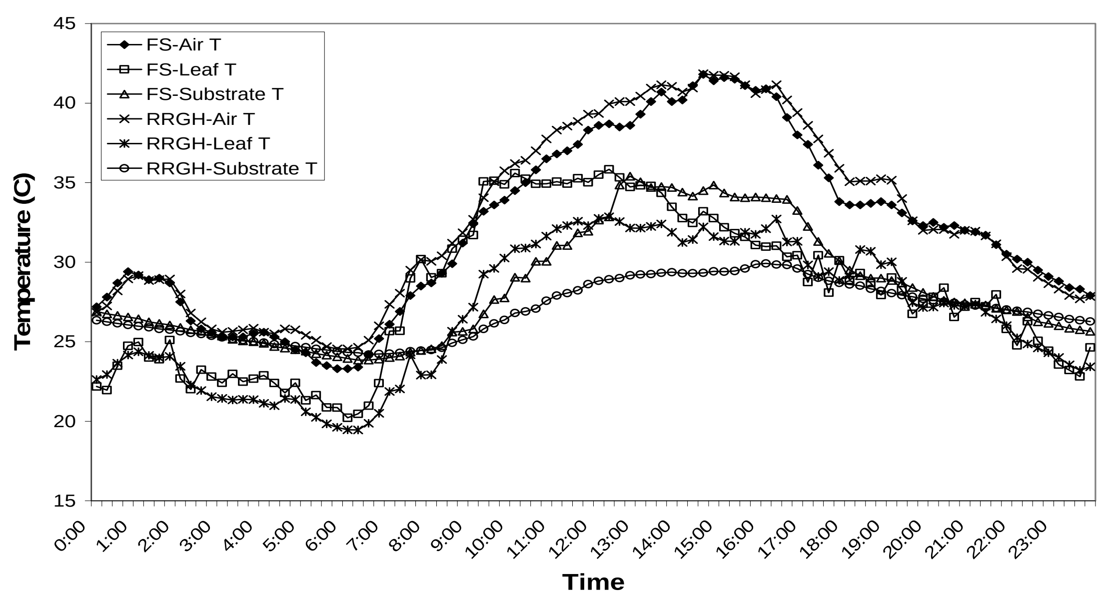

Figure 4.3.6.5. Temperatures in RRGH and full sun using Strategy II on July 31, 2004.

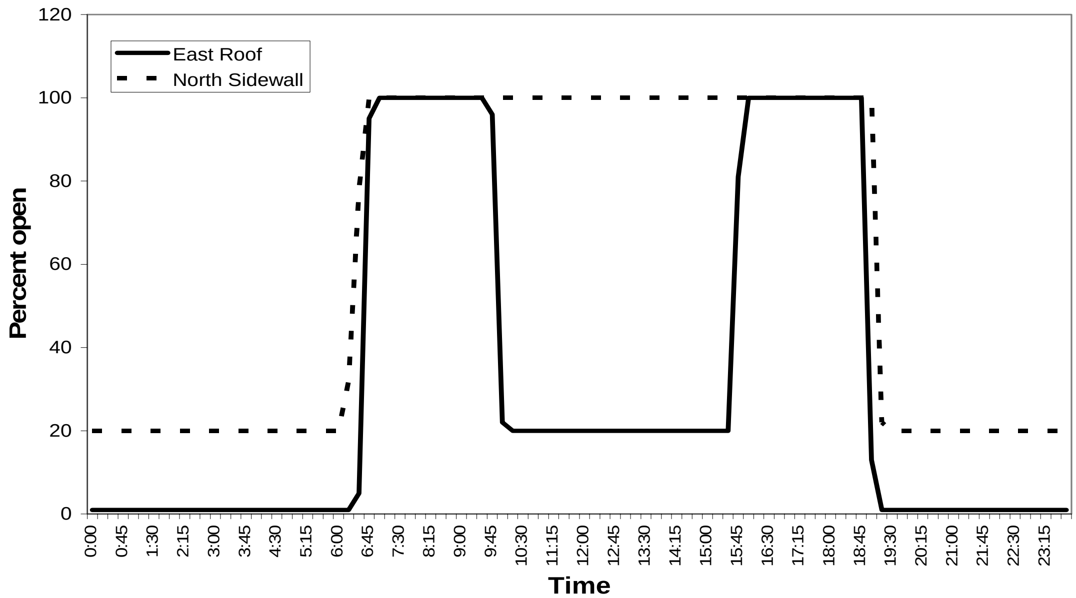

Figure 4.3.6.6. RRGH roof and wall curtain movement using Strategy II: solar radiation control on July 29, 2004. (Percent open: 0 – closed, 100 – open).

Plants grown in the RRGH under Strategy III, globe thermometer control, received additional radiation during the morning (Figure 4.3.6.7). The air temperatures were similar in the RRGH and in full sun, but leaf and substrate temperatures were lower in the RRGH compared to full sun (Figure 4.3.6.8). The roof opened in the morning and late afternoon under this strategy, but the roof opened late enough in the afternoon, that the additional radiation was not detectable in the light curve (Figure 4.3.6.7 and 4.3.6.9). Both solar radiation control and globe thermometer control increased fresh weight production compared to air temperature control, while also increasing leaf area and reducing flowering compared to full sun.

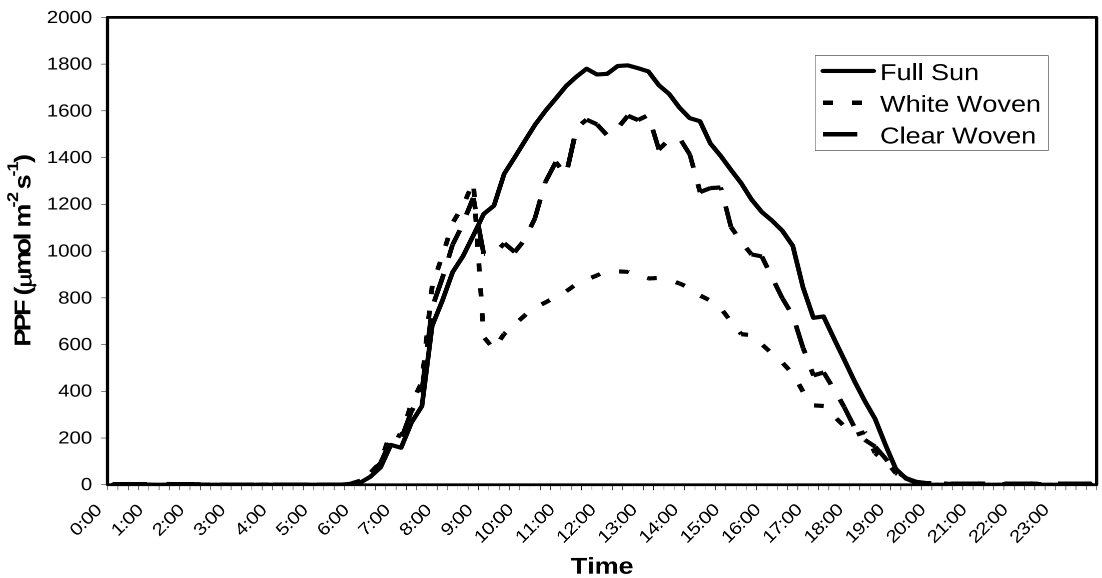

Figure 4.3.6.7. Daily PAR in three environments using strategy III: globe thermometer in the two RRGH environments on August 7, 2004.

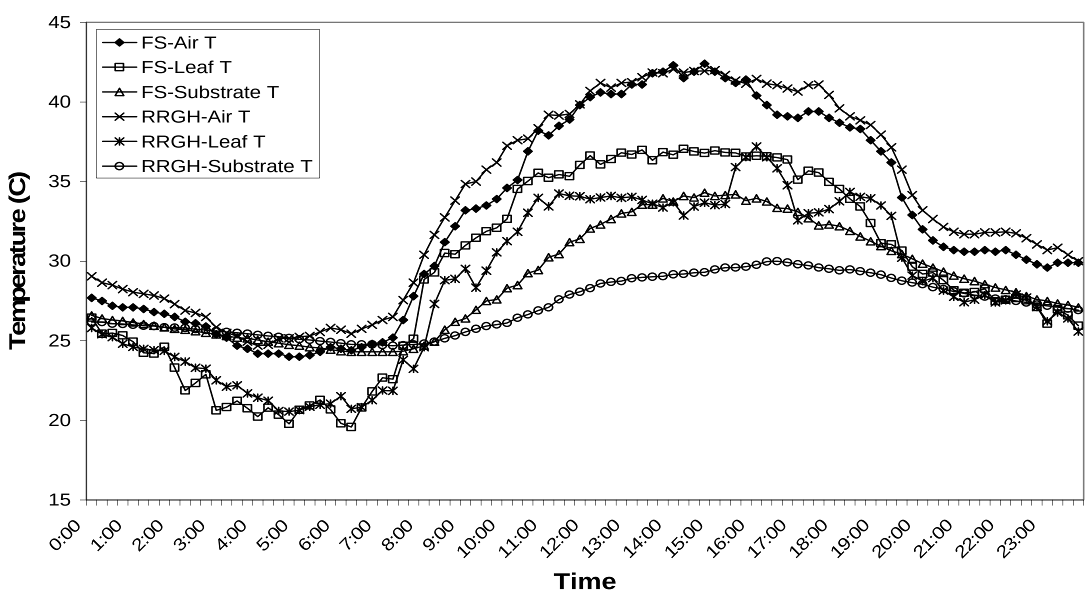

Figure 4.3.6.8. Temperatures in RRGH and full sun using Strategy III on August 7, 2004.

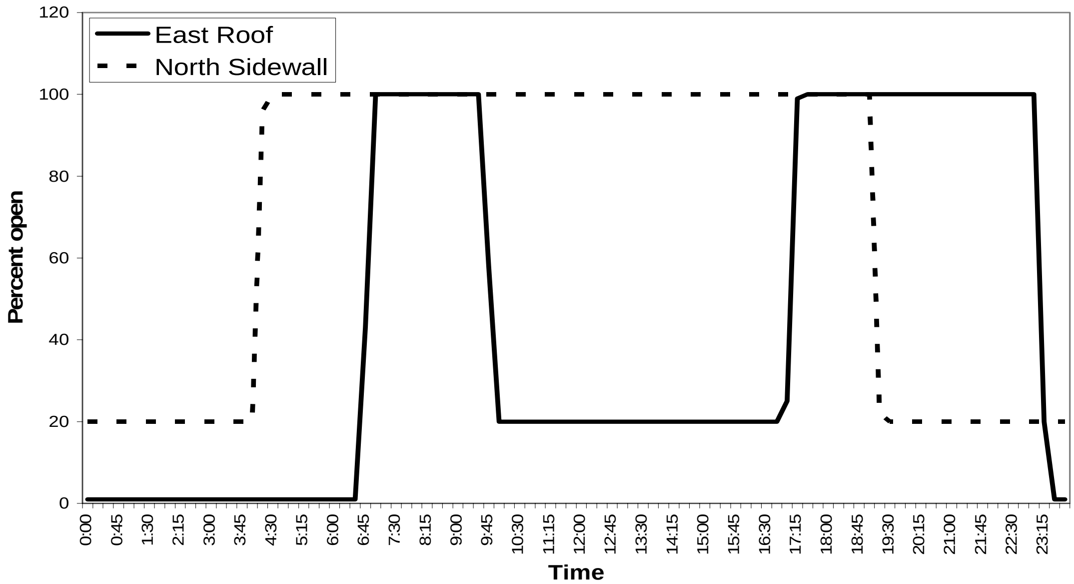

Figure 4.3.6.9. RRGH roof and wall curtain movement using Strategy III: globe thermometer control on August 3, 2004. (Percent open: 0 – closed, 100 – open).

The outdoor globe thermometer threshold setting was determined based on correlations between outdoor globe thermometer temperature and leaf temperatures, and correlations between leaf temperature and photosynthetic rates of basil. The thresholds for roof curtain movement were decided based on Figures 4.3.6.10 and 4.3.6.11. The roof curtain opened when the outdoor globe thermometer reading was below 35 °C and was closed except for a ventilation gap when the globe thermometer temperature reached 35 °C or above. The globe thermometer threshold of 35 °C was chosen to potentially maintain leaf temperatures below 30 °C in the RRGH in order to promote photosynthesis of basil.

