Improving Lettuce Production in Deep Water Culture in the Southeastern United States

by

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List of Abbreviations

°C	Degrees Celsius
AU	Auburn University
SI	Size Index
RDW	Root Dry Weight
HFW	Head Fresh Weight
g	gram
h	hours
L	Liters
ppm	parts per million
DWC	Deep Water Culture

Chapter I

Introduction and Literature Review

Hydroponics refers to the technique of growing plants without soil and instead placing roots in a nutrient solution (Jones, 2005; Resh, 2004). It is commonplace to include soilless culture in the definition of hydroponics, but understanding the difference is important. Soilless culture can be defined as "growing of plants in an inorganic substance or an organic material and periodically watered with a nutrient solution" and includes various types of plant production systems such as bag culture, Dutch bucket culture, and rockwool culture, among others (Jones, 2005). Hydroponics, strictly defined, allows for no substrate or rooting media and includes techniques such as raft culture, including Deep Water Culture (DWC) and deep flow culture (DFC), nutrient film technique (NFT), and several variations of each.

While some have speculated that the genesis of soilless culture can be traced back to the Aztecs (Conan and Quilter, 2007; Jones, 2005) or even as far back as the Babylonian empire and the rule of King Nebuchadnezzar II (604-562 BC) (Clayton and Price, 1993; Jones, 2005), the history of modern hydroponics is relatively short. Growing plants without soil was first attempted for research purposes, specifically to better understand plant nutrition. Experiments performed by German scientists Julius von Sachs and Wilhem Knop in the 1860s introduced water culture as a growing media for "artificially" growing plants (Morgan and O'Haire, 1978). Both Sachs and Knop were primarily interested in studying the effects of different chemical compounds on plant growth, so isolating plants from the soil provided the best opportunity to do so. From the mid 19th century into the early 20th century techniques developed by Sachs and

Knop were used to study plant nutrition and were referred to as “nutriculture”. Nutriculture techniques were popular with researchers interested in plant nutrition and root growth, but commercial applications of nutriculture were limited until a scientist named William F. Gericke produced a series of publications in the 1930s which reported on the technical aspects and commercialization strategies for growing plants without soil (Jones, 2005). In an article appearing in *Science* in 1937 Gericke coined the term hydroponics by combining the Greek words *hydro* and *ponos* meaning “water” and “to work”, respectively (Resh, 2004). During WWII, in an effort to provide fresh fruits and vegetables to wartime soldiers, the United States armed forces established hydroponic production systems as described by Gericke on Ascension Island, located in the South Atlantic between Africa and South America (Smith et al., 2008). Although successful, hydroponic systems were not utilized commercially for the production of vegetables and flowers until the 1980s (Jones, 2005). Improvements in greenhouse design and crop management allowed for the expansion of soilless techniques for production of fruits, vegetables, and ornamentals starting in the 1980s.

Greenhouse vegetable statistics

The increase in hydroponic vegetable production since the 1980s is largely a result of technological improvements in controlled environment agriculture (CEA), mainly greenhouses. In the United States, nearly all vegetables produced in greenhouses are grown in hydroponic or soilless systems. Therefore, the term “greenhouse vegetable production” has become synonymous with hydroponics in the United States, but differences in definitions exist worldwide.

Although there are disagreements on what the definition of a greenhouse should include, a greenhouse is generally defined as “a structure designed for the cultivation of plant to protect against extreme environmental conditions and/or pests (Hickman, 2016).” Therefore, a greenhouse vegetable is a vegetable (most commonly, tomato, pepper, cucumber or lettuce) grown in a greenhouse.

In 2013, there was an estimated retail value of U.S. Greenhouse Vegetable Sales of $3 billion. In the same year, 1424.7 hectares of greenhouse space were used to produce vegetables (tomatoes, peppers, cucumbers, and lettuce) in the U.S., of which 16 hectares were devoted to lettuce (Hickman, 2016).

In the most recent U.S. Census of Agriculture it was reported that 5,757 farms produced field-grown lettuce on over 130858.7 hectares (USDA, 2012). This was a slight increase from 2007 when there was a total of 3,839 farms over 126681.2 hectares. Leaf lettuce was the most popular in terms of number of farms, while head lettuce was the most popular in terms of hectares. In 2012, 14 farms reported producing field-grown lettuce on only 1.2 hectares in Alabama.

In the same year in the U.S., 174 farms reported producing lettuce under protected culture (including hydroponics) totaling 594,313 kg of lettuce (USDA, 2012). In 2014 there were 763 operations producing lettuce with 40.1 hectares under protection, nine of which were in Alabama with .28 hectares under protection. In total, 9,947,417 kg was produced, 70% (7,002,196 kg) was from hydroponic systems. In Alabama, 258275.4 kg, of lettuce was grown under protection, 92% (238,136 kg) of which was grown hydroponically.

Lettuce is the second most consumed vegetable in the US behind only potatoes and is the most valuable with annual sales nearing $2 billion annually (USDA-ERS, 2017b). Lettuce consumption in the U.S. is approximately 11.1 kg lettuce per person per year, 45% (5 kg) of which is specialty or leaf type lettuces. The population of Alabama was approximately 4.5 million persons in the latest U.S. Census (2010), so 22.5 million kg of specialty lettuce, which could be grown in greenhouses, is consumed each year in Alabama. Romaine lettuce currently (August 2017) sells for a weighted average price of $0.61/kg (USDA-ERS, 2017c). Market weight of hydroponic butterhead lettuce (the most common greenhouse lettuce), which includes the rootball, is 140 g (3.2 heads/lb), so a potential production cap for greenhouse-grown lettuce in Alabama would be 158.4 million heads per year. This is a conservative estimate because market weight includes the weight of the rootball, which would not be consumed. Wholesale for greenhouse lettuce in the U.S. in 2009 ranged from $24 – $30 per box (24 heads) or between $1.00 – $1.25 per head (Hickman, 2016). Therefore, wholesale market cap for Alabama-grown lettuce at 2009 prices is between $158-$198 million per year. Current retail market prices range from $1.50 – $2.00 (Ralf du Toit, personal communication), so a potential retail market cap for lettuce production in Alabama would range from $237.6 – $316.8 million per year. The majority of lettuce consumed state- and nationwide is wholesale, so true market cap is likely between $160 million and $200 million per year which would certainly represent a boon for Alabama farmers.

Niche markets for lettuce

There is an increase in popularity for locally-grown food (Hardesty, 2008) as people are becoming more concerned about where their food is produced (Xu et al., 2015). Consumers believe that locally-grown food is healthier (Hardesty, 2008), that it looks fresher, tastes fresher, and is safer (Tropp, 2008) and they are therefore willing to pay higher prices for locally-grown foods (Xu et al., 2015). The demand for locally-grown food continues to rise, so much so that in 2015 the USDA launched a survey to collect information on the local food sector in the United States. The results of the survey indicated that in 2015 U.S. farms sold "$8.7 billion in edible food directly to consumers, retailers, institutions, and local distributors" (USDA-NASS, 2016). Greenhouse-grown lettuce costs more to grow than conventionally grown lettuce (Jensen, 1999), so growers must make up for the cost differences by receiving a premium for their crop.

Advantages and disadvantages of greenhouse vegetable production

Controlled environment agriculture offers advantages including the ability to grow plants in the absence of suitable soil, reducing water and nutrient waste due to reduced or no leaching, and controlling more of what is supplied to the plant such as nutrients, water, additional light or shade, and better temperature control (Jones, 2005). The level of control afforded leads to increased yield potential per area compared with field production. Multiple studies have compared greenhouse lettuce production to conventional field methods. Greenhouse conditions can lead to lettuce yields of 6 – 11x higher compared to field conditions (Jensen, 1999). This difference in yield is primarily due to superior environmental and cultural controls afforded by greenhouses (Jones, 2005).

Water savings is another advantage of growing lettuce in greenhouses when compared to field-grown. According to Barbosa and colleagues (2015), hydroponic greenhouses used 13x less water to produce comparable lettuce yields compared to field operations. Use in agricultural production accounts for approximately 80% of all fresh water used in the US (USDA-ERS, 2017), so gains in water use efficiency are critically important for future agriculture development.

Yet another benefit of greenhouse lettuce production, compared with field production not explicitly expressed in the literature, is that it affords growers flexibility of location. Greenhouse lettuce production can be accomplished in multiple areas that are not conducive to field growing of lettuce. One example is the southeastern US which has a subtropical summer climate and temperate winter climate that is not conducive to extended field production of lettuce. Field production of lettuce in the southeast is limited to the cool season, which typically lasts from October through mid-April. Winter weather in the southeast is notoriously variable and leads to difficulties for growers. CEA affords some measures of environmental control that can overcome these climatic pitfalls.

Additional benefits of greenhouse vegetable production include elimination of soil presence on produce, elimination of soil-borne diseases, and elimination of other contaminants that would be present in a field soil (Fontana and Nicola, 2008).

Notable disadvantages of CEA production compared with field production include relatively significant investment costs, highly skilled labor, and high energy costs (Jensen, 1999). Greenhouses have many structural components and are relatively expensive to build (Jensen, 1999). Covering and flooring materials, heating/cooling systems, hydroponic systems, and other machinery need to be considered (Jones, 2005). CEA production relies on technologies that can control almost all aspects of the climate in the greenhouse including temperature, light, atmospheric gas composition, irrigation, and plant nutrition which necessitates that greenhouse workers have the necessary skills and education to manage the climate control systems and the nutrient solutions (Jones, 2005).

The most notable disadvantage of greenhouse production compared to field production is energy requirement as greenhouse lettuce production can account for up to 82x more energy consumption than conventional production systems (Barbosa et al., 2015). Relatively inexpensive energy can subsidize production costs for greenhouses, but if energy costs significantly increase, greenhouse growers will be at a disadvantage regardless of water and time savings. Alternative energy systems will become more important in order to make greenhouse production competitive with field production, especially in wholesale markets.

Greenhouse energy costs

Labor is the most expensive single cost for greenhouse production while energy is the second (Frantz et al., 2010). Currently reducing labor is not a feasible strategy for reducing production costs of greenhouse lettuce, however; there is opportunity to reduce energy costs. Reducing energy inputs, while keeping production yields high is essential for keeping greenhouse lettuce growers competitive in local, regional, and national markets. In 2015, the U.S. depended on coal (33.2%), natural gas (32.7%), nuclear power (20%) and renewable energy sources (13%) for electricity (Suplee, 2017). Inexpensive, renewable sources of energy like solar, geothermal, and wind power may provide an option for some growers to help decrease energy costs over time (Barbosa et al., 2015). Unfortunately, the initial investment in these systems deter many growers. More prudent energy usage with currently-available technologies may be the most feasible strategy for reducing greenhouse lettuce production costs in the short term.