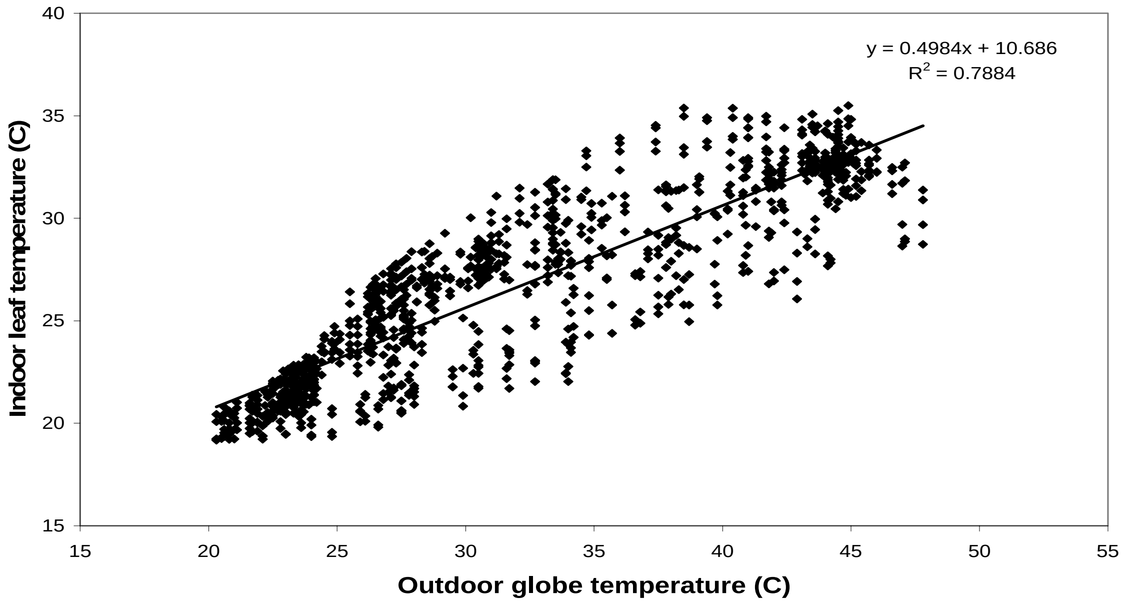

Figure 4.3.6.10. Early season correlation between outdoor globe thermometer and indoor leaf temperature.

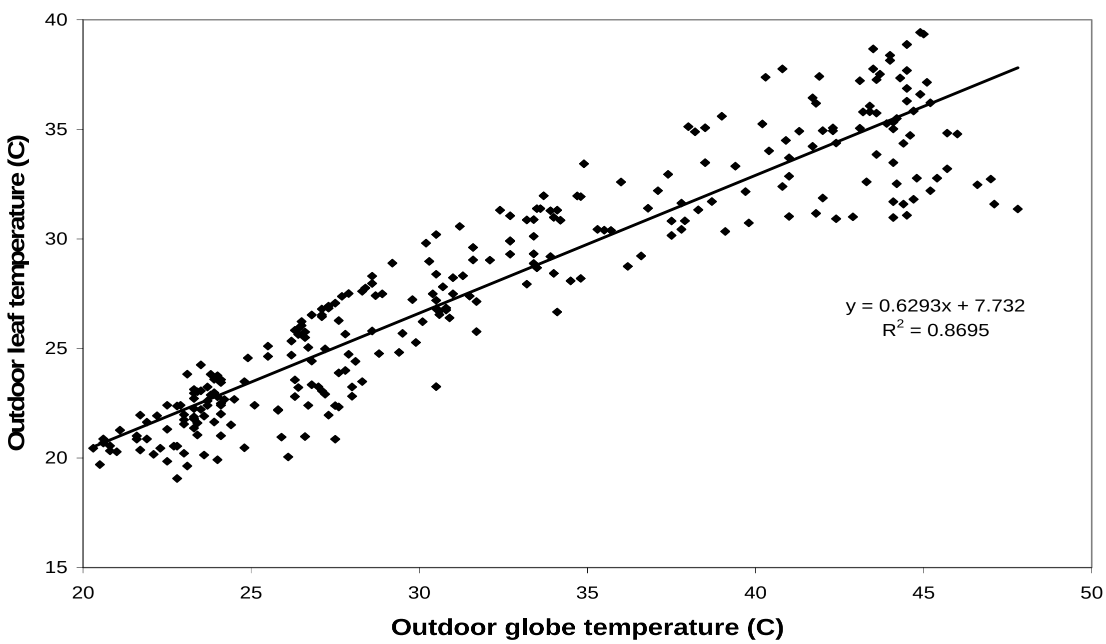

Figure 4.3.6.11. Early season correlation between outdoor globe thermometer and outdoor leaf temperature.

The three roof strategies rotated throughout the production period, so for comparison of the strategies within a specific environment, representative days were chosen, where the daily PPF in full sun was 52 mol m^{-2} d^{-1}. For figures 4.3.6.12 and 4.3.6.13, the representative days were July 6, 2004 for strategy I, July 30, 2004 for Strategy II and August 8, 2004 for Strategy III. In the RRGH, under the clear woven roof providing 35% shade, both Strategy II and III provided more light to the canopy compared to Strategy I, particularly in the morning and afternoon when the roof was open to expose the crop to full sun conditions (Figure 4.3.6.12). Both Strategy II and III provided additional morning light, and Strategy II provided additional afternoon light as well. The same trend in seen in the RRGH under the white woven roof which provided 50% shade (Figure 4.3.6.13). The additional light provided in the morning and afternoon is more noticeable in the diurnal solar radiation pattern under the white woven roof because solar radiation was dramatically reduced in this environment when the roof was closed.

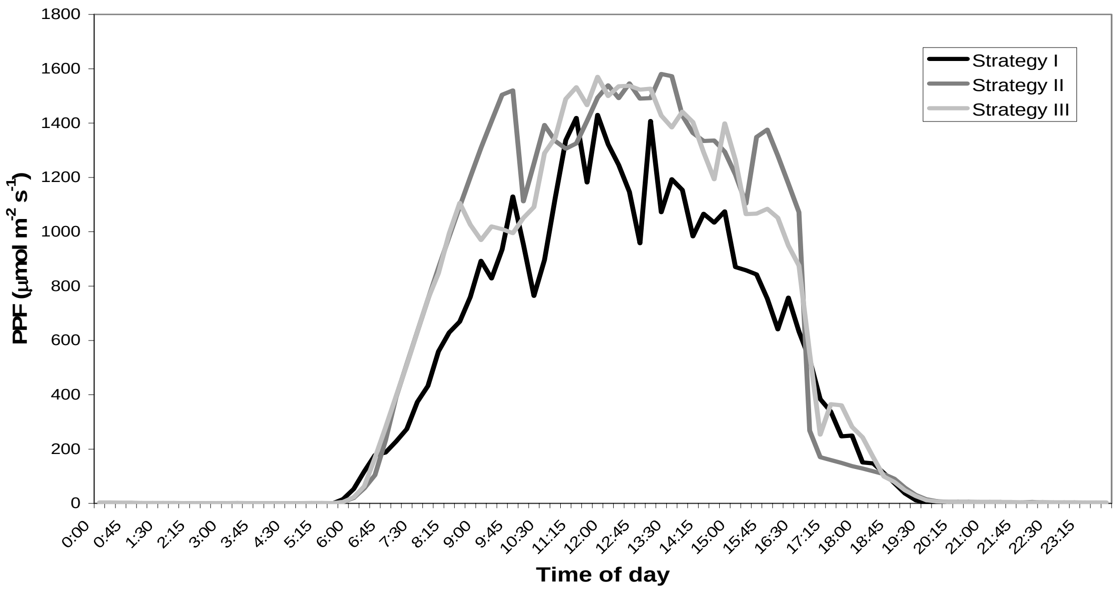

Figure 4.3.6.12. Daily PAR in RRGH under clear woven film using three roof control strategies.

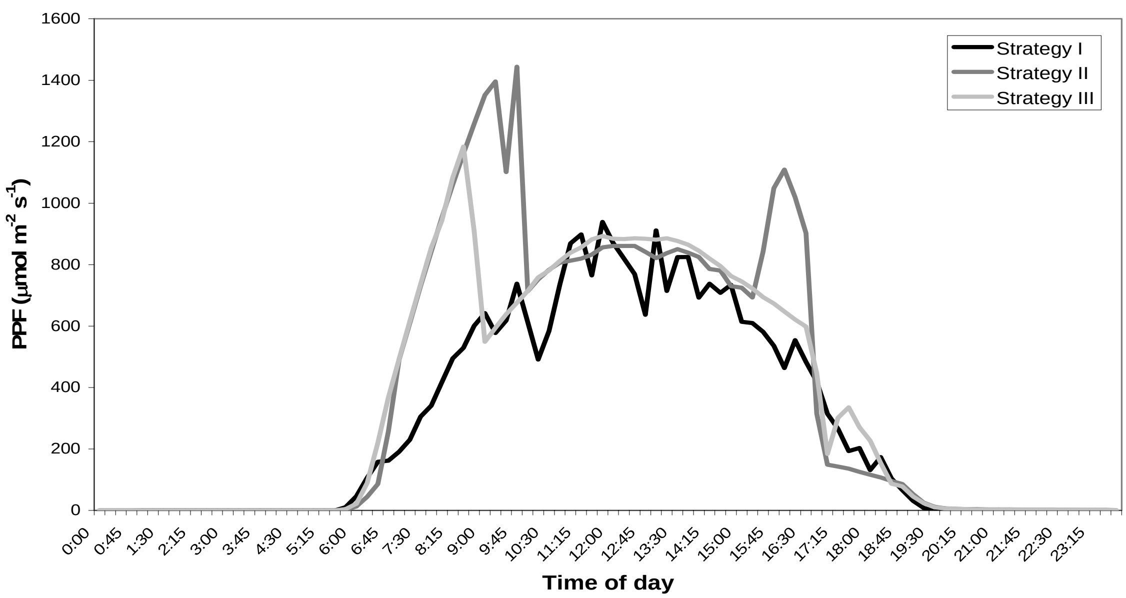

Figure 4.3.6.13. Daily PAR in RRGH under white woven film using three roof control strategies.

Solar radiation received by the basil canopy depended upon the environment in which it was grown. Within the RRGH, solar radiation received by the canopy was further affected by the roof control strategy employed; affecting the number of hours the plants within the RRGH were fully exposed to outdoor light intensities.

Average daily PPF values in the three environments and control strategies are given in Table 4.3.6.1. The full sun environment had no roof control strategy, therefore serves as a reference to the changing outdoor conditions during the experimental period. Table 4.3.6.1 summarizes the daily PPF averages over the two weeks where control strategies were consecutively repeated.

If ambient conditions had been constant, the values within the full sun column would be identical. Values within a row are readings taken during the same weeks and can be directly compared (Table 4.3.6.1). Percent values within a strategy indicate the PPF plants were exposed to in the RRGH environments relative to full sun.

Table 4.3.6.1. Daily PPF (mol m^{-2} d^{-1}) with standard errors (SE) in three environments using three roof control strategies. Percentages within a row indicate the percent of solar radiation in the RRGH compared to full sun.