Crop information

Lettuce (*Lactuca sativa* L.) is a semi-cool season crop that is susceptible to physiological problems such as tipburn, bolting, ribbiness, rib discoloration, and can develop loose, puffy heads when the temperature is above optimal. At below optimal temperature, growth can be slowed or plant death can occur. Optimal temperature ranges from 17 to 28 °C in the day and 3 to 12 °C at night. Optimal pH is 5.8-6.5 (Jones, 2005) and optimal EC is 1.5 (Resh, 2004). There are five common types of lettuce including Summer Crisp, Butterhead, Cos or Romaine, Leaf, and Crisphead (Ryder, 1999). Each type can be grown in greenhouses, but the most common type in the southeastern U.S. is Butterhead.

During the summer in the southeastern United States, two common problems encountered in greenhouse lettuce are tipburn and bolting. Tipburn is a physiological disorder caused by a calcium deficiency in young leaves (Jenni and Yan, 2009; Wien, 1997). This is usually not due to a lack of calcium in soil or nutrient solution, because tipburn can occur when adequate concentrations of calcium are available in the soil (Hartz et al., 2007). In fact, the exact causes of tipburn are not fully understood or explained in the literature.

High humidity in the southeast can significantly reduce transpiration. Calcium is transported exclusively in the xylem and therefore relies on transpiration to move through the plant, so under high humidity conditions tipburn is more likely to occur (Wien, 1997). Foliar sprays of calcium have relieved some tipburn symptoms (Corriveau, 2012), but do not work on tight heads (crisphead) (Wein,1997). Strategies that would increase transpiration, like blowing air across young leaves as heads start to form have reduced tipburn severity in some cases (Lee, 2013). Another proposed cause of tipburn is that as temperature increases, growth and nutrient requirements increase (Wien, 1997). Therefore, in combination with reduced transpiration, the plant is not able to move adequate nutrients fast enough to keep up with the rapid growth. Butterhead lettuce grown under artificial light showed to have increased biomass, growth rate, and leaves with tipburn with increased light intensity (Sago, 2016). Light intensity also increased calcium absorption. While the calcium content increased in the whole plant and outer leaves with light intensity, the calcium content in the inner leaves did not increase. It was thought that the outer leaves contained more calcium because of the increased transpiration from the increased light on the outer leaves.

Not all cultivars of lettuce have the same susceptibility to tipburn. This is likely due to selective breeding efforts (Nagata and Stratton, 1994; Ryder and Waycott, 1998). However, lettuce breeders have struggled to develop tipburn resistant cultivars for growers. Crisphead lettuce cultivars typically have a greater genetic variation for tipburn resistance compared to romaine and leaf types, possibly due to breeding efforts for this type (Jenni and Hayes, 2010).

Bolting is another common problem associated with growing lettuce in greenhouses in the southeast. Bolting is rapid stem elongation followed by flowering caused by high temperatures and long photoperiods ruining the marketability of the plant by causing an undesirable appearance and extreme bitterness (Silva et al., 1999). Apart from standard variety trials, experiments have been conducted to isolate genes which affect early and late flowering. These genes are closely associated with bolting (Ryder and Milligan, 2005). Breeding efforts have led to cultivars that are more reliably slow-bolting.

Lettuce in the southeast takes around 14 d from seed to transplant and 30 d after transplant (DAT) to reach market weight. Below optimal temperatures will increase this production time considerably. In the summer, lettuce is susceptible to physiological problems caused by high temperatures and therefore there are difficulties trying to grow lettuce. Selection of heat-tolerant cultivars that are resistant to tipburn and slow-bolting may help Alabama greenhouse growers meet local lettuce demands year-round.

Consumer preferences

Consumer preference surveys, or sensory evaluations have been conducted for a multitude of foods and products and can be important tools for deciding which crops to produce and market. Sensory evaluation studies have been conducted for individual produce items such as transgenic tomatoes (Lim et al., 2014) and processed foods such as mayonnaise prepared with ostrich eggs (Abu-Salem and Abou-Arab, 2008). Determining which organoleptic qualities consumers most desire in lettuce could help lettuce growers decide which cultivar to grow.

Sensory characteristics such as appearance, aroma, texture, and taste affect consumer preferences of produce, whether consciously or subconsciously. Biological instinct dictates sweet tasting food is more desirable than bitter tasting food (Clark, 1998). Although, as we age we may be able to desire more bitter-tasting foods due to acquired tastes. The idea of being able to acquire taste for a certain food indicates that other factors can affect preferences, like beliefs and expectations of a food (Clark, 1998). Most consumers expect lettuce to be crisp (Barrett et al., 2010) and, in general, consumers expect lettuce to not be bitter (Simonne et al., 2002), but expectations can change.

Greenhouse heating

A unit heater is a system that utilizes forced air to deliver heat throughout a greenhouse and is a popular choice for growers because of its low investment installation costs and reliability (Sanford, 2011). Unit heaters burn fuel, typically liquid propane or natural gas. Heat produced from combustion passes through a heat exchanger before it is exhausted from the greenhouse. A high-power fan forces air through the heat exchanger, exchanging heat in the process with greenhouse air (Nelson, 2012). Some operations utilize polytubes to help distribute the warm air down the length of the greenhouse. Forced air systems can be less efficient the other heating systems at uniformly heating the greenhouse because the hot air does not move down the greenhouse easily (McMahon, 1992). Horizontal Airflow (HAF) fans are often used to move the hot air from the heaters through the greenhouse (Ball, 1997). HAF FANS are effective at keeping cold air from sinking and the hot air from rising, but they keep the air that is not near the plants warmer than necessary for plant growth (Sanford, 2011). The use of forced air systems and HAF fans are effective, but using a system that radiates heat in the floor or closer to the crops maybe more energy-efficient.

Pipe coil type heaters offer a way to heat just the air around the plants. Hot water or steam, produced by boilers, is circulated throughout the greenhouse in iron or aluminum pipes. Hot water pipes radiate heat and are often placed along the inside perimeter of the greenhouse. They are placed overhead, in the floor, underneath greenhouse benches, or in a combination of these places (Nelson, 2012). Having pipe coil system set up close to the root-zone of the plant can allow the greenhouse air temperature to remain 3° to 6° C cooler without reducing growth or yield (Nelson, 2012)

Infrared-radiant heaters work by emitting infrared radiation and when the infrared waves are absorbed by the object, the energy is converted into heat (Bakker, 1995). For example, a plant will absorb the infrared waves, convert the energy into heat and then begin to heat the air around itself. Infrared radiation can be emitted by steel pipes that are above the plant canopy. Infrared-radiant heater can allow the greenhouse air temperature to 3° to 6°C cooler (Nelson, 2012). It is reported that growers save 30 to 50 percent on fuel using low-intensity infrared-radiant heaters compared to unit heaters (Stone and Youngsman, 2006). Disadvantages of infrared-radiant heaters include a non-uniform distribution of radiation leading to varying crop growth. Infrared-radiant heaters block light from reaching the plants which is already a common problem in the cooler months (Bakker, 1995).

Root zone heating

Root zone temperature affects many aspects of plant physiology including plant respiration, morphology, water absorption, and transpiration (Wien, 1997). Plant enzymes are controlled by temperature. As temperature increases, the biochemical reactions activated by enzymes increase until an optimal temperature is met. Temperature above what is optimal results in a suppression of some enzyme-driven reactions (Nelson, 2012). Allowing root-zone temperature to consistently stay well below or above the optimal growing temperature will slow production and waste resources.

Heating or cooling plant root zones is a technique used to either speed up production in the winter or reduce heat induced issues (i.e. bolting and tipburn) in the summer. In an experiment conducted in Greece, heating the nutrient solution to 15 C and 20 C increased shoot growth for ‘Marbello’ and ‘Bastion’ lettuces, respectively (Economakis and Said, 2002). In a similar experiment, biomass increased for NFT strawberries grown in heated water (Economakis and Krulj, 2001). In a related experiment, Boxall (1971) that heating the soil to 18 °C (64 °F), thereby heating the root zone, decreased the length of the production cycle of butterhead lettuce by 14-17 days in the field. Similarly, Thompson and others (1998) reported decreased production time with increased root zone temperatures ‘Ostinata’ Butterhead lettuce. Decreasing production times may decrease energy needs on a per plant basis, hence production, costs.

Plant temperature and not air temperature is what controls plant growth (Nelson, 2012). Providing heat where it can benefit the plant and not where it is useless to the plant be a good way to improve energy efficiency of greenhouse lettuce production. It may be advantageous to focus heating in the root zone of lettuce instead of attempting to heat greenhouse air. Water has a higher heat capacity than air (water has a heat capacity of 4.18 J/°C g while air has a heat capacity of 1.01 J/°C g), so it takes about 4x more energy to heat water than air (Office of Marine Programs, 2001). The same principle also allows water to lose heat less rapidly than air. Improved heating efficiencies are a promising way to reduce energy costs for greenhouse lettuce production thereby improving potential profitability.

Research Objectives

Higher-than-optimum air temperatures cause problems for greenhouse lettuce growers in the southeast. Growers need more information on cultivars that will perform well in the hottest months of the summer. Objective 1 of this research is to determine which cultivars of lettuce are most heat tolerant when grown in a hydroponic system in a greenhouse in the southeast US. Objective 2 is to determine which lettuce cultivars are most preferred by consumers and determine which lettuce cultivars satisfy both heat-tolerance and consumer preference standards. Objective 3 is to evaluate the effects of heating nutrient solutions in a DWC system on lettuce growth in a greenhouse.

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Chapter II

Heat tolerance of *Lactuca sativa* L. varieties grown hydroponically and consumer sensory evaluation of heat tolerant hydroponic lettuce

Abstract

Twenty cultivars were trialed for heat tolerance in Deep Water Culture (DWC) starting on 30 June and 19 August 2016. Lettuce seeds were germinated and grown for two weeks in OASIS® cubes (OASIS® Grower Solutions, Kent, Ohio) (2.54 cm X 3.18 cm X 3.81 cm). Seedlings were fertilized with 150, 80, 200, 150, and 35 mg L^{-1} N, P, K, Ca, and Mg, respectively every other day for two weeks before being transplanted to DWC containing the same nutrient solution mixture. The 20 cultivars were ‘Aerostar’, ‘Coastal Star’, ‘Flashy Trout Back’, ‘Green Forest’, ‘Green Towers’, ‘Jericho’, ‘Monte Carlo’, ‘Parris Island’, ‘Salvius’, ‘Sparx’, ‘Truchas’, ‘Adriana’, ‘Bambi’, ‘Buttercrunch’, ‘Rex’, ‘Skyphos’, ‘Magenta’, ‘Muir’, ‘Nevada’, and ‘Teide’. At 30 days after transplant (DAT) size index was quantified ([height + width1 + width2]/3), bolting was quantified by assigning each experimental unit a rating (0 = no stem elongation, 1 = some stem elongation, 2= dense head forming, 3 = dense head formed, 4 = flowers formation), and tipburn was quantified by assigning each experimental unit a rating (0 = no tipburn, 1 = widest tipburn spot less than 6.4 mm, 2 = widest spot less than 12.7 mm, 3 = widest spot less than 25.5 mm or larger). Lettuce heads were then cut at the base, weighed to determine fresh weight. The experiment was a generalized complete block design with four blocks and eight replicates per cultivar. Each pool was a block and each block contained two plants of each cultivar for a total of 40 experimental units per block. Experimental units were completely randomized within each block. Of the romaine cultivars trialed, ‘Monte Carlo’ had a lower bolting rating than ‘Green Towers’ and ‘Jericho’, while ‘Monte Carlo’ and ‘Truchas’ had

lower tipburn ratings than ‘Green Towers’ and ‘Jericho’. Within the Summercrisp group ‘Muir’ had a higher HFW than ‘Nevada’, but was similar to ‘Magenta’. ‘Muir’ had the highest bolting rating while ‘Nevada’ had the lowest. ‘Muir’ also had the highest tipburn rating.

On 17 November 2016, nine cultivars of hydroponically-grown lettuce (*Lactuca sativa* L.), selected based on heat tolerance from the cultivar trial, were evaluated for sensory attributes and marketability by 50 untrained, consumer panelists recruited from students, faculty, and staff members at Auburn University. Cultivars evaluated were ‘Adriana’, ‘Aerostar’, ‘Monte Carlo,’ ‘Nevada’, ‘Parris Island’, ‘Rex’, ‘Salvius’, ‘Skyphos’, and ‘Sparx’. Each cultivar was randomly-assigned a 3-digit numerical code. The order of presentation of each cultivar to each participant was randomized. Unsalted crackers and water were provided to cleanse the palate between samples. Samples were evaluated under fluorescent lighting within compartmentalized sensory evaluation booths. Sample portions were individual leaves that did not include innermost or outermost leaves. Samples were provided to each panelist individually and in succession. Sample ballots prompted panelists to rate their perception of crispness, bitterness, overall texture, overall flavor, and marketability. Sample ballots utilized a 5-point scale with descriptive anchors for each criterion. ‘Salvius’ had a higher marketability rating than ‘Adriana’ and ‘Skyphos’ but was similar to all other cultivars. ‘Monte Carlo’ and ‘Salvius’ had the highest crispness ratings while ‘Adriana’ had the lowest. ‘Skyphos’ had the lowest overall texture rating. No differences existed among cultivars for bitterness and overall flavor. All sensory criteria were correlated except bitterness and crispness. Higher crispness, lower bitterness, higher overall texture, and higher overall flavor correlated to higher marketability ratings regardless of cultivar. ‘Adriana’ and ‘Skyphos’ are heat-tolerant lettuce cultivars that received low marketability ratings.

Introduction

Lettuce and physiological problems due to heat

Lettuce (*Lactuca sativa* L.) is a semi-cool season crop that is susceptible to physiological problems such as tipburn, bolting, ribbiness, rib discoloration, and development of loose, puffy heads when the temperature is above optimal. At below optimal temperatures, growth can be slowed or plant death can occur. Optimal temperatures range from 17 to 28 °C in the day and 3 to 12 °C at night (Jones, 2005). Optimal pH and EC are 5.8-6.5 and 1.5, respectively (Resh, 2004). There are five common types of lettuce including Summer Crisp, Butterhead, Cos or Romaine, Leaf, and Crisphead (Ryder, 1999). Summercrisp, Butterhead, Romaine, and Leaf types can be grown in greenhouses with the most common type in the southeastern U.S. being Butterhead.

During the summer in the southeastern United States, two common problems encountered in greenhouse lettuce are tipburn and bolting. Tipburn is a physiological disorder caused by a calcium deficiency in young leaves (Jenni and Yan, 2009; Wien, 1997). Tipburn is usually not due to a lack of calcium in soil or nutrient solution, because it occurs even when soils are not deficient in calcium (Hartz et al., 2007). The exact causes of tipburn are not fully understood or explained in the literature.

High humidity in the southeast can significantly reduce transpiration compared to more arid climates. Calcium is transported exclusively in the xylem and therefore relies on transpiration to move through the plant, so under high humidity conditions tipburn is more likely to occur (Wien, 1997). Foliar sprays of calcium have relieved tipburn symptoms in some cases (Corriveau, 2012), but are not effective on tight heads (crisphead) and have limited success on other types. Strategies that would increase transpiration, like blowing air across young leaves as heads start to form have reduced tipburn severity in some cases (Lee, 2013). Another proposed cause of tipburn is that as temperature increases, growth and nutrient requirements increase (Wien, 1997). Therefore, in combination with reduced transpiration, the plant is not able to move adequate nutrients fast enough to keep up with the rapid growth.

Not all cultivars of lettuce have the same susceptibility to tipburn, which is likely due to selective breeding efforts (Nagata and Stratton, 1994; Ryder and Waycott, 1998). However, lettuce breeders have struggled to develop fully tipburn resistant cultivars for growers. Crisphead lettuce cultivars typically have a greater genetic variation for tipburn resistance compared to romaine and leaf types (Jenni and Hayes, 2010). It is possible that breeding for tipburn resistance in other lettuce types could be a successful strategy to mitigate tipburn severity of greenhouse-grown lettuce.

Bolting is another problem common to greenhouse lettuce in the southeast. Bolting is rapid stem elongation followed by flowering and is caused by high temperatures and long photoperiods. Bolting ruins the marketability of the plant by causing an undesirable appearance and extreme bitterness (Silva et al., 1999). Apart from variety trials, experiments have been conducted to isolate genes which affect early and late flowering. These genes have been found to be closely associated with bolting (Ryder and Milligan, 2005). Breeding efforts has led to numerous slow bolting cultivars. Since selective breeding is a long process, a better understanding of tipburn and bolting resistance of current genetic lines is needed.

When grown in a greenhouse, lettuce takes approximately 14 d from seed to transplant and 30 d after transplant (DAT) to reach market weight. In the summer, lettuce is susceptible to physiological problems caused by high temperatures and therefore is sometimes not produced.

Lettuce growers often use this time to clean the greenhouse and prepare for another crop when the temperatures are optimal (Tyson et al., 2013). Selection of heat-tolerant cultivars that are resistant to tipburn and bolting may help greenhouse lettuce growers in the southeast meet local lettuce demands year-round.

Importance of consumer sensory evaluation of heat-tolerant, hydroponically grown lettuce

Butterhead/Bibb is the most commonly grown hydroponic lettuce type (Tyson et al., 2013). Hydroponic lettuce growers in the Southeast need good recommendations of varieties and cultivars to expand their markets. For example, Romaine lettuce is in high demand and is considered a cool season lettuce variety in field production (Dufault et al., 2009). However, specific information regarding heat tolerance in hydroponic systems is unavailable in the literature.

Consumer preference surveys, or sensory evaluations, have been conducted for a multitude of foods and products and can be important tools for deciding which crops to produce and market. Sensory evaluation studies have been conducted for individual produce items such as transgenic tomatoes (Lim et al., 2014) and processed foods such as mayonnaise prepared with ostrich eggs (Abu-Salem and Abou-Arab, 2008). Determining which organoleptic (like taste, sight, smell, and touch) qualities consumers most desire in lettuce could help lettuce growers select the best cultivars for production.

Sensory characteristics such as appearance, aroma, texture, and taste affect consumer preferences of produce, whether consciously or subconsciously. Biological instinct dictates that sweet tasting food is more desirable than bitter tasting food, although, as we age we may desire more bitter foods due to acquired tastes. The idea of being able to acquire taste for a certain food indicates that other factors can affect preferences, like beliefs and expectations of a food (Clark, 1998). Most consumers expect lettuce to be crisp (Barrett et al., 2010) and, in general, consumers expect lettuce to not be bitter (Simonne et al., 2002). However, it is unclear in the literature to what extent sensory criteria affect the marketability of greenhouse-grown lettuce.

Research Objectives

The objectives of this study were to select lettuce cultivars that performed well in a greenhouse environment in the southeast during summer months and to evaluate consumer preferences of those cultivars through sensory evaluation in order to make cultivar recommendations to greenhouse growers in the southeast.

Materials and Methods

Objective 1

Heat tolerance of Lactuca sativa L. varieties grown hydroponically

On 30 June and 19 August 2016, twenty cultivars of lettuce (*Lactuca sativa* L.) were grown in Deep Water Culture (DWC) in a greenhouse at Auburn University (32.5970° N, 85.4880° W). Cultivars of different types of lettuce, marketed as heat-tolerant, slow-bolting, or both, were selected. Eleven Romaine cultivars were ‘Aerostar’, ‘Coastal Star’, ‘Flashy Trout Back’, ‘Green Forest’, ‘Green Towers’, ‘Jericho’, ‘Monte Carlo’, ‘Parris Island’, ‘Salvius’, ‘Sparx’, and ‘Truchas’, two Bibb cultivars were ‘Bambi’ and ‘Buttercrunch’, three Butterhead cultivars were ‘Adriana’, ‘Rex’, and ‘Skyphos’, and four Summercrisp cultivars were ‘Magenta’, ‘Muir’, ‘Nevada’, and ‘Teide’ (Table 2.2).

Lettuce seeds were sown on 16 June and 15 August 2016 and grown for two weeks in OASIS® horticubes (OASIS® Grower Solutions, Kent, Ohio) (2.54 cm X 3.18 cm X 3.81 cm) and were fertilized with nutrient solution from municipal water (Auburn, AL) containing 150, 80, 200, 150, and 35 mg•L^{-1} N, P, K, Ca, and Mg, respectively from water-soluble 8N-6.5P-30K (Gramp's Original hydroponic lettuce fertilizer, Ballinger, TX), calcium nitrate (15.5N-0P-0K), and magnesium sulfate (10% Mg). Seedlings were irrigated overhead with nutrient solution every other day for two weeks before being transplanted to one of four separate DWC pools, each containing the same nutrient solution used on seedlings.