	Date	Full Sun	Clear Woven	White Woven
Strategy				
I: Air Temperature	July 6 to July 19	46 (1.7)	34 (1.4) 74%	23 (0.8) 50%
II: Solar Radiation	July 20 to Aug 2	48 (1.6)	42 (1.1) 88%	33 (1.1) 69%
III: Globe Thermometer	Aug 3 to Aug 16	42 (2.4)	36 (1.9) 86%	25 (1.2) 60%
I: Air Temperature	Aug 17 to Aug 30	47 (1.9)	36 (1.5) 77%	24 (1.1) 51%
II: Solar Radiation	Aug 31 to Sep 13	46 (1.2)	39 (0.6) 85%	31 (0.2) 67%
III: Globe Thermometer	Sep 14 to Sep 27	42 (2.1)	35 (1.7) 83%	27 (1.6) 64%

The differences in integrated daily PPF between environments and systems in Table 4.3.6.1 indicates that the total radiation received by the canopy in the RRGH was increased by solar radiation and globe thermometer control compared to air temperature control. Under the clear woven roof in the RRGH, integrated daily PPF was increased by 14% (8 mol m^{-2} d^{-1}) and 12% (4 mol m^{-2} d^{-1}) for the solar radiation and globe thermometer strategies, respectively, compared to air temperature control in the early season strategy repetitions. Under the white woven roof in the RRGH, integrated daily PPF was increased by 19% (10 mol m^{-2} d^{-1}) and 10% (2 mol m^{-2} d^{-1}) by the solar radiation and globe thermometer strategies, respectively, compared to control based on air temperature in the early season strategy repetitions. The percent increase in integrated PPF within the RRGH was due to morning and afternoon solar radiation when based on solar radiation control, and due to only morning solar radiation when based on globe thermometer control.

Air temperature was a poor indicator of the different microclimate experienced by the crop in the RRGH compared to full sun, and the main environmental differences were due to differences in radiation received by the specific environment. High ventilation rates in the RRGH kept air temperatures similar to the full sun environment (Figure 4.3.6.14, Figure 4.3.6.15). During the day, temperatures could be greater in the RRGH compared to full sun due to some heat trapped within the structure. At night, the structure was always closed, and air temperatures could be several degrees warmer than outdoors.

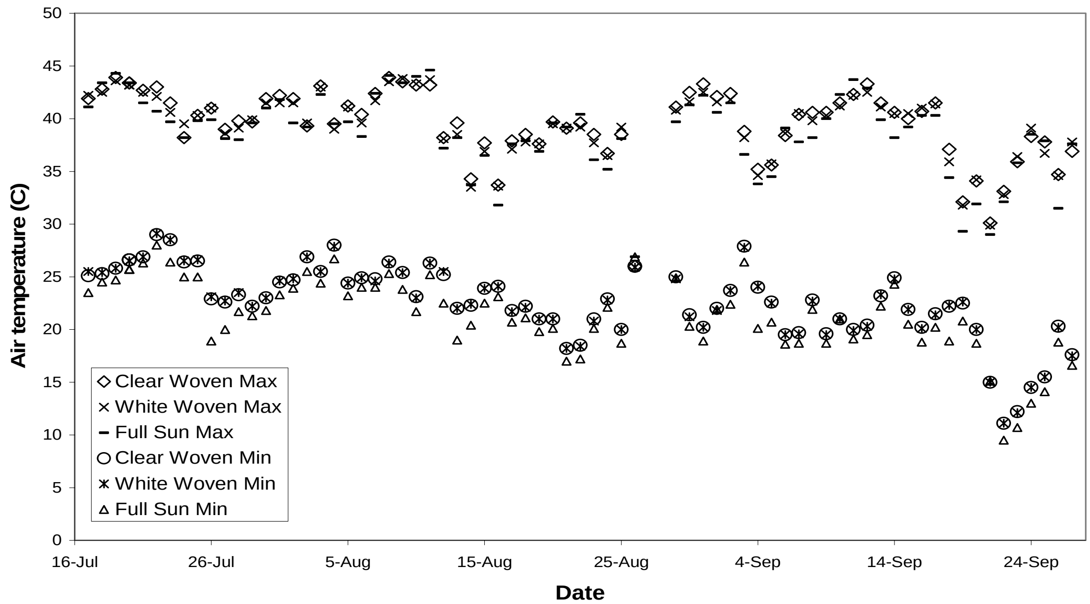

Figure 4.3.6.14. Max and min air temperatures in three environments throughout the entire production period.

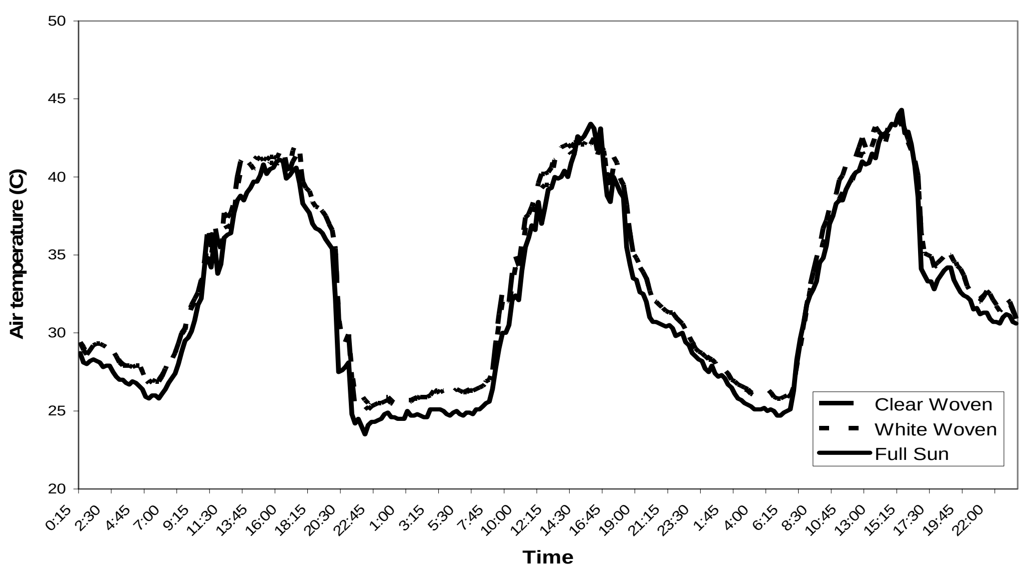

Figure 4.3.6.15. Daily air temperatures in three environments from July 17 to 19, 2004.

Substrate temperature and leaf temperature which are strongly affected by radiation load showed differences between the three environments even though air temperatures did not (Figures 4.3.6.16, 4.3.6.17, 4.3.6.18, 4.3.6.19). Ventilation could not make the substrate temperatures similar in the three environments as quickly as the air temperature. Substrate temperatures were always greater in full sun compared to the RRGH for both production systems. Substrate temperatures in Figures 4.3.6.16 and 4.3.6.17 represent raised bed substrate temperatures.

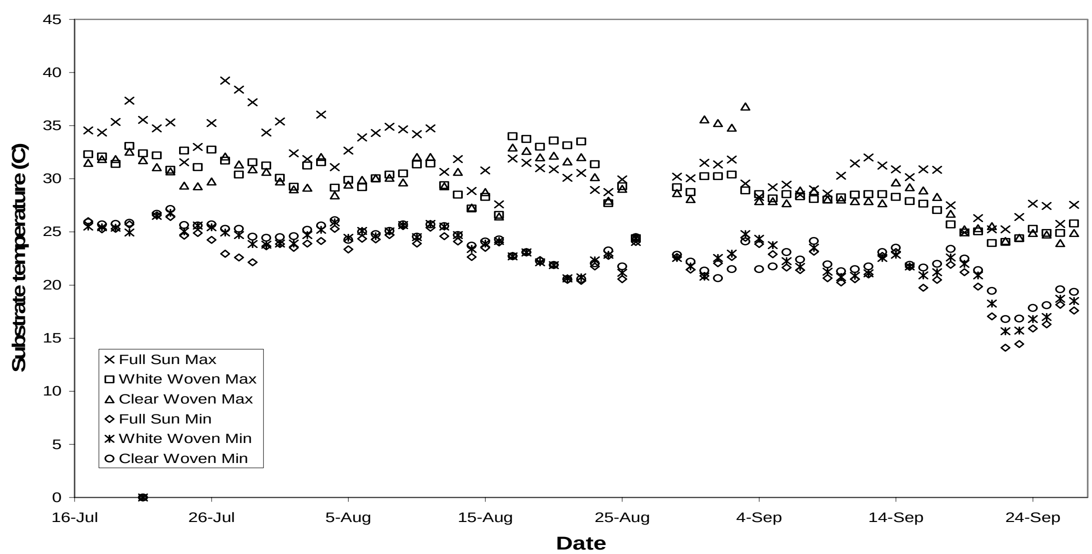

Figure 4.3.6.16. Maximum and minimum substrate temperatures in raised beds in three environments throughout the entire production period.

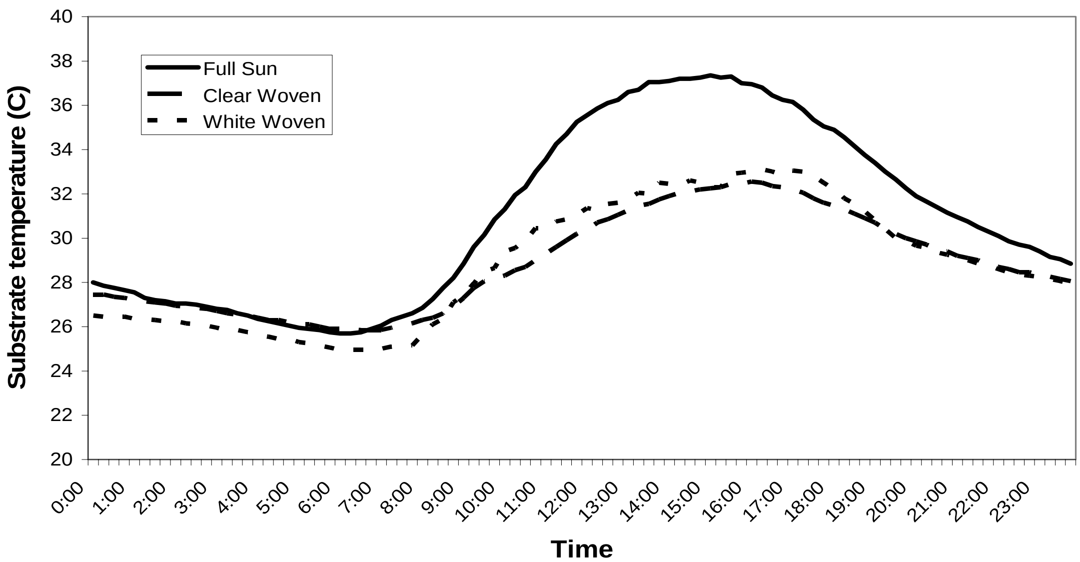

Figure 4.3.6.17. Substrate temperature of perlite in raised beds in three environments on July 20, 2004.

Between production systems, perlite within the vertical system reached higher temperatures than in the raised beds particularly at the beginning of the season when the plant canopy did not fully cover the stacked pots. Later in the season, vertical system substrate temperatures were also higher than all other environments and systems due to low plant survival which exposed the towers to high light intensities. The small substrate volume in each pot reached temperatures greater than raised beds in all environments (Figure 4.3.6.18). Once the plant canopy covered the pots, substrate temperatures were similar in both production systems.

The low survival rates of basil in the vertical system in full sun were partially due to high winds, but the high substrate temperatures may have contributed to plant loss, although in the 2003 trial root zone temperature reaching 45 °C were not detrimental to plants in rockwool. ‘Genovese Compact’ may have been more sensitive to high root zone temperature compared to ‘Genovese’ in the 2003 trial. High root zone temperatures have been shown to cause plant death, despite the hardiness of the shoots under high temperatures, particularly at root zone temperatures greater than 37.8 °C (Mathers, 2003). Cooler substrate temperatures and the subsequent growth improvements found under retractable roof greenhouse environments have been well documented (Mathers, 2003).