Each pool measured 1.2 m x 2.4 m and was framed with treated lumber planks (5-cm x 30.5-cm x 2.4-m). Frames were stabilized by 10-cm x 10-cm x 30.5-cm treated lumber posts in each corner and were connected to each post using 10-cm deck screws. Pools were lined with 6-mil black construction film and filled with nutrient solution to 254-cm depth to conform the liner to pool sidewalls. The pools were filled with 7,315 L of nutrient solution. Excess liner was then rolled and fastened to pool frames using wooden slats and deck screws. Sixty-eight evenly-spaced (20-cm, center-to-center) circular holes, each measuring 2.2 cm in diameter, were drilled into four Styrofoam boards (2.54-cm thick, R 5 Unfaced Polystyrene Foam Board Insulation, Kingspan Insulation, Atlanta, Georgia), which had been cut to fit the dimensions of each pool. Each board was floated on top of nutrient solution in each pool and lettuce plants were transplanted onto the floating boards by fitting Oasis® Horticubes (OASIS® Grower Solutions, Kent, Ohio) snugly into each hole and aligning the top of the root cube to the surface of the foam board. 'Rex' lettuce plants were planted as a border row along the entire edge of each board. Two plants of each cultivar were then randomly selected and placed into two of the 40 remaining holes. Each pool was supplied with 30 L min^{-1} of air pushed through four airstones using one of two pumps (Hailea ACO-9730 Air Pump, Guangdong, China). Greenhouse air temperature at plant height, and nutrient solution temperature was measured every hour for the duration of the experiment using WatchDog® B-Series Button Loggers (Spectrum Technologies, Inc. Aurora, IL). Solution pH and EC were measured weekly using LAQUA Twin pH Meter and LAQUA Twin EC Meter (Spectrum Technologies, Inc., Aurora, IL), respectively. At 30 days after transplant (DAT) a size index was measured ([height + width1 + width2]/3), bolting was quantified by assigning each experimental unit a rating (0 = no stem elongation, 1 = some stem elongation, 2= dense head forming, 3 = dense head formed, 4 = flowers formation), and tip burn was quantified by assigning each experimental unit a rating (0 = no tipburn, 1 = widest tipburn spot less than 6.4 mm, 2 = widest spot less than 12.7 mm, 3 = widest spot less than 25.5 mm or larger) (USDA-AMS, 1997). Lettuce heads were then cut at the base and weighed to determine head fresh weight.

An analysis of variance was performed on all responses using PROC GLIMMIX in SAS version 9.4 (SAS Institute, Cary, NC). The experimental design was a generalized randomized complete block with experimental run in the model as a random variable. Four blocks contained eight replicates per cultivar in total. Each pool was a block and each block contained two plants of each cultivar for a total of 40 experimental units per block. Experimental units were completely randomized within each block. Head fresh weight and size index were analyzed using the normal probability distribution. Where residual plots and a significant covariance test for homogeneity indicated heterogeneous variance among treatments, a RANDOM statement with the GROUP option was used to correct heterogeneity. Least squares means comparisons between cultivars within types were determined using the simulated method. Where there were only two cultivars within a type, differences were determined using the main effect F-test. Bolting and tip burn ratings were analyzed using the multinomial probability distribution with a cumulative log link. All possible paired comparisons among treatments were estimated. Reported were medians (Table 2.7). All significances were at $\alpha = 0.05$.

Objective 2

Using Sensory Evaluation to Assess Consumer Preferences for Hydroponically-grown Lettuce

On 17 November 2016, nine cultivars of lettuce grown in DWC, were evaluated for sensory attributes and marketability by 50 untrained, consumer panelists recruited from students, faculty, and staff members at Auburn University. Cultivars were selected for this study by criteria of median bolting and tipburn ratings ≤ 2.5 and ≤ 1, respectively in the previous experiment. Selected cultivars were ‘Adriana’, ‘Aerostar’, ‘Monte Carlo,’ ‘Nevada’, ‘Parris Island’, ‘Rex’, ‘Salvius’, ‘Skyphos’, and ‘Sparx’. The sensory evaluation study was approved by the Institutional Review Board (IRB) as "Exempt" under federal regulation 45 CFR 46.101(b)(6). Sensory evaluation was conducted in Auburn University’s Research Kitchen & Sensory Laboratory (Poultry Science Department, Auburn University, AL). Prior to sensory evaluation, samples of each cultivar were thoroughly rinsed with tap water, dried with paper towels, and stored for 24h at 4 C in zipper-sealed plastic bags. Each cultivar was randomly-assigned a 3-digit numerical code. The order of presentation of each cultivar to each participant was randomized. Unsalted crackers and water were provided to cleanse the participants’ palates between samples. Samples were evaluated under fluorescent lighting within compartmentalized sensory evaluation booths. Sample portions were individual leaves that did not include innermost or outermost leaves. Samples were provided to each panelist individually and in succession. Sample ballots prompted panelists to rate their perception of crispness, bitterness, overall texture, overall flavor, and marketability. Sample ballots utilized a 5-point scale with descriptive anchors for each criterion (Fig. 2.1). Scores of 1 indicated “not crisp”, “very bitter”, “poor texture”, “poor flavor”, and “unlikely to buy” for crispness, bitterness, overall texture, overall flavor, and marketability, respectively, while scores of 5 indicated “very crisp”, “not bitter”, “excellent texture”, “excellent flavor”, and “likely to buy.”

An analysis of variance was conducted in SAS using PROC GLIMMIX (SAS Institute, Cary, NC) and panelist was treated as random variable. Medians were separated using the simulated method. Spearman correlation coefficients of medians were determined in SAS using PROC CORR. The experiment was a Randomized Complete Block Design with panelists serving as blocks. All significances were at $\alpha = 0.05$.

Results

Heat tolerance of Lactuca sativa L. varieties grown hydroponically

For the experiment, the data were pooled for Run 1 and Run 2. Average air temperatures were 33 and 24.5 C for day and night, respectively (Table 2.1).

‘Truchas’ had the lowest size index (SI) and head fresh weight (HFW) within the Romaine group while ‘Green Forest’, ‘Salvius’, and ‘Sparx’ had the highest HFW. ‘Monte Carlo’ was larger than ‘Truchas’, but smaller than all other Romaine cultivars while ‘Green Forest’, ‘Salvius’, and ‘Sparx’ had the highest HFW (Table 2.3). ‘Monte Carlo’ had a lower bolting rating than ‘Green Towers’ and ‘Jericho’, while ‘Monte Carlo’ and ‘Truchas’ had lower tipburn ratings than ‘Green Towers’ and ‘Jericho’.

Within the Bibb group ‘Buttercrunch’ had a higher size index (SI) than ‘Bambi’, but HFW, bolting rating, and tipburn rating were not significant (Table 2.4).

Within the Butterhead group 'Adriana' had the highest SI, but HFW, bolting rating, and tipburn rating were not significant (Table 2.5).

Within the Summercrisp group 'Muir' had a higher HFW than 'Nevada', but was similar to 'Magenta' (Table 2.6). 'Muir' had the highest bolting rating while 'Nevada' had the lowest. 'Muir' also had the highest tipburn rating.

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Monte Carlo had a higher crispness rating than 'Rex', 'Adriana', 'Skyphos', 'Nevada', and 'Parris Island', but was similar to 'Salvius', 'Aerostar', and 'Sparx' (Table 2.8). 'Salvius' and 'Aerostar' had higher bitterness ratings than 'Adriana', but was similar to others. 'Salvius' and 'Monte Carlo' had higher Overall Texture ratings than 'Rex', 'Adriana', and 'Skyphos', but was similar to 'Aerostar', 'Sparx', 'Nevada', and 'Parris Island'. Overall Flavor was not significant. 'Salvius' and 'Aerostar' had high Marketability than 'Adriana' and 'Skyphos', but was similar to the rest. Bitterness did not correlate to Crispness (Table 2.9), but Marketability correlated with Crispness, Bitterness, Overall Texture, and Overall Flavor.

Discussion

Heat tolerance of Lactuca sativa L. varieties grown hydroponically

Each cultivar trialed exhibited some level of bolting and/or tipburn, but the temperature in the greenhouse for Run 1 and Run 2 (32 °C-34 °C day temperature) was higher than what growers would hope to keep their greenhouses. Even though all cultivars trialed were labeled "heat-tolerant" and/or "slow bolting" at least one of the cultivars had a very low heat-tolerance compared to the other cultivars. 'Flashy Trout Back' was the only cultivar to have a median bolting rating of 4, higher than any other cultivar. At the end of both runs, ‘Flashy Trout Back’ had developed flowers.

A few lettuce cultivar trials have been done using some of the same cultivars and same criteria. An experiment done in West Virginia evaluated heat tolerance in five cultivars that were trialed in the *Heat tolerance of Lactuca sativa L. varieties grown hydroponically* study, but the experiment was done in a high tunnel and the lettuce seedlings were transplanted into white plastic mulch instead of grown hydroponically (Jett, 2012). Two runs were completed from April to September. The five cultivars appeared to do well and suffered little heat damage. The five cultivars were reported to have experienced no bolting and the overall texture and flavor for all five of the cultivars did not receive a rating below 4 (using a scale 1-5; 1=poor flavor/texture, 5=excellent flavor texture) (Jett, 2012). These finding were not similar to the findings in this *Heat tolerance* trial because during that trial each cultivar suffered at least some heat related issues.

A study conducted in Indiana had similar results to this *Heat tolerance* study (Maynard, 2014). They used several of the cultivars that were used in the present study, but did not use hydroponics. They evaluated bolting and taste, along with other criteria. They found that ‘Green Towers’ and ‘Aerostar’ suffered 50% bolting after 70 days from seed. Cultivars that did not bolt 100% until after 76 days or more were ‘Aerostar’ and ‘Nevada’. The cultivars in the present study all suffered a degree of bolting or tipburn by the end of each run (45 days from seeding). Maynard (2014), discussed the need to reduce the amount of cultivars trialed in future studies. Of the 15 that they selected to advance, because they performed the best in their systems, nine were in our trial. Four (‘Adriana’, ‘Aerostar’, ‘Salvius’, ‘Nevada’) of their nine were advanced to our

Using Sensory Evaluation to Assess Consumer Preferences for Hydroponically-grown Lettuce study.

Results from this *Heat tolerance* experiment showed that ‘Adriana’, ‘Aerostar’, ‘Monte Carlo,’ ‘Nevada’, ‘Parris Island’, ‘Rex’, ‘Salvius’, ‘Skyphos’, and ‘Sparx’ had the lowest median ratings of the cultivars trialed (Table 2.6). Cultivars were selected for the *Using Sensory Evaluation to Assess Consumer Preferences for Hydroponically-grown Lettuce* study by a criterion ≤ 2.5 for bolting rating and a criterion ≤ 1 tipburn rating. 'Magenta' and 'Teide' would have been included in this study, but were not, due to poor germination.

Using Sensory Evaluation to Assess Consumer Preferences for Hydroponically-grown Lettuce

Results for the consumer preference showed that the lower the crispness rating (higher perceived crispness) the lower the marketability rating (Table 2.8). Results also showed that the lower the bitterness rating (more bitter) the lower the marketability (Table 2.8). The survey participants were asked to fill out had all negative points warranting a 1 and all positives warranting a 5. For crispness, overall texture, overall flavor, and overall marketability this made sense. There is a chance that for bitterness, participants that wanted to rate a lettuce "very bitter" might give the lettuce a 5 without noticing that a 5 meant "not bitter".

In a study evaluating lettuce cultivars, cultivars were evaluated by bitterness and flavor (Maynard, 2014). Five of the cultivars trialed were also in our *Consumer Preferences* study. ‘Nevada’ in both studies received low bitterness ratings for bitterness. ‘Adriana’, ‘Aerostar’, and ‘Salvius’ had moderately intense flavor ratings and while ‘Overall Flavor’ was not significant in our *Consumer Preferences* study, these three cultivars did receive high ratings in the other criteria.

In conclusion, we would recommend ‘Salvius’, ‘Rex’, ‘Aerostar’, ‘Sparx’, ‘Monte Carlo’, ‘Nevada’, and ‘Parris Island’ to growers in the Southeastern United States looking for heat-tolerant lettuce cultivars. We would not recommend ‘Skyphos’ and ‘Adriana’ due to low marketability ratings.

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Table 2. 1. Mean temperatures during a cultivar trial of greenhouse lettuce cultivars grown in Deep Water Culture.

	Location	
Time	Greenhouse Air[y]	Nutrient Solution[z]
Day	33.0 °C	29.5 °C
Night	24.5 °C	27.5 °C

[z]Nutrient solution temperature was recorded by WatchDog® B-Series Button Loggers (Spectrum Technologies, Inc. Aurora, IL).
[y]Greenhouse air temperature was recorded at approximately 1 meter above the ground.

Table 2. 2. Cultivars sorted into type for a cultivar trial for greenhouse lettuce cultivars grown in Deep Water Culture

Type[y]	Cultivars[z]
Romaine	Aerostar
	Coastal Star
	Flashy Trout Back
	Green Forest
	Green Towers
	Jericho
	Monte Carlo
	Parris Island
	Salvius
	Sparx
	Truchas
Bibb	Bambi
	Buttercrunch
Butterhead	Adriana
	Rex
	Skyphos
Summer crisp	Magenta
	Muir
	Nevada
	Teide

[z]Cultivars were labeled for heat tolerance and/or slow-bolting.
[y]Marketing language was used for identifying type.

Table 2. 3. Differences in Size Index, Head Fresh Weight, Bolting Rating, Tipburn Rating among cultivars in Romaine lettuce in Deep Water Culture for a 30-day period

Cultivar[z]	Size Index[y]	Head Fresh Weight (g)	Bolting Rating[x]	Tipburn Rating[w]
Aerostar	31.1cd[v]	278.5b	1.0ab	1.0ab
Coastal Star	34.9abc	242.4bc	1.5ab	1.5ab
Flashy Trout Back	34.7abc	241.5bc	2.0ab	2.0ab
Green Forest	37.4a	384.8a	1.0ab	1.0ab
Green Towers	33.3abc	230.8bc	2.0a	2.0a
Jericho	31.9bc	244.8bc	2.0a	2.0a
Monte Carlo	26.2d	174.0c	0.5b	0.5b
Parris Island	32.8abc	196.4bc	1.0ab	1.0ab
Salvius	37.1ab	410.5a	1.0ab	1.0ab
Sparx	37.2a	402.1a	1.0ab	0.5ab
Truchas	20.6e	78.0d	1.0ab	1.0b

[z]Cultivars were selected for the Consumer Preference Study by a criterion ≤ 2.5 for bolting rating and a criterion ≤ 1 tipburn rating.

[y]Size index was recorded at harvest 30 DAT. Growth index was measured in cm as: [(Height + Widest Width + Perpendicular Width) / 3].

[x] Ratings for bolting: 0 = no stem elongation, 1 = some stem elongation, 2= dense head forming, 3 = dense head formed, 4 = flowers formation

[w] Ratings for tipburn: 0 = no tipburn, 1 = widest tipburn spot less than 6.4 mm, 2 = widest spot less than 12.7 mm, 3 = widest spot less than 25.5 mm or larger

[v]Values in column sharing a letter were not significantly different according to Tukey's Honest Significance Difference Test at $\alpha=0.05$ for Size Index and Head Fresh Weight data and the simulated method at $\alpha=0.05$ for Bolting and Tipburn rating data.

Table 2. 4. Differences in Size Index, Head Fresh Weight, Bolting Rating, Tipburn Rating among cultivars in Bibb lettuce in Deep Water Culture for a 30-day period

Cultivar[z]	Size Index[y]	Head Fresh Weight(g)	Bolting Rating[x]	Tipburn Rating[w]
Bambi	18.9b	112.3ns	3.0ns	2.0ns
Buttercrunch	22.9a	126.4	3.0	2.0

[z]Cultivars were selected for the Consumer Preference Study by a criterion ≤ 2.5 for bolting rating and a criterion ≤ 1 tipburn rating.

[y]Size index was recorded at harvest 30 DAT. Growth index was measured in cm as: [(Height + Widest Width + Perpendicular Width) / 3].

[x] Ratings for bolting: 0 = no stem elongation, 1 = some stem elongation, 2= dense head forming, 3 = dense head formed, 4 = flowers formation

[w] Ratings for tipburn: 0 = no tipburn, 1 = widest tipburn spot less than 6.4 mm, 2 = widest spot less than 12.7 mm, 3 = widest spot less than 25.5 mm or larger

[v]Values in column sharing a letter were not significantly different according to Tukey's Honest Significance Difference Test at α=0.05 for Size Index and Head Fresh Weight data and the simulated method at α=0.05 for Bolting and Tipburn rating data.

Table 2. 5. Differences in Size Index, Head Fresh Weight, Bolting Rating, Tipburn Rating among cultivars in Butterhead lettuce in Deep Water Culture for a 30-day period

Cultivar[z]	Size Index[y]	Head Fresh Weight(g)	Bolting Rating[x]	Tipburn Rating[w]
Adriana	27.1a	179.8ns	2.0ns	0.0ns
Rex	22.3b	135.2	2.0	0.0
Skyphos	20.7b	132.1	1.0	0.0

[z]Cultivars were selected for the Consumer Preference Study by a criterion ≤ 2.5 for bolting rating and a criterion ≤ 1 tipburn rating.

[y]Size index was recorded at harvest 30 DAT. Growth index was measured in cm as: [(Height + Widest Width + Perpendicular Width) / 3].

[x] Ratings for bolting: 0 = no stem elongation, 1 = some stem elongation, 2= dense head forming, 3 = dense head formed, 4 = flowers formation

[w] Ratings for tipburn: 0 = no tipburn, 1 = widest tipburn spot less than 6.4 mm, 2 = widest spot less than 12.7 mm, 3 = widest spot less than 25.5 mm or larger

[v]Values in column sharing a letter were not significantly different according to Tukey's Honest Significance Difference Test at $\alpha=0.05$ for Size Index and Head Fresh Weight data and the simulated method at $\alpha=0.05$ for Bolting and Tipburn rating data.

Table 2. 6. Differences in Size Index, Head Fresh Weight, Bolting Rating, Tipburn Rating among cultivars in Summer Crisp lettuce in Deep Water Culture for a 30-day period

Cultivar[z]	Size Index[y]	Head Fresh Weight (g)	Bolting Rating[x]	Tipburn Rating[w]
Muir	25.8ns	196.3a	2.5a	2.0a
Magenta	25.8	171.1ab	2.0b	2.5b
Nevada	22.3	137.4b	1.0c	1.0b

[z]Cultivars were selected for the Consumer Preference Study by a criterion ≤ 2.5 for bolting rating and a criterion ≤ 1 tipburn rating.

[y]Size index was recorded at harvest 30 DAT. Growth index was measured in cm as: [(Height + Widest Width + Perpendicular Width) / 3].

[x] Ratings for bolting: 0 = no stem elongation, 1 = some stem elongation, 2= dense head forming, 3 = dense head formed, 4 = flowers formation

[w] Ratings for tipburn: 0 = no tipburn, 1 = widest tipburn spot less than 6.4 mm, 2 = widest spot less than 12.7 mm, 3 = widest spot less than 25.5 mm or larger

[v]Values in column sharing a letter were not significantly different according to Tukey's Honest Significance Difference Test at α=0.05 for Size Index and Head Fresh Weight data and the simulated method at α=0.05 for Bolting and Tipburn rating data.

Table 2. 7. Median ratings for bolting and tipburn on different cultivars of *Lactuca sativa* L.

Cultivars	Bolting[z]	Tipburn[y]
Adriana	2.0	0.0
Aerostar	2.0	1.0
Bambi	3.0	2.0
Buttercrunch	3.0	2.0
Coastal Star	3.0	1.5
Flashy Trout Back	4.0	2.0
Green Forests	3.0	1.0
Green Towers	3.0	2.0
Jericho	3.0	2.0
Magenta	2.0	1.0
Monte Carlo	2.0	0.5
Muir	2.5	0.0
Nevada	1.0	0.0
Parris Island	2.5	1.0
Rex	2.0	0.0
Salvius	2.5	1.0
Skyphos	1.0	0.0
Sparx	2.5	0.5
Truchas	3.0	1.0

[z] Ratings for bolting: 0 = no stem elongation, 1 = some stem elongation, 2= dense head forming, 3 = dense head formed, 4 = flowers formation

[y] Ratings for tipburn: 0 = no tipburn, 1 = widest tipburn spot less than 6.4 mm, 2 = widest spot less than 12.7 mm, 3 = widest spot less than 25.5 mm or larger

Table 2. 8. Cultivar differences by sensory criteria for consumer sensory evaluation study

Cultivar	Crispness[z]	Bitterness[y]	Overall Texture[x]	Overall Flavor[w]	Marketability[v]
Salvius	4.0ab[u]	4.0a	4.0a	4.0ns[t]	4.0a
Rex	3.0cd	3.0ab	3.0bc	3	4.0abc
Aerostar	3.0ab	4.0a	4.0ab	3	4.0a
Sparx	3.0ab	3.0ab	4.0ab	3	3.0ab
Adriana	2.0d	3.0b	3.0cd	3	2.0c
Skyphos	3.0d	3.0ab	2.0d	3	2.5bc
Monte Carlo	4.0a	3.0ab	4.0a	3	4.0ab
Nevada	3.0bc	4.0ab	3.5ab	3	3.5ab
Parris Island	3.0bc	3.0ab	3.0ab	3	3.0abc

[z]Crispness was rated on a scale from 1 to 5 with 1 being not crisp and 5 being very crisp.