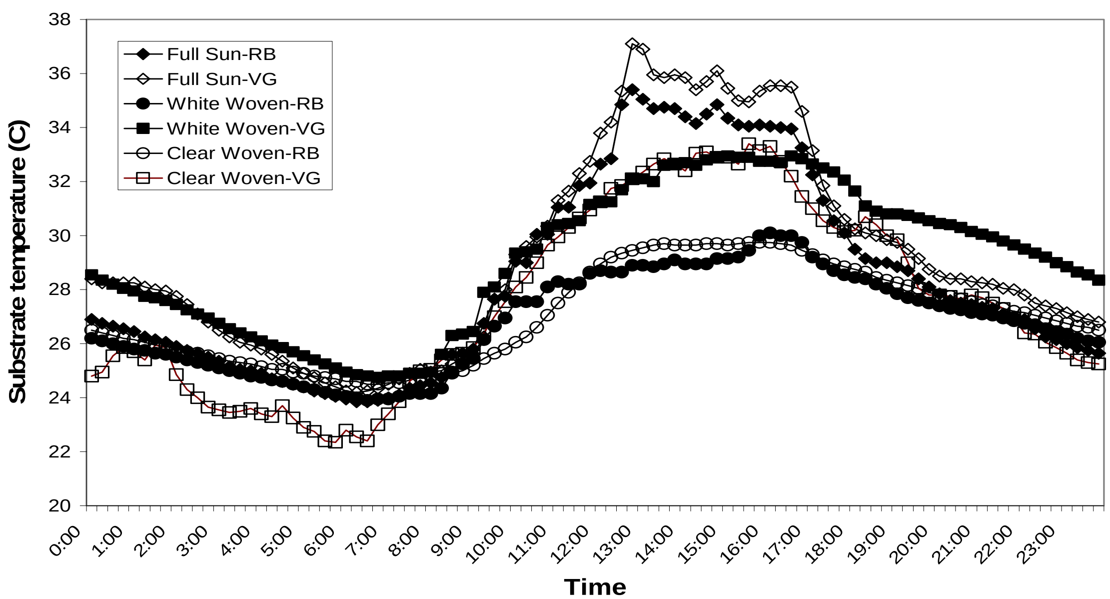

Figure 4.3.6.18. Substrate temperature of perlite in two production systems in three environments on July 31, 2004.

Leaf temperatures and substrate temperatures were typically 5 °C cooler in the RRGH compared to full sun in the middle of the day. Air temperatures in the RRGH and full sun were similar yet leaf temperatures showed differences between the environments (Figure 4.3.6.19). At the end of the day, after 1800 HR, leaf temperatures in the RRGH and full sun were similar.

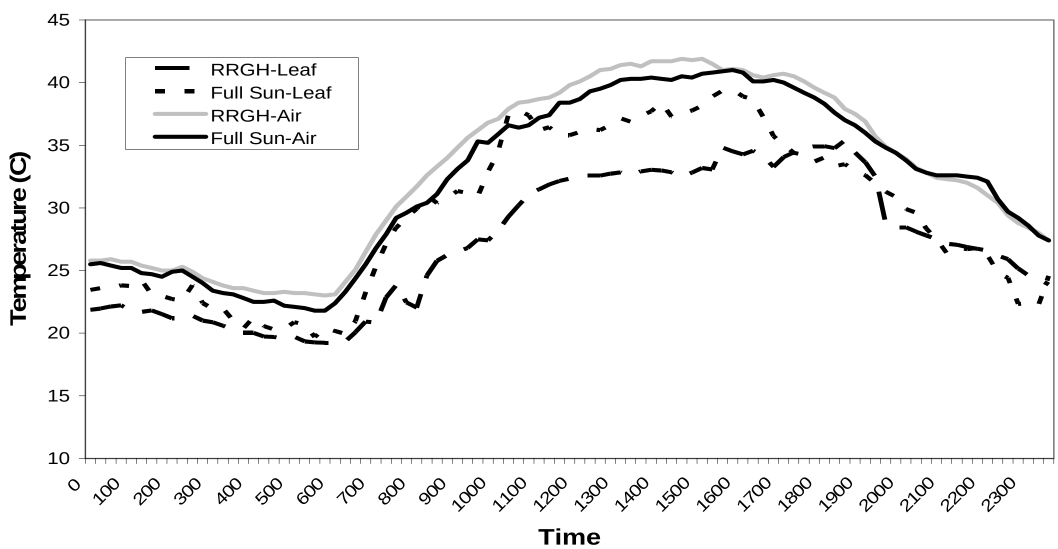

Figure 4.3.6.19. Air and leaf temperatures in the RRGH and full sun on July 30, 2004.

Fertigation events were controlled by the quantum sensors in the RRGH and the pyranometer in full sun. Each environment had the same threshold to trigger an irrigation event, yet different light conditions which affected daily irrigation volumes depending on daily weather conditions, environment, and roof control strategy (Figure 4.3.6.20).

Emitters used in each system applied different irrigation volumes due to different substrate volumes in each production system.

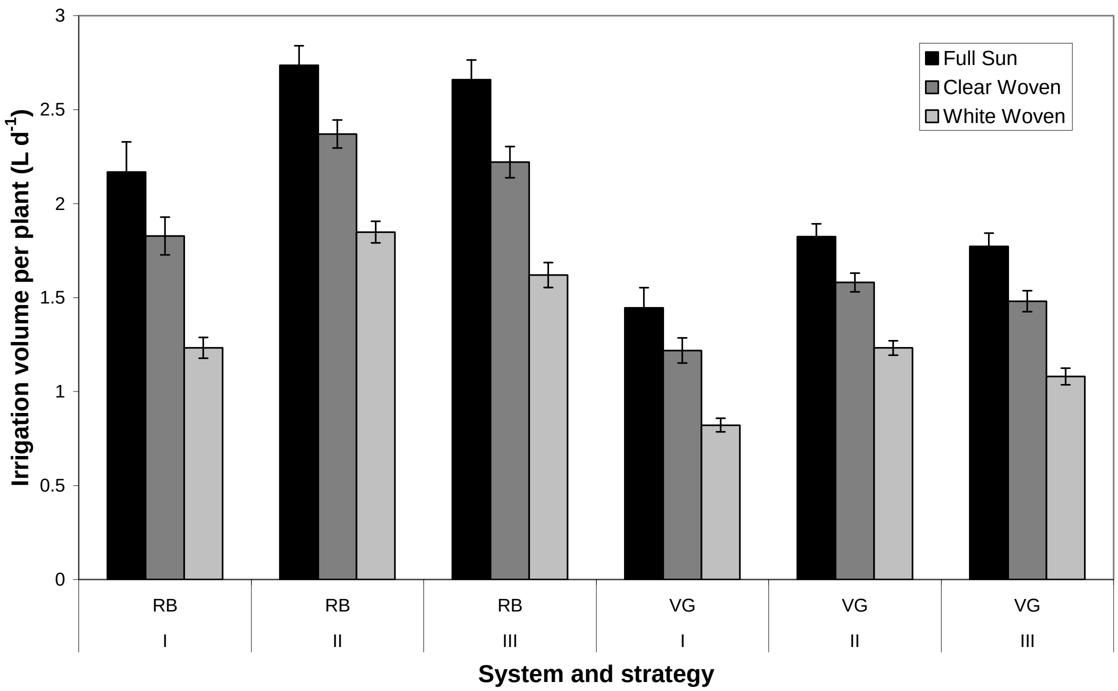

Figure 4.3.6.20. Daily irrigation volume per plant per system, environment, and roof control strategy throughout the entire production period.

Raised beds, in general, received 88% more water than the vertical system due to the greater media volume per plant (Figure 4.2.6.20). Overall, water applied in full sun was 60% greater than in the white woven environment, and 18% greater than in the clear woven environment. Reduced water and fertilizer use has been reported for RRGH compared to full sun due to decrease in evapotranspirational demand (Svenson, 2000).

Within each particular system, water application was increased by increased solar radiation. Irrigation events were triggered by accumulated light so overall plants were watered more in full sun than in the RRGH. Water applied within the RRGH was increased by Strategy II and III which opened the roof more than Strategy I. Differences in full sun water usage within a particular production system indicate differences in weather conditions that would adjust irrigation events. Also contributing to differences found within the strategy effects is that the first two repetitions of Strategy I occurred when the plants were not fully mature and only received three minute irrigation durations compared to the five minute durations throughout the rest of the production period. Each column represents an average of 28 days of water applied, but for Strategy I, 14 of these days include lower volumes due to plant age, artificially reducing the apparent water usage under this roof control strategy, although a certain degree of reduced water usage under this roof strategy would be expected as the roof was closed throughout most of the day.

4.4. Conclusions

Following the results and suggestions of the 2003 basil trial, roof and wall control strategies in the RRGH were evaluated in addition to more economical production systems that are alternatives to rockwool culture. Fresh weight yields in raised beds were equal to yields in rockwool culture from the previous year on a per plant basis, and double that of the vertical system in all environments. Production within the raised beds and vertical system were affected by strategy, indicating curtain control has important effects on plant productivity under these cultural practices. Control based on either solar radiation or globe thermometer increased productivity of basil by 30% when grown in raised beds and by 14% in the vertical system compared to air temperature based control. The vertical system was additionally affected by environment within the RRGH, producing 18% more per plant under the clear woven roof compared to the white woven roof.

Overall plants grown in full sun had similar biomass accumulation compared to the RRGH in both production systems, with slightly lower yields than the RRGH during the beginning of the season, and slightly higher yields at the end of the season once plants had acclimated to full sun conditions. While productivity was similar in full sun, plants in the upper pots in the vertical system had low survival rates due to lack of protection from high winds and possibly due to high substrate temperatures. Plant quality in full sun was also lower than in the RRGH characterized by smaller leaf areas, shorter internode lengths and more flowers. Additionally, in full sun, hydroponic equipment is not protected and degrades more rapidly than within the RRGH. Plants grown in full sun would also require post harvest cleaning due to dirt on the crop at the time of harvest.

The increased quality found within both shade environments of the RRGH for basil grown in both production system resulted from the microclimate modifications provided by the structure. Air temperature was found to be a poor indicator of what the plant experiences in the root and shoot environment. Air temperatures were similar in all three environments, yet the shoot and root temperatures within the RRGH from the reduction in solar gain in the house provide a cooler microclimate for the crop. The shade of the RRGH increased the leaf area and internodes of the crop while reducing the number of flowers each week which improved the overall marketability of the crop for high end niche markets resulting in higher prices compared to traditional field products.

5. PHOTOSYNTHESIS OF ‘GENOVESE’ AND ‘PURPLE RUFFLES’ BASIL IN RESPONSE TO TEMPERATURE AND LIGHT IN A GROWTH CHAMBER

5.1. Introduction

The accumulation of net carbohydrates through photosynthesis governs biomass production of plants. The effects of light on photosynthesis and the increase in photosynthesis with increasing light up to saturating conditions have been well documented (Salisbury and Ross, 1992). Environmental conditions that optimize photosynthesis, including light and temperature, are critical in maximizing biomass accumulation. Published guidelines for production of basil state only general environmental conditions such as daytime temperature range between 20 to 30 °C, night temperature range of 15 to 20 °C, full sun, and no specific humidity requirements. For optimum production of basil, knowledge of specific photosynthetic response to a range of environmental conditions is valuable. The objective of this study was to determine how photosynthesis of two cultivars of basil, ‘Genovese’ and ‘Purple Ruffles’, responds to different temperatures and light intensities.

5.2. Materials and Methods

5.2.1. Growth Chamber Description

The environment in the growth chamber was controlled by a Campbell 21x datalogger (CR 21x datalogger, Campbell Scientific, Inc., Logan, UT). The growth chamber contained 400 W high pressure sodium lamps, humidifiers, dehumidifiers, a mechanical refrigeration unit, and carbon dioxide enrichment. Temperature and humidity were controlled throughout the three studies. Temperature was controlled within 2 °C of the setpoint and relative humidity fluctuated ± 20% of the setpoint of 60%.

5.2.2. Basil Cultivation

Two cultivars of basil (*Ocimum basilicum* L.), ‘Genovese’ and ‘Purple Ruffles’ were grown in containers. Three experiments were conducted, two during summer in August and one during winter in February. Seeds were started in cell trays in a mist house for all three experiments. After cotyledon emergence, seedlings were irrigated with a half strength (EC, 0.8 dS m^{-1}) nutrient solution every other day (nutrient solution specified in Chapter 3). After 3 to 4 leaf pairs had developed, basil plants were transplanted to containers filled with Sunshine Mix #1 (Sun Gro, Bellevue, WA) and perlite (Therm-O-Rock West Inc., Chandler, AZ) (3:1 vol.). Basil plants for the summer experiments were transplanted to 18 L containers and were grown in a retractable roof greenhouse under a white woven roof providing approximately 50% shade. Plants were transferred to the growth chamber in August at the age of five months. Basil plants for the winter experiment were transplanted to 5 L containers and were grown on benches in an environmentally controlled greenhouse until the time of measurement. Once transplanted to containers, basil plants were irrigated with a full strength nutrient solution (EC, 1.8 dS m^{-1}). Basil plants for the winter experiment remained in the greenhouse until February when they were transferred to the growth chamber at the age of five months.