[y]Bitterness was rated on a scale from 1 to 5 with 1 being very bitter and 5 being not bitter.

[x]Overall Texture was rated on a scale from 1 to 5 with 1 being poor texture and 5 being excellent texture.

[w]Overall Flavor was rated on a scale from 1 to 5 with 1 being poor flavor and 5 being excellent flavor.

[v]Marketability was rated on a scale from 1 to 5 with 1 being unlikely to buy and 5 being likely to buy.

[u]Reported are medians. Estimated cultivar differences using the simulated method at $\alpha=0.05$.

[t]NS=not significant

Table 2. 9. Correlations between sensory criteria for consumer preferences for hydroponically-grown lettuce

	Crispness	Bitterness	Overall Texture	Overall Flavor	Marketability
Crispness	1.0000	0.0622	0.601	0.3065	0.4671
	--	***0.1977***	***<.0001***	***<.0001***	***<.0001***
Bitterness	0.0622	1.0000	0.2493	0.5527	0.5101
	0.1977	--	***<.0001***	***<.0001***	***<.0001***
Overall Texture	0.601	0.2493	1.0000	0.5393	0.7112
	<.0001	***<.0001***	--	***<.0001***	***<.0001***
Overall Flavor	0.3065	0.5527	0.5393	1.0000	0.7715
	<.0001	***<.0001***	***<.0001***	--	***<.0001***
Marketability	0.4671	0.5101	0.7112	0.7715	1.0000
	<.0001	***<.0001***	***<.0001***	***<.0001***	--

[z] Crispness was rated on a scale from 1 to 5 with 1 being not crisp and 5 being very crisp.

[y] Bitterness was rated on a scale from 1 to 5 with 1 being very bitter and 5 being not bitter.

[x] Overall Texture was rated on a scale from 1 to 5 with 1 being poor texture and 5 being excellent texture.

[w]Overall Texture was rated on a scale from 1 to 5 with 1 being poor texture and 5 being excellent texture.

[v] Overall Flavor was rated on a scale from 1 to 5 with 1 being poor flavor and 5 being excellent flavor.

[u]Medians were separated using the Shaffer-simulated method

[t]Spearman correlation coefficients of medians were determined in SAS using PROC CORR

Figure 2. 1. Sample sensory evaluation survey for heat-tolerant, hydroponically grown lettuce

(**Sample number)**

Lettuce Sensory

You will be presented with 9 different Lettuce leaves. Please tear off a sample piece and evaluate the sample for the listed attributes.

Please rinse between each sample. Place the sample back on the tray when you finish with each one and a new one will be presented to you.

Crispness				
Not Crisp				Very Crisp
1	2	3	4	5

Bitterness				
Very Bitter				Not Bitter
1	2	3	4	5

Overall Texture				
Poor Texture				Excellent Texture
1	2	3	4	5

Overall Flavor				
Poor Flavor				Excellent Flavor
1	2	3	4	5

Marketability				
Unlikely to Buy				Likely to Buy
1	2	3	4	5

Chapter III

Influence of heating nutrient solution on greenhouse-grown hydroponic lettuce

Abstract

An experiment was conducted from 24 February 2016 to 4 April 2016 in a heated greenhouse to determine effects of heating nutrient solutions for growing lettuce (*Lactuca sativa* L. ‘Rex’) in Deep Water Culture. Lettuce seeds were germinated and grown for two weeks in OASIS® cubes (OASIS® Grower Solutions, Kent, Ohio) (2.54 cm X 3.18 cm X 3.81 cm). Seedlings were fertilized with 50 mg L^{-1} N from Gramp’s Original hydroponic lettuce fertilizer (Ballinger, TX) 8-15-36, 100 mg L^{-1} N from calcium nitrate (15.5-0-0), and 40 mg L^{-1} Mg from magnesium sulfate (10% Mg) before being transplanted to Deep Water Culture containing the same nutrient solution mixture. Seedlings were randomly assigned to one of twelve Styrofoam boards (2.54 cm thick), which were floated on nutrient solutions contained in one of twelve, 42.5-L plastic boxes (AKRO-MILS® Multi-load Tote). Nutrient solutions were either unheated (control), continuously heated to a target temperature of 16 °C, or continuously heated to a target temperature of 22 °C using aquarium heaters (Hailea® Aquarium Heater 200w, Guangdong, China). Outdoor and greenhouse air temperatures, along with nutrient solution temperatures, were recorded hourly. Greenhouse daytime and nighttime air temperatures averaged 25.9 and 17.6 °C, respectively. Nutrient solution temperatures for the unheated control, target 16 °C and target 22 °C averaged 20.4, 21.8, and 23.2 °C, respectively. Head fresh weight was highest when nutrient solution was heated to 22 °C (68.8 g), but was not significantly different between 16 °C and unheated control treatments (53.4 and 58.3, respectively). Root fresh weight was also highest when nutrient solution was heated to 22 °C (14.8 g), but was not different between 16 °C and

unheated control treatments (12.1 and 11.9 g, respectively). Growers could use the practice of heating nutrient solution to decrease energy costs by solely heating the nutrient solution and not the air, or by also using the nutrient solution heating method to decrease production times.

Introduction

Hydroponic lettuce production is increasingly popular in the southeastern United States, but one of the disadvantages of this type of lettuce production in the costs. Labor is the most expensive single cost for greenhouse production while energy is the second (Frantz et al., 2010). Determining methods of reducing energy costs, while keeping production yields high is essential for keeping greenhouse lettuce growers competitive in local, regional, and national markets. Energy costs, therefore represent the largest single factor that can be reduced in order to be competitive in these markets.

Greenhouses are typically heated using a unit heater, which is a system that utilizes forced air to deliver heat throughout a greenhouse. A unit heater is a popular choice for growers because of its low investment installation costs and reliability (Sanford, 2011). Unit heaters burn fuel, typically liquid propane or natural gas. A high-power fan forces air, heated through combustion, through a heat exchanger, exchanging heat in the process with greenhouse air (Nelson, 2012). Forced-air systems can be less efficient than other heating systems at uniformly heating the greenhouse because the hot air does not move down the greenhouse easily (McMahon, 1992). Horizontal Airflow (HAF) fans are typically used to move the hot air from the heaters down the greenhouse (Ball, 1997). HAF fans are effective at keeping cold air from sinking and the hot air from rising, but they keep the air that is not near the plants warmer than necessary for plant growth (Sanford, 2011). The use of forced-air systems and HAF fans are effective, but using a system that radiates heat in the floor or closer to the crops maybe more energy-efficient.

Radiative heat systems offer a way to heat just the air around the plants. Hot water or steam, produced by boilers, is circulated throughout the greenhouse in iron or aluminum pipes. Hot water pipes radiate heat and are often placed along the inside perimeter of the greenhouse. They are placed overhead, in the floor, underneath greenhouse benches, or in a combination of these places (Nelson, 2012). Having pipe coil system set up close to the root-zone of the plant can allow the greenhouse air temperature to remain 3° to 6° C cooler without reducing growth or yield (Nelson, 2012)

Infrared radiant heaters work by emitting infrared radiation and when the infrared waves are absorbed by the object, the energy is converted into heat (Bakker, 1995). For example, a plant will absorb the infrared waves, convert the energy into heat and then begin to heat the air around itself. Infrared radiation can be emitted by steel pipes that are above the plant canopy. Infrared-radiant heater can allow the greenhouse air temperature to 3° to 6°C cooler (Nelson, 2012). It is reported that growers save 30 to 50 percent on fuel using low-intensity infrared-radiant heaters compared to unit heaters (Stone and Youngsman, 2006). Disadvantages of infrared-radiant heaters include a non-uniform distribution of radiation leading to varying crop growth. Infrared-radiant heaters block light from reaching the plants which is already a common problem in the cooler months (Bakker, 1995).

Root zone heating

Root zone temperature affects several aspects of plant physiology including plant respiration, morphology, water absorption, and transpiration (Wien, 1997). Plant enzymes are also controlled by temperature. As temperature increases, biochemical reactions catalyzed by enzymes increase until an optimal temperature is met. Temperature above what is optimal results in a suppression of some enzyme-driven reactions (Nelson, 2012). Allowing root-zone temperature to consistently stay well below or above the optimal growing temperature will slow production and waste resources.

Heating or cooling plant root zones is a technique used to either speed up production in the winter or reduce heat induced issues (i.e. bolting and tipburn) in the summer since plant temperature, not air temperature controls plant growth (Nelson, 2012). In an experiment conducted in Greece, lettuce cultivars ‘Marbello’ and ‘Bastion’ lettuces were grown in an NFT system and were given three different nutrient solution temperatures (unheated, 15 °C, 20 °C) (Economakis and Said, 2002). For ‘Marbello’ shoot fresh weight increased from unheated to 15 °C but 100 g and from unheated to 20 °C by 95 g. For ‘Bastion’ shoot fresh weight increased from unheated to 15 °C by 105 g and from unheated to 20 °C by 155 g. In a similar experiment, biomass increased for NFT strawberries grown in heated water (Economakis and Krulj, 2001). There were three nutrient solution temperature treatments; unheated, 20 °C, and 25 °C. Yield and early fruit set were also significantly increased by increased nutrient solution temperature. The number of malformed fruits also increased with increased temperature. The may have been caused by the temperature being close to above optimum temperature. In a related experiment, Boxall (1971) discovered that heating the soil to 18 °C (64 °F), thereby heating the root zone, decreased the length of the production cycle of butterhead lettuce by 14-17 days in the field. Likewise, Thompson et al. (1998) reported decreased production time with increased root zone temperatures in ‘Ostinata’ Butterhead lettuce. Decreasing production times may decrease energy, hence production, costs.

An experiment was conducted to determine effects of heating the nutrient solution on lettuce growth in DWC during the winter in a greenhouse in the southeast.

Materials and Methods

Germination

Lettuce (*Lactuca sativa* L.) 'Rex' was used to determine the effects of heating nutrient solution in Deep Water Culture (DWC) on growth of hydroponic lettuce. On 5 January, 10 February, and 24 February 2016 one flat of 104 Oasis® Horticubes (OASIS® Grower Solutions, Kent, Ohio) was sown with lettuce 'Rex' and covered with clear plastic humidity domes and placed on a greenhouse bench. After germination, seedlings were irrigated with municipal water (Auburn, AL) every other day for seven days followed by irrigation with a complete nutrient solution containing 150, 80, 200, 150, and 35 mg L^{-1} N, P, K, Ca, and Mg, respectively every other day for another seven days. Fertilizers used included Gramp's Original hydroponic lettuce fertilizer (Ballinger, TX) 8-15-36, calcium nitrate 15.5-0-0, and magnesium sulfate 10% Mg. Plants were then transplanted into DWC located in a separate greenhouse. Plants were grown for 28 d and harvested on 24 February, 23 March, and 6 April, 2016.

Experiment Setup

In an unheated greenhouse at Auburn University (32.5970 °N, 85. 4880 °W), twelve individual heavy-duty plastic boxes (AKRO-MILS® Multi-load Tote – 42.5 L capacity, Akron, Ohio) were filled with nutrient solution containing 150, 80, 200, 150, and 35 mg L^{-1} N, P, K, Ca, and Mg, respectively from water-soluble 8N-6.5P-30K (Gramp's Original hydroponic lettuce fertilizer, Ballinger, TX), calcium nitrate (15.5N-0P-0K), and magnesium sulfate (10% Mg).

Seedlings were randomly assigned to one of twelve Styrofoam boards (2.54 cm thick), which were floated on nutrient solutions contained in one of twelve, plastic boxes on 19 January, 24 February and 9 March 2016. Nutrient solutions were either unheated (control), continuously heated to a target temperature of 16 °C, or continuously heated to a target temperature of 22 °C using aquarium heaters (Hailea® Aquarium Heater, Guangdong, China). The experiment was a completely randomized design, with four replications per treatment. Styrofoam boards that were 2.54 cm thick were used to suspend the plants in each nutrient solution of varying temperatures and supported six lettuce plants each. Data loggers (WatchDog® B-Series Button Loggers Spectrum Technologies, Inc. Aurora, IL.) recorded temperature of greenhouse air at plant height (approximately 1 meter about the ground) and nutrient solution temperature hourly of each experimental unit.

Harvesting and data collection

At 28 days after transplant (DAT) size index was quantified ([height + width1 + width2] ÷ 3) for each head. Lettuce heads were then cut at the base, weighed to determine fresh weight. Roots were weighed then dried in a forced-air drying oven at 72 °C for 72 h and weighed to determine root dry weight (RDW).

The experiment was a completely randomized design with experimental run in the model as a random variable. Each box was an experimental unit containing six subsamples (lettuce plants). An analysis of variance was performed on all responses using PROC GLIMMIX in SAS version 9.4 (SAS Institute, Cary, NC) in which target temperature was considered a categorical variable. Where residual plots and a significant covariance test for homogeneity indicated heterogeneous variance among treatments, a RANDOM statement with the GROUP option was used to correct heterogeneity. Least squares means comparisons among treatments were determined using Tukey's Studentized Range Test. All responses were then subjected to regression analysis using PROC GLIMMIX to test for linear or quadratic trends based on actual air and nutrient solution temperatures during the day and night. All significances were at $\alpha = 0.05$.

Results

Plants grown in nutrient solution heated to a target temperature of 22.2 C had greater head fresh weight (HFW) than those grown in unheated nutrient solution, but, were similar to those grown in nutrient solution heated to a target of 16.7 °C (Table 3.1). However, size index and root dry weights were not significant based on target temperatures. While the two heated treatments had target temperatures, the actual temperatures for the two heated treatments were a few degrees higher than the target. Actual nutrient solution temperature averages for unheated was 20.5 °C, for 16.7 °C was 21.7 °C, and for 22.2 °C was 23.3 °C (Table 3.2).

Predictions for Size Index, Head Fresh Weight, and Root Dry Weight are linear and positively correlated (Fig 3.1, Fig 3.2, Fig 3.3). This would indicate that the higher the nutrient solution temperature, the larger SI, HFW, and RDW. In Fig. 3.4, Fig. 3.5, and Fig 3.6 show a linear correlation between SI, HFW, RDW, respectably with increasing water temperature. There is a steeper slope for average night temperature than average day temperature, which may indicate that night temperature is more important for increasing size than day temperature.

Size index (SI), head fresh weight (HFW), and root dry weight (RDW) of lettuce plants increased linearly as actual temperature increased. The equations for Size Index, Head Fresh Weight, and Root Dry Weight were linear.

Discussion

Plants grown in 22.2 °C had a higher SI and HFW than those grown in unheated tanks, but were similar to 16.7 °C. There was a 26.6 % increase in HFW from unheated to 22.2 °C. There were similar findings from an experiment by Economakis and Said (2002), when ‘Marbello’ and ‘Bastion’ (lettuce cultivars) were grown in three different nutrient solution temperatures (control, 15 °C, 20 °C) in an NFT system. Both cultivars had an increased HFW in the two treated nutrient solutions compared to unheated. For ‘Marbello’ shoot fresh weight increased from unheated to 15 °C by 66% and from unheated to 20 °C by 63%. For ‘Bastion’ shoot fresh weight increased from unheated to 15 °C by 87% and from unheated to 20 °C by 129%. This experiment was done in an unheated greenhouse where the control was around 10 °C. This would explain the increase in HFW in both 15 °C and 20 °C, compared to our study where there was no significant increase between unheated (around 20.5 °C) and 16.7 °C (around 21.7 °C). It would also partly explain the large difference in size increase, 63%-129% (depending on temperature and cultivar), compared to the present study that has 26% as its largest size increase.

Root Dry Weight in the present study was found to be not significant. Findings by Economakis (1997) showed RDW for lettuce grown in NFT systems decreased with increased solution temperature.

Increased biomass because of increasing temperatures would result in less production time. This would mean that plants grown in 22.2 °C would take less time to reach market harvest weight, which could reduce production costs. In this experiment the cost of using the heaters was not evaluated, but this would be important for deciding if using them would reduce costs in the end. Ideally, the nutrient solution heaters would be used instead, or primarily, to heating the air.

Day and night temperatures appeared to have an effect on lettuce growth. In Fig. 3.4, Fig. 3.5, and Fig 3.6, there are two lines representing the average day and average night temperatures correlated with SI, HFW, and RDW. The line representing the night temperature has a steeper slope than the line representing the day temperature. This indicates the night temperature may be more important at increasing biomass than the day temperature. Although, in an experiment studying different combinations of day and night temperatures, Yang (2016) found that a positive DIF (difference between night and day temperature) had a higher influence on plant growth than a negative DIF (negative DIF meaning the night temperature was higher than the day temperature).

During the day plants photosynthesize, then at night they respire; where the plant uses oxygen and products from photosynthesis to make energy. Lower than optimal temperatures slow down enzymes that help with plant processes, including respiration (Wein, 1997). Controlling for the drop in temperature at night by keeping the nutrient solution heated will allow the plant to benefit from the constant increased nutrient solution temperature and will cause the plant to respire more during the night. Although, it is possible that night temperature will not affect respiration as much as would be desired, as found by Frantz et al. (2004). Their study examined lettuce, tomato, and soybean in growth chambers and saw respiration increased only 20–46 % for each 10 °C rise in temperature. Future experiments can look at heating the nutrient solution in Deep Water Culture just at night to see how that effects plant growth. Being able to concentrate just on heating nutrient solutions at night would help in reducing energy costs.

Overall, lettuce plants grown in the 22.2 °C treatment were larger than those grown in unheated and 16.7 °C treatments. Heating Deep Water Culture nutrient solution to at least 22.2 °C may decrease lettuce production time during winter months. As experiments are conducted to evaluate costs, such as the cost to heat the nutrient solution and not the air, this practice could help decrease production times and decrease production costs for growers in the Southeastern United States.

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Table 3. 1. Effects of nutrient solution temperature on size index, head fresh weight, and root dry weight of *Lactuca sativa* L. 'Rex' grown in Deep Water Culture for 28 d.

Target Temperature[z]	Actual Temperature[y]	Size Index[x]	Head Fresh Weight (g)	Root Dry Weight (g)
Unheated	20.5	16.4	48.19 b[w]	0.22
16.7	21.7	17	53.84 ab	0.22
22.2	23.3	17	61.02 a	0.26
Significance[v]		*NS*	*	*NS*

[z]Values in °C; Nutrient solution was heated continuously to target temperature using an aquarium heater (Hailea® Aquarium Heater 200w, Guangdong, China).
[y]Actual temperature was measured hourly using a data logger (WatchDog® B-Series Button Loggers Spectrum Technologies, Inc. Aurora, IL).
[x]Size index was measured in cm as: [(Height + Widest Width + Perpendicular Width) / 3].
[w]Values in columns sharing the same letter were not different according to Tukey's Honest Significance Difference Test (α = 0.05).
[v]An analysis of variance was used to test the significance of the treatment (target temperature) on size index, head fresh weight, and root dry weight. NS = not significant; $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.001$ (***).

Table 3. 2. Temperatures for Effects of nutrient solution temperature on size index, head fresh weight, and root dry weight of *Lactuca sativa* L. 'Rex' grown in Deep Water Culture for 28 d.

	Day	Night
Unheated	21.0 °C (69.8 °F)[y]	20.7 °C (69.3 °F)
16.7 °C (62 °F)[z]	22.5 °C (72.5 °F)[x]	21.5 °C (70.7 °F)
22.2 °C (72 °F)	23.7 °C (74.7 °F)	23.1 °C (73.6 °F)
Inside Greenhouse (Air)	25.2 °C (77.4 °F)	20.0 °C (68.1 °F)

[z]Nutrient solution was heated continuously to target temperature using an aquarium heater (Hailea® Aquarium Heater 200w, Guangdong, China).
[y]Actual temperature was measured hourly using a data logger (Watchdog Series B, Spectrum Technologies, Inc.).
[x]Each box had a data logger and greenhouse air temperature was recorded approximately 1 meter above ground.