Basil plants grown in the RRGH for five months prior to growth chamber measurements in August were regularly exposed to daytime/nighttime temperatures of

45/20 °C and maximum PPF of 2000 µmol m^{-2} s^{-1}. Basil plants grown in the environmentally controlled greenhouse for five months prior to growth chamber measurements in February were maintained daytime/nighttime temperature setpoints of 25/18 °C and maximum PPF of 500 µmol m^{-2} s^{-1}.

5.2.3. Photosynthesis Measurement

Leaf gas exchange was measured using a Ciras-2 (PP Systems, Amesbury, MA). Photosynthetically active radiation (PAR) was provided from an internal light source within the instrument. The Ciras-2 provided PAR levels starting at 2000 µmol m^{-2} s^{-1} followed by 1500 µmol m^{-2} s^{-1}, 1000 µmol m^{-2} s^{-1}, 500 µmol m^{-2} s^{-1}, 250 µmol m^{-2} s^{-1}, and 0 µmol m^{-2} s^{-1} for the measurements. Carbon dioxide in the growth chamber was maintained at 350 µmol mol^{-1} and was maintained at 400 µmol m^{-2} s^{-1} within the leaf chamber of the Ciras-2. The Ciras-2 was set to take readings assuming a 50/50 stomatal ratio for either side of the leaf. At each measurement, the Ciras-2 recorded the carbon dioxide level supplied to the leaf, the leaf temperature, PPF, evaporation, stomatal conductance, and photosynthesis. Water use efficiency was calculated by dividing photosynthesis by evaporation.

Leaves were exposed to 2000 µmol m^{-2} s^{-1} for two consecutive measurements and only the second reading was used for data analysis. The Ciras-2 equilibrates for two minutes after the specific PPF is applied before recording data. Photosynthesis rates show a sudden increase when high PPF intensities are applied until steady state conditions are reached. It has been shown that this rapid increase and period of fluctuation is complete within 2 minutes of applying a different PPF intensity (Ernstsen et al., 1997). Therefore, the 2 minute delay within the Ciras-2 after application of the specific PPF accurately represents close to steady state conditions.

5.2.4. Acclimation to Temperature Conditions

For each of the three experiments, the procedure of acclimating the plants to the temperature setpoints varied by the number of hours plants were exposed to a specific temperature before photosynthesis was measured.

During the first summer experiment plants were maintained at 20 °C in darkness for 4 hours in between each temperature treatment followed by 2 hours under 300 μmol m^{-2} s^{-1} at the specific new temperature setpoint. After 2 hours of light at the specific temperature setpoint, photosynthetic readings were taken. At night, plants were maintained in darkness at 20 °C. The measurement period was 3 days. On the first day, the plants were held at 20 °C in darkness the previous night. The first measurements were taken at the temperature setpoint of 25 °C after a 2 hour acclimation period with the high pressure sodium lights providing approximately 300 μmol m^{-2} s^{-1}. After measurement, the plants were maintained at 20 °C in darkness for 4 hours. The temperature setpoint was then changed to 30 °C and lights were turned on. After 2 hours of equilibration, measurements were taken. After the 30 °C measurements, the plants were held overnight at 20 °C in darkness. This procedure was repeated the second day with temperatures setpoints of 35 °C and 40 °C, and the third day temperature setpoints of 20 °C followed by 15 °C. Photosynthesis at 15 °C was measured last to prevent possible chilling injury of the cold sensitive basil plants.

During the second summer experiment, a similar procedure was used, although the time in 20 °C darkness was uniform so that there was not a longer overnight period followed by a shorter 4 hour period of acclimation prior to the second temperature setpoint of each day. In this experiment, the plants were held at 20 °C in darkness for 7 hours, followed by a 2 hour acclimation period at the specific temperature setpoint with the lights on, followed by a 3 hour measurement period. This 12 hour cycle was repeated for three days. The order of the temperature setpoints was the same as in the first experiment with 25 °C then 30 °C on the first day, 35 °C then 40 °C on the second day, and 20 °C followed by 15 °C on the third day.

During the winter experiment, one temperature treatment was used each day. Different plants were used for each temperature treatment during this experiment, so the order of the temperatures was not specified, as there was no potential risk of chilling injury. Plants remained in the greenhouse when not being measured, so no dark period was provided in the growth chamber. Each morning, five containers of each cultivar were placed in the growth chamber, and were acclimated for four hours at the specific temperature treatment with the lights on. After four hours, measurements were taken and plants were then returned to the greenhouse. The experiment lasted six days starting with 15 °C and increasing temperatures in 5 °C increments up to 40 °C.

5.2.5. Experimental Design and Analysis

During the summer experiments, three containers of each cultivar were placed in the growth chamber and were used for all temperature setpoints. Three basil plants were grown in each container. At each temperature setpoint, three measurements were recorded. One newly matured, fully expanded leaf at the top of the canopy was chosen from each container for measurement.

For the winter experiment, five containers, each with one plant, were used for both cultivars. For each of the six temperature treatments, a new set of five plants from each cultivar were used. One recently matured fully expanded leaf from each container was measured at each temperature setpoint.

Data were analyzed with the software program JMP IN (SAS Institute Inc., Cary, NC). ANOVA was used to compare temperature and light treatments and means were separated by Tukey's HSD. Each cultivar and experiment were analyzed separately for light saturation point of photosynthesis (Pn_{sat}), photosynthetic efficiency, slope between 0 to 250 µmol m^{-2} s^{-1}, light compensation point, respiration and water use efficiency at the different temperature and light conditions.

5.3. Results and Discussion

5.3.1. 'Genovese' Response to Temperature and Light: Summer 1

During the first summer study, Pn_{sat} of 'Genovese' basil was significantly different due to temperature (p=0.0465, Table 5.3.1.1), although mean separation by Tukey's HSD did not indicate a difference between means. Light saturated photosynthetic rate was measured at a temperature of 35 °C and a light intensity of 1500 µmol m^{-2} s^{-1} (Figure 5.3.1.1). Photosynthetic efficiency did not differ between temperature treatments, and the mean was 0.031 (p=0.1029). Respiration of ‘Genovese’ basil occurred when no light was provided by the Ciras-2, although low intensity light from the chamber was available. Respiration under these conditions was significantly different due to temperature (p<0.0001, Table 5.3.1.1). Additionally, temperature was a significant factor for water use efficiency (moles of CO_2 fixed per moles H_2O lost) (p=0.0005) and light compensation point (LCP) (p=0.000.2, Table 5.3.1.1). Figure 5.3.1.1 shows the photosynthetic response curves for each temperature and light condition.

Pn_{sat}, while not different by mean separation, was greatest at 35 °C, followed by 25 °C and 20 °C. Pn_{sat} rates at 15 °C, 30 °C, and 40 °C were similar and up to 48% lower than those at 35 °C. Basil plants had grown under temperature conditions regularly reaching 35 °C in the RRGH prior to being placed in the growth chamber, making the maximum response at this temperature likely, as plants show optimal Pn rates close to their growth conditions (Lambers et al., 1998). The low Pn at 15 °C may be due to the acclimation of plants to summer temperatures and therefore the optimum response close to the growth temperature conditions. The sudden drop of maximum photosynthetic rate at 40 °C may be due to the fact that plants acclimated to hot environments, such as the summer conditions in the RRGH, show optimum temperatures close to the temperature of enzymatic inactivity (Lambers et al., 1998).

Respiration rates were significantly different and ‘Genovese’ basil acclimated to either 35 °C or 40 °C had respiration rates four times higher than plants acclimated to either 15 °C or 20 °C. Respiration rates have been reported to increase with increasing temperatures for many plant species (Lambers et al., 1998), and the respiration rates of ‘Genovese’ basil followed the same trend.

Water use efficiency for basil acclimated to either 15 °C or 20 °C was 137% greater than basil acclimated to 40 °C. Maximum photosynthesis rates were similar for these three temperatures, specifically 15 °C and 40 °C, but the amount of water necessary to cool the leaf by transpiration at 40 °C was significantly greater, creating lower water use efficiency at this temperature.

The light compensation point increased with increasing temperature. The greatest LCP was at 35 °C and 40 °C and was 57% greater than both 25 °C and 30 °C and 24 times greater than the lowest LCP at 15 °C. The increase in LCP with increasing temperature is due to the increased rate of respiration at higher temperatures (Salisbury and Ross, 1992).

Table 5.3.1.1. Light saturation point (Pn_{sat}, µmol m^{-2} s^{-1}), respiration rate (µmol m^{-2} s^{-1}), water use efficiency (WUE, moles CO_2 fixed per moles H_2O lost) and light compensation point (LCP, µmol m^{-2} s^{-1}) of 'Genovese' basil under six temperature treatments (Summer 1).

Temperature (° C)	Pn_{sat}	Respiration	WUE	LCP
15	11.2	-0.066 d*	5.71 a	2.3 b
20	14.0	-0.633 cd	4.87 a	20.1 ab
25	17.7	-1.500 ab	4.58 ab	42.4 ab
30	11.6	-0.966 abc	4.22 ab	35.3 ab
35	21.6	-1.966 a	2.82 bc	56.3 a
40	12.1	-1.633 a	2.23 c	61.1 a

*Means within a column followed by a different letter are significantly different at $p<0.05$.

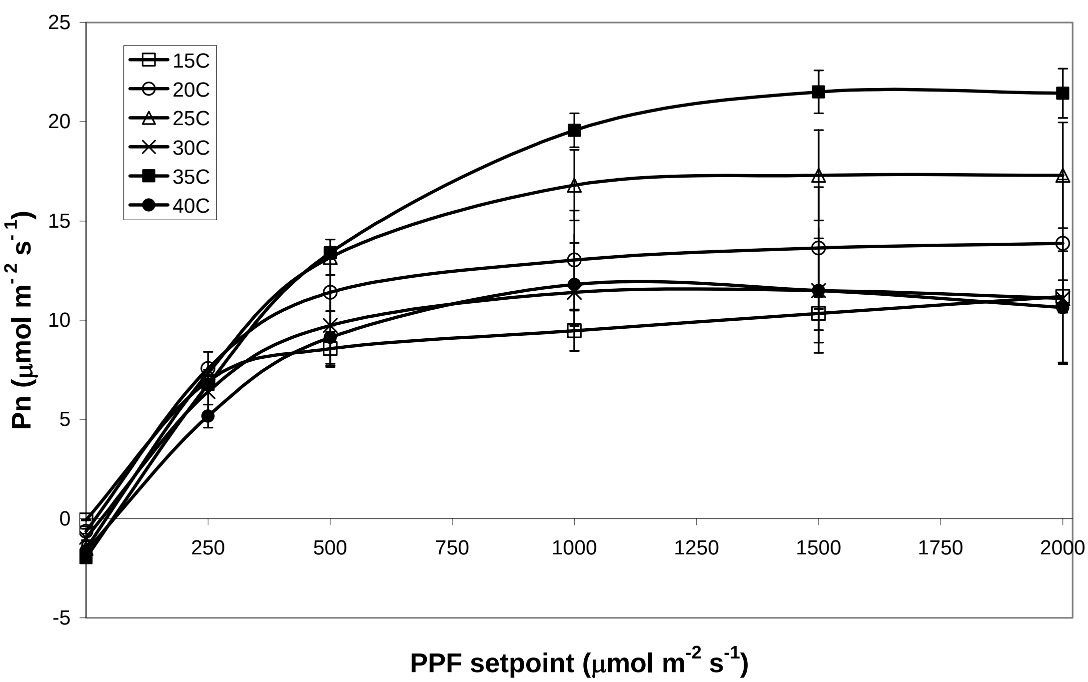

Figure 5.3.1.1. 'Genovese' basil temperature response curves during the first summer run. Each data point represents the average of three plants; bars represent standard error of the mean.

5.3.2. 'Purple Ruffles' Response to Temperature and Light: Summer 1

Pn_{sat} of 'Purple Ruffles' basil was significantly different when exposed to different temperatures (p=0.0023) with maximum photosynthesis measured at 35 °C at 1500 µmol m^{-2} s^{-1} (Figure 5.3.2.1, Table 5.3.2.1). Additionally affected by temperature was the photosynthetic efficiency (p=0.0163), respiration (p=0.0007), water use efficiency (p<0.0001), and light compensation point (p=0.0107, Table 5.3.2.1). Photosynthetic rates for each temperature and light conditions are presented in Figure 5.3.2.1.

Pn_{sat} at 35 °C was 149% greater than plants acclimated to 15 °C. As stated for 'Genovese' basil, 'Purple Ruffles' plants in the RRGH environment were previously acclimated to high temperatures prior to acclimation to any growth chamber temperature setpoint. Photosynthetic efficiency was 32% greater for 'Purple Ruffles' basil acclimated to 35 °C compared to 40 °C. Pn_{sat} for 'Purple Ruffles' was 18% less than 'Genovese'. Pn_{sat} rate and photosynthetic efficiency are variables resulting in biomass accumulation, with Pn_{sat} being the most important variable for plants grown in summer when PPF is not limiting, and photosynthetic efficiency being most important during winter when low light intensities are typical. For 'Purple Ruffles' acclimated to high temperatures and light intensities prior to initiation of the growth chamber studies, 35 °C was the temperature which maximized photosynthesis rates and photosynthetic efficiency. As with the 'Genovese' basil, respiration rate increased with increasing temperature in 'Purple Ruffles'. Plants acclimated to 35 °C and had respiration rates 10% greater than plants acclimated to either 15 °C or 20 °C.

Water use efficiency of ‘Purple Ruffles’ basil acclimated to 30 °C was 103% greater than basil acclimated to either 35 °C or 40 °C. The low water use efficiency at 35 °C and 40 °C was expected, yet the higher efficiency at 30 °C, 25 °C and 20 °C was less anticipated. In general, ‘Purple Ruffles’ has lower water use efficiencies than ‘Genovese’ due to the lower photosynthesis rates of this cultivar yet similar water use for transpiration.

The light compensation point of ‘Purple Ruffles’ was 91% greater at 35 °C compared to 15 °C. The percent increase of LCP between temperatures was much less pronounced in ‘Purple Ruffles’ compared to ‘Genovese’ due to the lower percent increase in respiration rates between temperature treatments for the two cultivars.

Table 5.3.2.1. Light saturation point (Pn_{sat}, µmol m^{-2} s^{-1}), respiration rate (µmol m^{-2} s^{-1}), water use efficiency (WUE, moles CO_2 fixed per moles H_2O lost) and light compensation point (LCP, µmol m^{-2} s^{-1}) of ‘Purple Ruffles’ basil under six temperature treatments (Summer 1).

Temperature (°C)	Pn_{sat}	Pn Efficiency	Respiration	WUE	LCP
15	7.17 bc*	0.019 b	-0.600 bc	3.19 b	32.3 b
20	9.53 abc	0.022 ab	-0.800 bc	3.63 ab	36.8 ab
25	14.80 ab	0.023 ab	-1.466 ab	3.34 ab	63.6 a
30	11.40 abc	0.023 ab	-0.900 abc	4.01 a	40.5 ab
35	17.83 a	0.025 a	-1.533 a	2.35 c	61.9 a
40	11.73 abc	0.019 b	-0.800 bc	1.61 c	42.6 ab

*Means within a column followed by a different letter are significantly different at $p<0.05$.

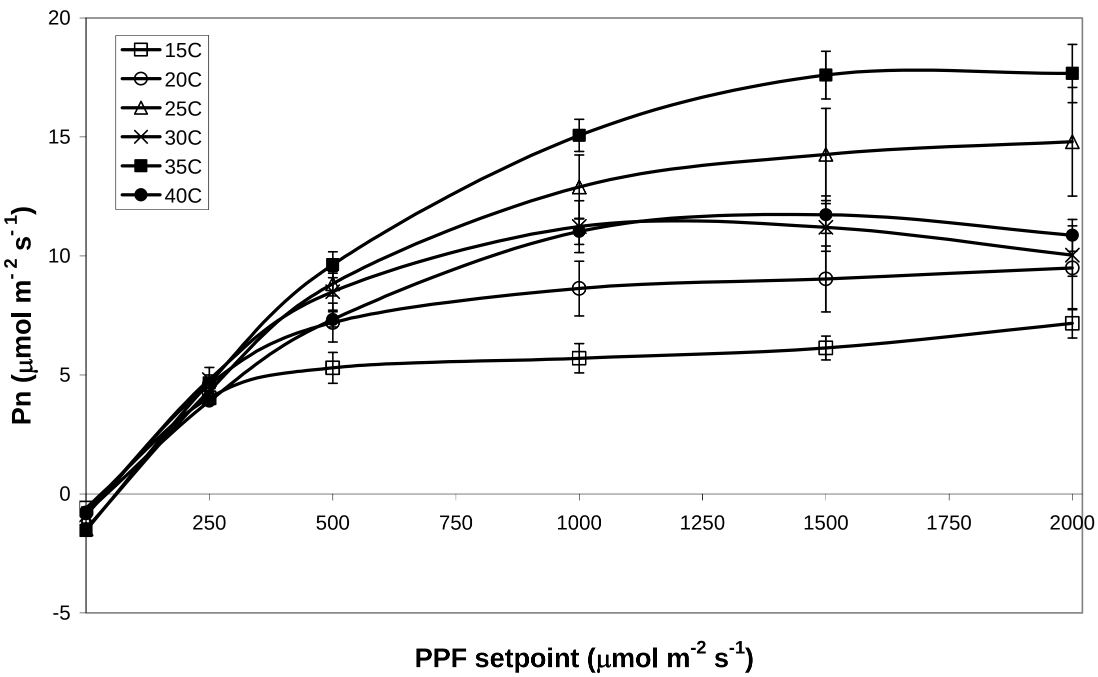

Figure 5.3.2.1. 'Purple Ruffles' basil temperature response curves during the first summer run. Each data point represents the average of three plants; bars represent standard error of the mean.

5.3.3. 'Genovese' Response to Temperature and Light: Summer 2

During the second summer study, Pn_{sat}, photosynthetic efficiency, respiration, water use efficiency and light compensation point for 'Genovese' basil were significantly different due to temperature ($p=0.0026$, Table 5.3.3.1). Pn_{sat} rate was at 25 °C at 1500 μmol m^{-2} s^{-1} (Figure 5.3.3.1).

Pn_{sat} rate at 25 °C was two times higher than the rate at 15 °C. Photosynthesis rates at 35 °C were second highest compared to 25 °C, showing that plants acclimated to high summer temperatures showed high photosynthesis rates at warm temperatures. The drop in photosynthesis rates at 30 °C is puzzling and may be due to inadequate watering prior to measurement.

Photosynthetic efficiency of 'Genovese' basil was also greatest at 25 °C, and was 48% greater than at either 15 °C, 30 °C or 40 °C. Respiration increased more than 9 times when 'Genovese' basil was acclimated to 35 °C compared to 20 °C. Water use efficiency increased by 148% for 'Genovese' basil acclimated to either 15 °C or 20 °C compared to 40 °C. Light compensation points were 9 times greater at 35 °C compared to 15 °C, but did not increase with increasing temperature as regularly as the first summer study and instead were relatively similar at all other temperatures compared to 15 ° C.

The second summer study for 'Genovese' basil was similar to the first summer study in terms of Pn response of plants to temperature and light. 'Genovese' basil also showed Pn_{sat} rates at light intensities of 1500 µmol m^{-2} s^{-1} which were regularly reached during growth of the plants during summer in the RRGH.

Table 5.3.3.1. Light saturation point (Pn_{sat}, µmol m^{-2} s^{-1}), photosynthetic efficiency, respiration rate (µmol m^{-2} s^{-1}), water use efficiency (WUE, moles CO_2 fixed per moles H_2O lost) and light compensation point (LCP, µmol m^{-2} s^{-1}) of 'Genovese' basil under six temperature treatments (Summer 2).

Temperature (° C)	Pn_{sat}	Pn Efficiency	Respiration	WUE	LCP
15	6.73 c*	0.023 b	-0.866 bcd	5.78 a	36.9 b
20	12.50 bc	0.031 ab	-0.233 cd	6.28 a	7.6 c
25	20.20 a	0.037 a	-1.133 bc	4.86 ab	30.5 b
30	8.86 bc	0.027 b	-1.066 bc	3.51 bc	38.9 b
35	16.23 ab	0.033 ab	-2.466 a	3.21 bc	76.2 a
40	9.47 bc	0.024 b	-0.766 bcd	2.43 c	31.6 b

*Means within a column followed by a different letter are significantly different at $p<0.05$.

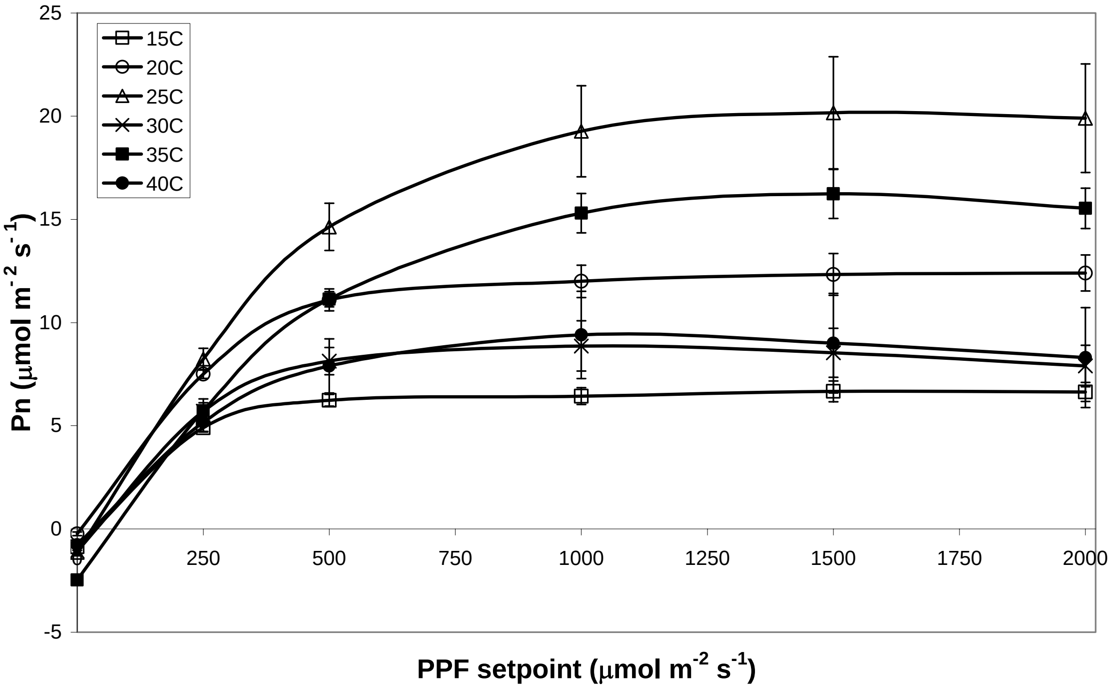

Figure 5.3.3.1. 'Genovese' basil temperature response curves during the second summer run. Each data point represents the average of three plants; bars represent standard error of the mean.

5.3.4. 'Purple Ruffles' Response to Temperature and Light: Summer 2

During the second summer study, Pn_{sat}, photosynthetic efficiency, respiration and water use efficiency were significantly different (p=0.0043, Table 5.3.4.1). Maximum photosynthesis was measured at 35 °C at 1500 μmol m^{-2} s^{-1} (Figure 5.3.4.1).

Pn_{sat} of 'Purple Ruffles' basil at 35 °C was 59% greater than at either 15 °C, 20 °C, or 40 °C. Compared to 35 °C, 25 °C had the highest photosynthetic rate. As with the 'Genovese' basil during the second summer study, 30 °C showed much lower rates compared to 25 °C and 35 °C, which may be due to the plants not being fully hydrated at the time of measurement.

Photosynthetic efficiency of ‘Purple Ruffles’ basil was 40% greater at 25 °C compared to 15 °C. Respiration was 161% greater at 35 °C compared to either 20 °C or 40 °C. The lower respiration rate at 40 °C is unusual and most likely due to the relatively high photosynthesis rates for this temperature during this run. Water use efficiency was 68% greater at either 15 °C or 30 °C compared to either 35 °C or 40 °C. The light compensation point was 59% greater at 35 °C compared to all other temperatures, which were not significantly different from one another.

Response of ‘Purple Ruffles’ basil in both summer trials was similar with highest photosynthesis rates occurring at 1500 µmol m^{-2} s^{-1} PPF, which were similar light intensities compared to the summer conditions in the RRGH. The photosynthesis rates were also high with the maximum rates between 10 to 20 µmol m^{-2} s^{-1}. Maximum rates during summer experiments were high, yet lower for ‘Purple Ruffles’ as a cultivar compared to ‘Genovese’. Overall growth and biomass accumulation of ‘Purple Ruffles’ was lower than ‘Genovese’ throughout the production studies most likely due to the overall lower photosynthetic efficiencies and rates seen in the temperature response curves compared to ‘Genovese’.

Table 5.3.4.1. Light saturation point (Pn_{sat}, µmol m^{-2} s^{-1}), photosynthetic efficiency, respiration rate (µmol m^{-2} s^{-1}), water use efficiency (WUE, moles CO_2 fixed per moles H_2O lost) and light compensation point (LCP, µmol m^{-2} s^{-1}) of 'Purple Ruffles' basil under six temperature treatments (Summer 2).

Temperature (° C)	Pn_{sat}	Pn Efficiency	Respiration	WUE	LCP
15	6.07 c*	0.015 c	-1.067 ab	3.06 a	69.2 b
20	7.80 bc	0.020 ab	-0.667 b	2.93 ab	33.3 b
25	11.00 ab	0.021 a	-1.467 ab	2.86 ab	69.2 b
30	8.27 bc	0.019 abc	-1.100 ab	3.07 a	58.4 b
35	11.73 a	0.019 abc	-2.000 a	1.82 b	103.4 a
40	8.57 ab	0.016 bc	-0.867 b	1.82 b	54.4 b

*Means within a column followed by a different letter are significantly different at $p<0.05$.

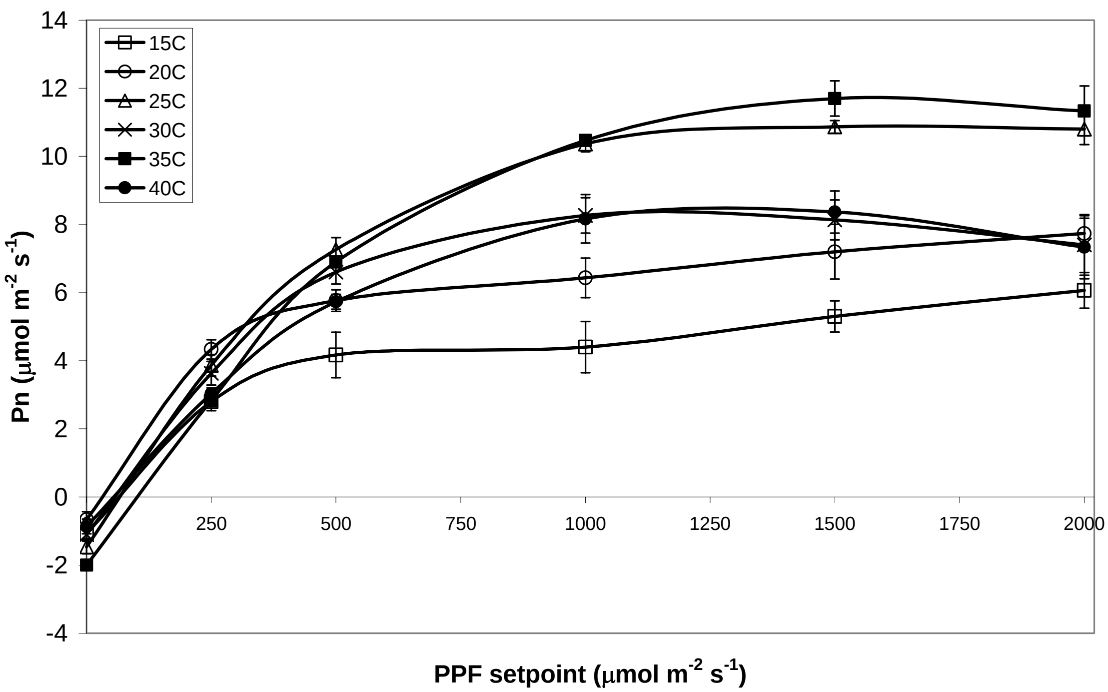

Figure 5.3.4.1. 'Purple Ruffles' basil temperature response curves during the second summer run. Each data point represents the average of three plants; bars represent standard error of the mean.

5.3.5. 'Genovese' Response to Temperature and Light: Winter

During the winter study, Pn_{sat}, photosynthetic efficiency and water use efficiency were significantly (p=0.0394) due to temperature (Table 5.3.5.1). Maximum photosynthesis rate was measured at 20 °C at 2000 µmol m^{-2} s^{-1} (Figure 5.3.5.1).

Pn_{sat} of 'Genovese' basil were 155% higher at 20 °C compared to 30 °C. Compared to the rates of 'Genovese' plants acclimated to summer conditions in the RRGH, rates of plants grown during low light intensity winter conditions were much lower with maximum photosynthesis rates of 2.5 µmol m^{-2} s^{-1}.

Photosynthetic efficiency of 'Genovese' basil acclimated to low light intensity winter conditions was not different by mean separation, but the highest photosynthetic efficiency was at 20 °C. Photosynthetic efficiency is more important than maximum photosynthesis rates for plants grown in winter under low light intensities compared to plants grown under high light intensity summer conditions. Photosynthetic rates and efficiencies were lower for 'Genovese' basil plants grown in winter compared to summer. Biomass accumulation under low light intensities would be severely reduced by the decrease in both photosynthetic rate and photosynthetic efficiency.

Water use efficiency was 157% greater for plants acclimated to 15 °C or 20 °C compared to plants acclimated to either 25 °C, 30 °C, 35 °C or 40 °C. Water use efficiency increased with lower temperatures for plants acclimated to cooler temperatures.

Light compensation points of basil plants acclimated to low light intensities were almost double that of the plants acclimated to summer conditions in the summer experiments for ‘Genovese’ basil. LCP was again greatest at 35 °C, and 14 times greater than at 20 °C.

Table 5.3.5.1. Light saturation point (Pn_{sat}, µmol m^{-2} s^{-1}), photosynthetic efficiency, respiration rate (µmol m^{-2} s^{-1}), water use efficiency (WUE, moles CO_2 fixed per moles H_2O lost) and light compensation point (LCP, µmol m^{-2} s^{-1}) of ‘Genovese’ basil under six temperature treatments (Winter 1).

Temperature (° C)	Pn_{sat}	Pn Efficiency	WUE	LCP
15	2.00 ab*	0.0088	4.27 a	63.5 ab
20	2.50 a	0.0097	3.89 a	47.0 b
25	1.84 ab	0.0074	2.59 bc	66.3 ab
30	0.98 b	0.0058	1.36 bcd	130.0 ab
35	1.24 ab	0.0060	1.21 cd	149.2 a
40	1.38 ab	0.0061	1.20 cd	77.2 ab

*Means within a column followed by a different letter are significantly different at $p<0.05$.

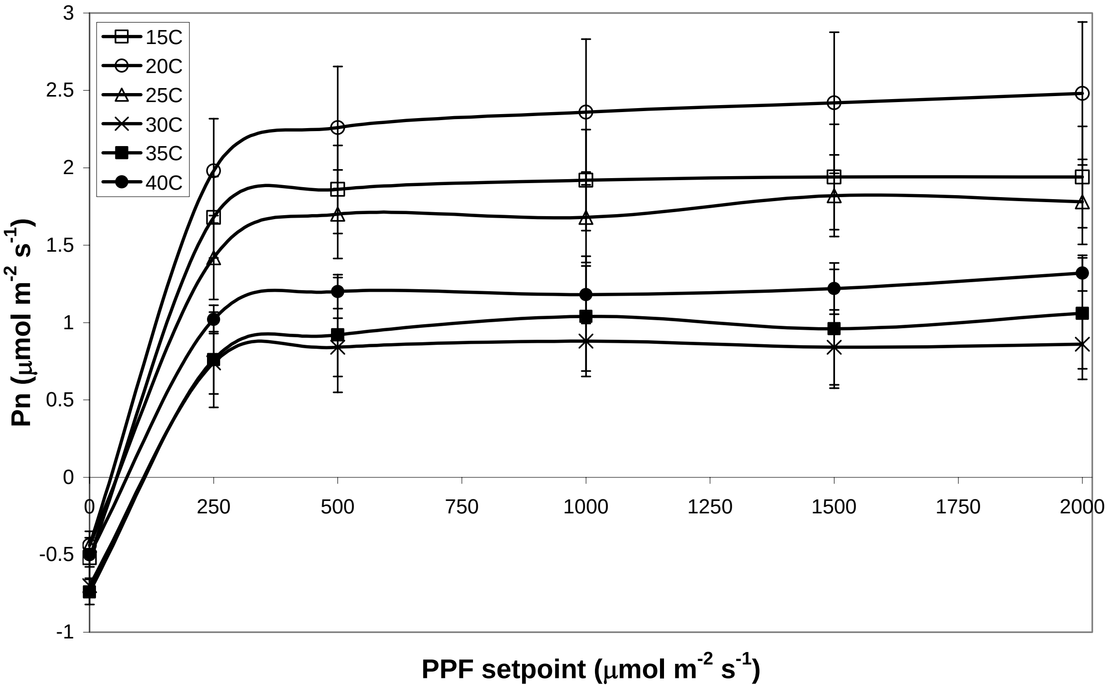

Figure 5.3.5.1. 'Genovese' basil temperature response curves during the winter run. Each data point represents the average of five plants; bars represent standard error of the mean.

5.3.6. 'Purple Ruffles' Response to Temperature and Light: Winter

During the winter study, Pn_{sat}, photosynthetic efficiency, respiration and water use efficiency for 'Purple Ruffles' basil were significantly different due to temperature ($p=0.0175$, Table 5.3.6.1). Maximum photosynthesis was measured at 40 °C at 1500 μmol m^{-2} s^{-1} (Figure 5.3.6.1).

Pn_{sat} rate of 'Purple Ruffles' basil grown during low light intensity winter conditions was 75% higher at either 35 °C or 40 °C compared to 15 °C. The preference of basil for high light and warm temperatures was still apparent despite it being grown under winter conditions. Pn_{sat} rates were still higher at warm temperatures, although were lower than the summer rates, reaching maximums of 6.5 μmol m^{-2} s^{-1} during winter.

Photosynthetic efficiency of ‘Purple Ruffles’ basil was 13 times greater at either 20 °C, 25 °C, or 30 °C compared to 15 °C. Photosynthetic efficiency was lower for plants grown during the winter, but the efficiency was not as reduced in ‘Purple Ruffles’ between seasons compared to the reduction in Pn efficiency found between seasons for ‘Genovese’. The greater Pn_{sat} and Pn efficiency of ‘Purple Ruffles’ compared to ‘Genovese’ during winter may result in greater biomass accumulation of this cultivar during winter, although winter production of the two cultivars was not evaluated in these studies.

Respiration rates of ‘Purple Ruffles’ were 264% higher for all temperatures compared to 15 °C. Water use efficiency was 82% greater at 25 °C compared to either 35 °C or 40 °C. Light compensation points of ‘Purple Ruffles’ basil plants acclimated to low light intensity winter conditions were greater than when plants were acclimated to high light intensity summer conditions. LCP was 74% greater for all temperatures compared to 15 °C.

Table 5.3.6.1. Light saturation point (Pn_{sat}, µmol m^{-2} s^{-1}), photosynthetic efficiency, respiration rate (µmol m^{-2} s^{-1}), water use efficiency (WUE, moles CO_2 fixed per moles H_2O lost) and light compensation point (LCP, µmol m^{-2} s^{-1}) of 'Purple Ruffles' basil under six temperature treatments (Winter 1).

Temperature (° C)	Pn_{sat}	Pn Efficiency	Respiration	WUE	LCP
15	3.64 b*	0.001 b	-0.280 b	2.32 ab	29.7 b
20	4.94 ab	0.014 a	-1.160 a	2.12 bc	81.5 a
25	5.80 ab	0.014 a	-1.020 a	2.86 a	72.8 a
30	5.14 ab	0.014 a	-1.020 a	2.34 ab	72.1 a
35	6.28 a	0.013 ab	-0.940 a	1.65 c	74.1 a
40	6.46 a	0.013 ab	-0.960 a	1.50 c	75.3 a

*Means within a column followed by a different letter are significantly different at $p<0.05$.

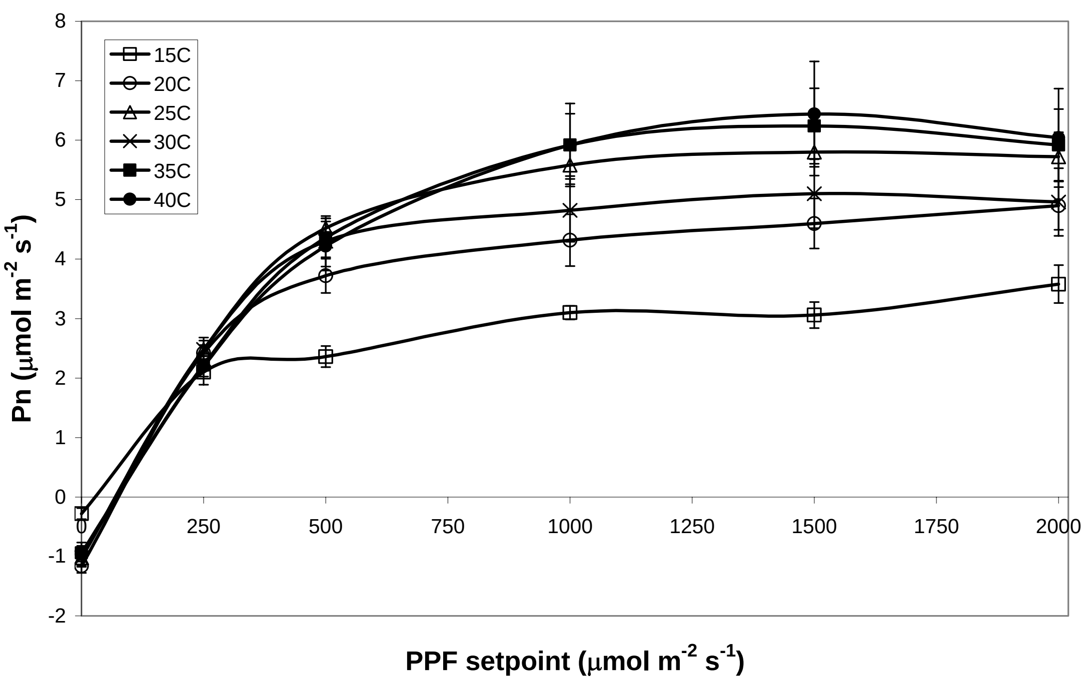

Figure 5.3.6.1. 'Purple Ruffles' basil temperature response curves during the winter run. Each data point represents the average of five plants; bars represent standard error of the mean.

5.3.7. Discussion and Conclusions

Photosynthetic rates of basil under different light intensities have been previously evaluated by Ernstsen et al. (1997). Basil plants were grown in a greenhouse with daytime/nighttime temperature setpoints of 25/20 °C, under three light environments; 1800 µmol m^{-2} s^{-1}, 180 µmol m^{-2} s^{-1}, and fluctuating light between the previous two intensities at 15 minute intervals for 15 hour photoperiods. Results indicated no significant differences between steady state photosynthetic rates at a light intensity of 1180 µmol m^{-2} s^{-1} between plants that had developed under the three different light intensities with a mean photosynthetic rate of 6.7 µmol m^{-2} s^{-1}.

The findings of Ernstsen et al. (1997) do not coincide with the findings of the growth chamber studies reported here. The results of Ernstsen indicated that it is commonly reported that species have different photosynthetic responses based on their previous conditioning, but that this case was an exception which has also been noted for some polar species. In the present study, photosynthesis rates for basil were always different between low and high light intensities, with maximum photosynthesis rates at 1500 µmol m^{-2} s^{-1}.

Pn_{sat} rates are most important under light saturating conditions, whereas photosynthetic efficiencies are more critical to plant growth under low light intensity environments. Overall, plants grown during summer environmental conditions had greater photosynthetic rates and efficiencies compared to plants grown during winter environmental conditions for both basil cultivars. During summer, Pn_{sat} was 22 µmol m^{-2} s^{-1} for 'Genovese' and 18 µmol m^{-2} s^{-1} for 'Purple Ruffles'. During winter Pn_{sat} was 2.5

μmol m^{-2} s^{-1} for ‘Genovese’ and 6.5 μmol m^{-2} s^{-1}. The increasing difference in photosynthetic rate between temperature treatments became more pronounced with increasing light intensities which has been reported for many species (Berry and Bjorkman, 1980). During the summer trials, ‘Genovese’ had greater photosynthetic rates than ‘Purple Ruffles’. While both cultivars had greater Pn rates and efficiencies during the summer trials, ‘Purple Ruffles’ maintained respectively higher rates than ‘Genovese’ in winter. The ability for ‘Purple Ruffles’ to maintain higher rates in winter may translate to greater biomass accumulation during winter production if temperatures can be maintained at optimal levels.

Saturating light intensities were similar for both cultivars. During summer experiments, maximum Pn most frequently occurred at 1500 μmol m^{-2} s^{-1}. During winter, ‘Genovese’ began to reach saturation at much lower light intensities at approximately 500 μmol m^{-2} s^{-1}, whereas ‘Purple Ruffles’ maintained high saturation intensities.

The maximum photosynthesis rates were found at conditions most similar to the growth environment of the plant for ‘Genovese’, which had higher Pn rates at higher temperatures and light intensities when acclimated to summer conditions, and lower Pn values at lower temperatures and light intensities when acclimated to winter conditions. ‘Purple Ruffles’ independent of growth conditions, maintained its preference for high light intensities and temperatures.

The effects of respiration resulted in differences in water use efficiencies and light compensation points for both cultivars. Respiration rates increased with increasing temperature resulting in lower water use efficiencies and greater light compensation points. Additionally, light compensation points were greater for the winter trials in both cultivars after being acclimated to low light conditions.

Plants acclimated to high light intensities are known to have higher photosynthetic rates than plants acclimated to low light intensities, independent from whether or not they are referred to as sun or shade plants (Boardman, 1977). Both ‘Genovese’ and ‘Purple Ruffles’ had higher photosynthetic rates when acclimated to higher light intensities, irrespective of the temperatures or light intensities they were acclimated to in the growth chamber. The short term acclimation procedure did not supersede the conditions they had adapted to during initial growth, although it has been reported that full acclimation to new growth conditions can be achieved, but with a minimum of one week of conditioning (Berry and Bjorkman, 1980).

Photosynthetic response of two cultivars of basil was highest within the ranges given for general production guidelines of basil. For ‘Genovese’ basil, in summer photosynthesis was greatest between 25 to 35 °C at a light intensity above 1500 µmol m^{-2} s^{-1}. During winter, ‘Genovese’ basil showed highest rates of photosynthesis between 15 to 25 °C at light intensities above 500 µmol m^{-2} s^{-1}. Photosynthesis of ‘Purple Ruffles’ basil was greatest between 25 to 35 °C during both summer and winter at light intensities above 1500 µmol m^{-2} s^{-1} during summer and 1000 µmol m^{-2} s^{-1} during winter. The experimental measurements confirmed the currently recommended optimum temperature and light conditions for basil production.

6. CONCLUSIONS

Basil can be successfully grown under several cultural practices and environmental conditions during summer in a semi-arid climate. The demand for superior quality fresh basil throughout the year that commands high prices even during summer coupled with the short post-harvest shelf life creates considerable potential for niche market opportunities. Different cultural practices and manipulation of environmental conditions to produce significant quantities of superior quality basil in retractable roof greenhouses in semi-arid regions have been explored as alternatives to seasonal field production.

'Genovese', the pesto basil, is most commonly produced throughout the United States, but other cultivars are gaining popularity. Therefore differences in cultural and environmental practices for individual cultivars, as well as the differences in productivity, pricing, and returns when growing different cultivars need to be investigated. Three cultivars, 'Genovese', 'Genovese Compact' and 'Purple Ruffles' were evaluated in the retractable roof greenhouse and in full sun. 'Genovese' and 'Genovese Compact' were similar within treatments in terms of productivity and quality, and both produced twice the amount of 'Purple Ruffles'. The reduced productivity of 'Purple Ruffles' as a cultivar would require an increased price to maintain profit margins.

Quality of the three basil cultivars was primarily affected by environment, and quantity of basil was largely affected by production system. Quality of the three basil cultivars was superior when grown in the RRGH under either shade in all of the production systems compared to full sun. Quality of plants grown in the RRGH was greater compared to full sun due to plants under shade having larger leaf areas, greater survival, less flowering, and no need to clean the product before marketing.

Biomass accumulation was predominately affected by production system. On a per plant basis, ‘Genovese’ basil grown in rockwool or raised beds produced almost one and a half times more than basil grown in containers and almost double that of basil grown in the vertical system or in soil. Although these two systems produced more biomass on a per plant basis, the vertical system has the capability to produce more per unit area as the density of plants in the vertical system was four-fold greater than the rockwool system and soil and two-fold greater than the density in raised beds.

Biomass accumulation in full sun was greatly increased in the 2004 basil trial when hydroponic systems were introduced to the outdoor environment compared to the 2003 trial with plants grown in soil in the ground. The increased productivity confirmed the importance of cultural practice on basil biomass accumulation. The increased control over root zone nutrient and irrigation management based on light provided plants with the appropriate fertigation under changing environmental conditions.

Productivity of basil grown in the RRGH was additionally affected by RRGH curtain control strategies. Strategies based on solar radiation or the globe thermometer increased productivity compared to the strategy based on air temperature. Control based on solar radiation or the globe thermometer increased exposure of the canopy to full sun solar radiation intensities in the morning and afternoon while moderating temperatures in the root zone and leaves compared to plants in full sun during midday.

The full sun preferences of basil, as recommended in production guidelines and by seed companies, are enhanced by the use of production systems providing more careful and direct management of the root zone. Management of environmental conditions in the high light intensity conditions of a semi-arid climate are important since full sun conditions in other regions of the country are much lower than full sun conditions in the semi-arid climate of Arizona. The optimum growing conditions for basil in summer as indicated by the growth chamber study range between 25 and 35 °C accompanied by light intensities of 1500 µmol m^{-2} s^{-1}, yet in the summer in Arizona a light intensity of 1500 µmol m^{-2} s^{-1} is accompanied by air temperature reaching up to 45 °C at certain times. The RRGH provides an opportunity to take advantage of high solar radiation while mediating excessive substrate and leaf temperatures compared to full sun and can enhance photosynthesis and subsequent plant productivity.

The RRGH was not able to extend the production of basil once outdoor temperatures dropped to 0 °C. The highly porous curtain materials of the RRGH would most likely make heating of the structure uneconomical. Potential possibilities to extend the season may include the addition of heat curtains and high tunnels within the structure during winter so that only a small area would be heated.

Overall, hydroponic production of basil in a RRGH produces a significant quantity of high quality product during summer production in Arizona.

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