Figure 3. 1. Predicted Size Index of *Lactuca sativa* L. 'Rex', Grown in Deep Water Culture for 28 d, Based on Average Water Temperature

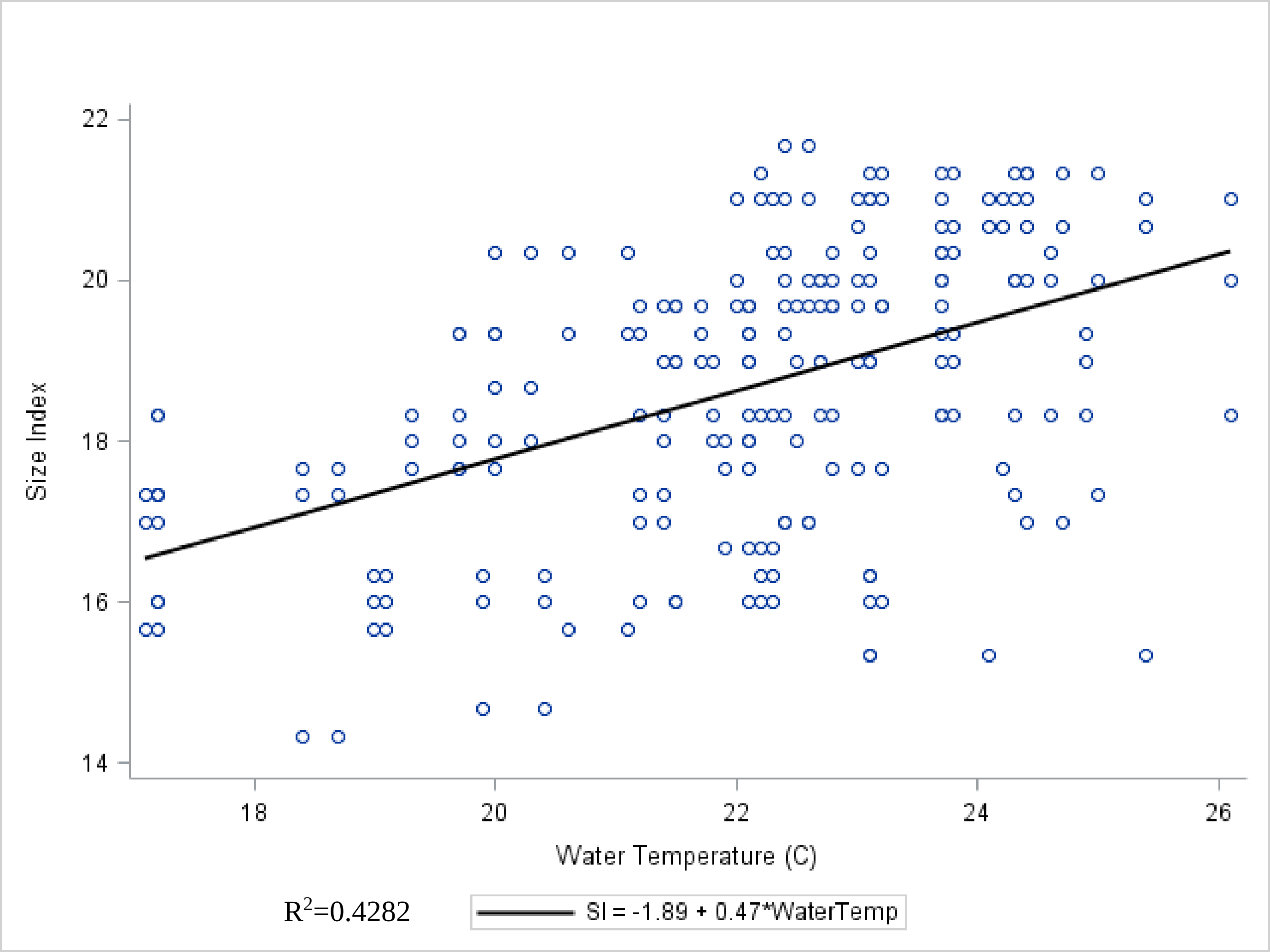


Figure 3. 2. Predicted Head Fresh Weight of *Lactuca sativa* L. ‘Rex’, Grown in Deep Water Culture for 28 d, Based on Average Water Temperature

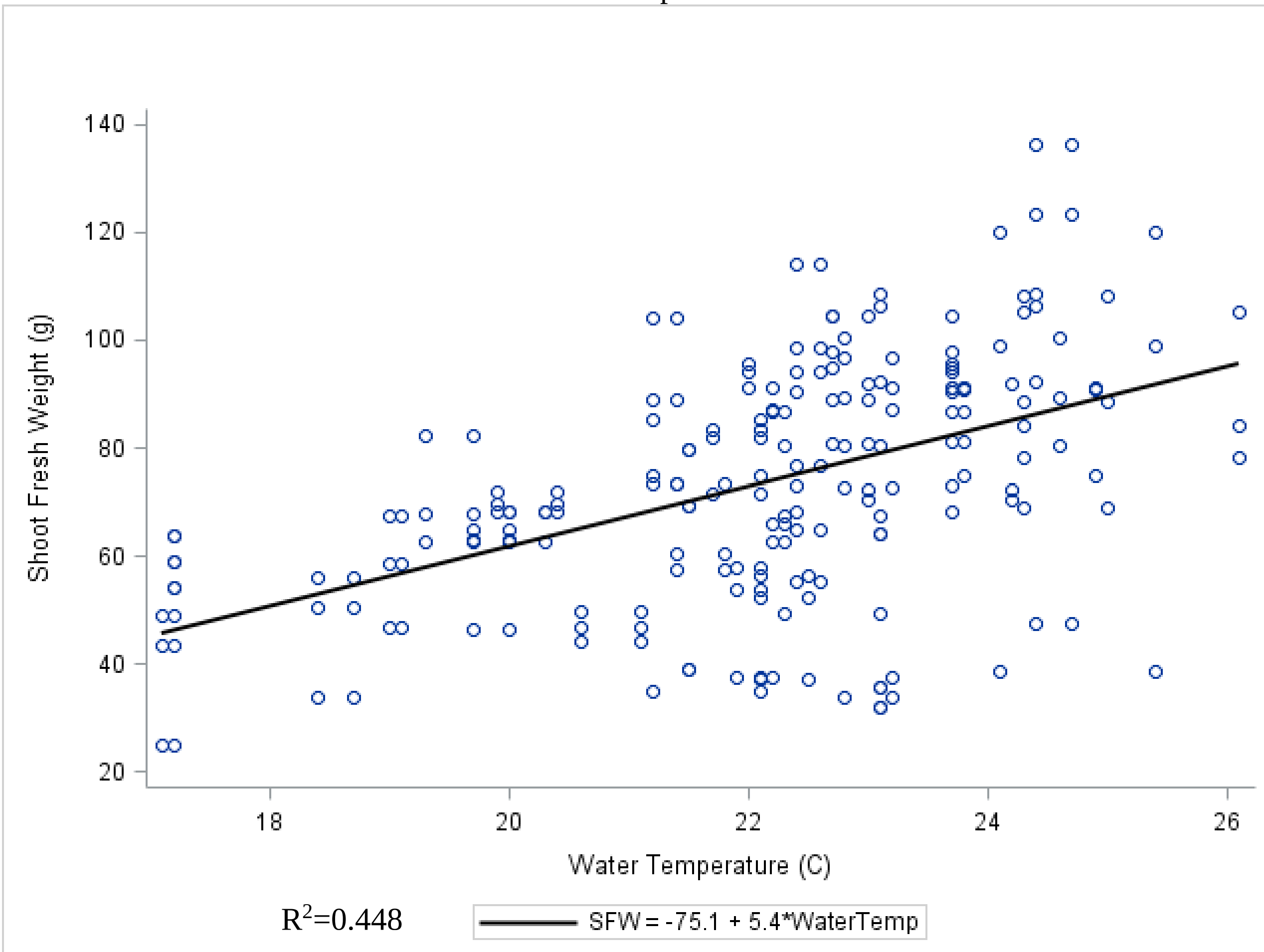
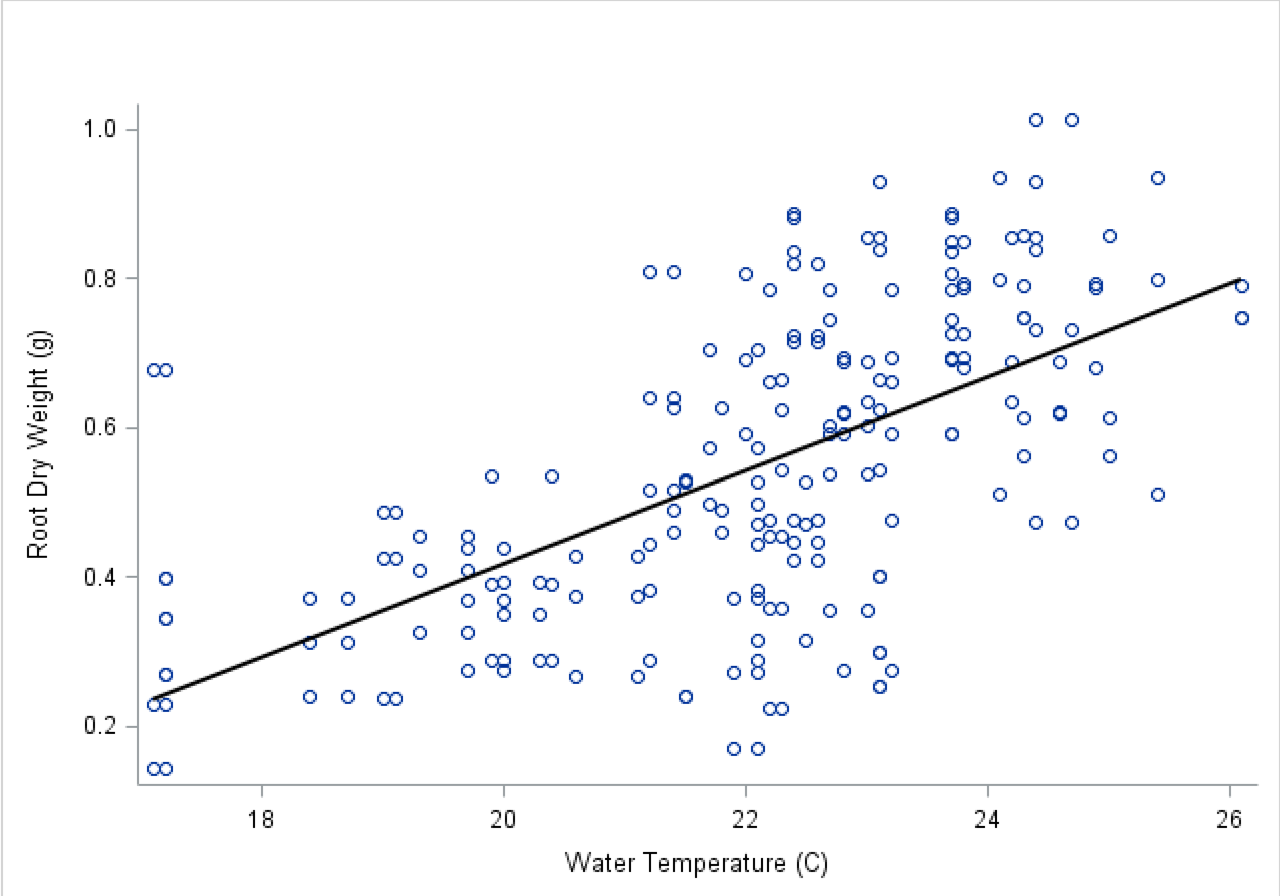


Figure 3. 3. Predicted Root Dry Weight of *Lactuca sativa* L. ‘Rex’, Grown in Deep Water Culture for 28 d, Based on Average Water Temperature



R^2=0.4522

Figure 3. 4. Predicted Size Index of *Lactuca sativa* L. ‘Rex’ Based on Average Day and Night Water Temperature

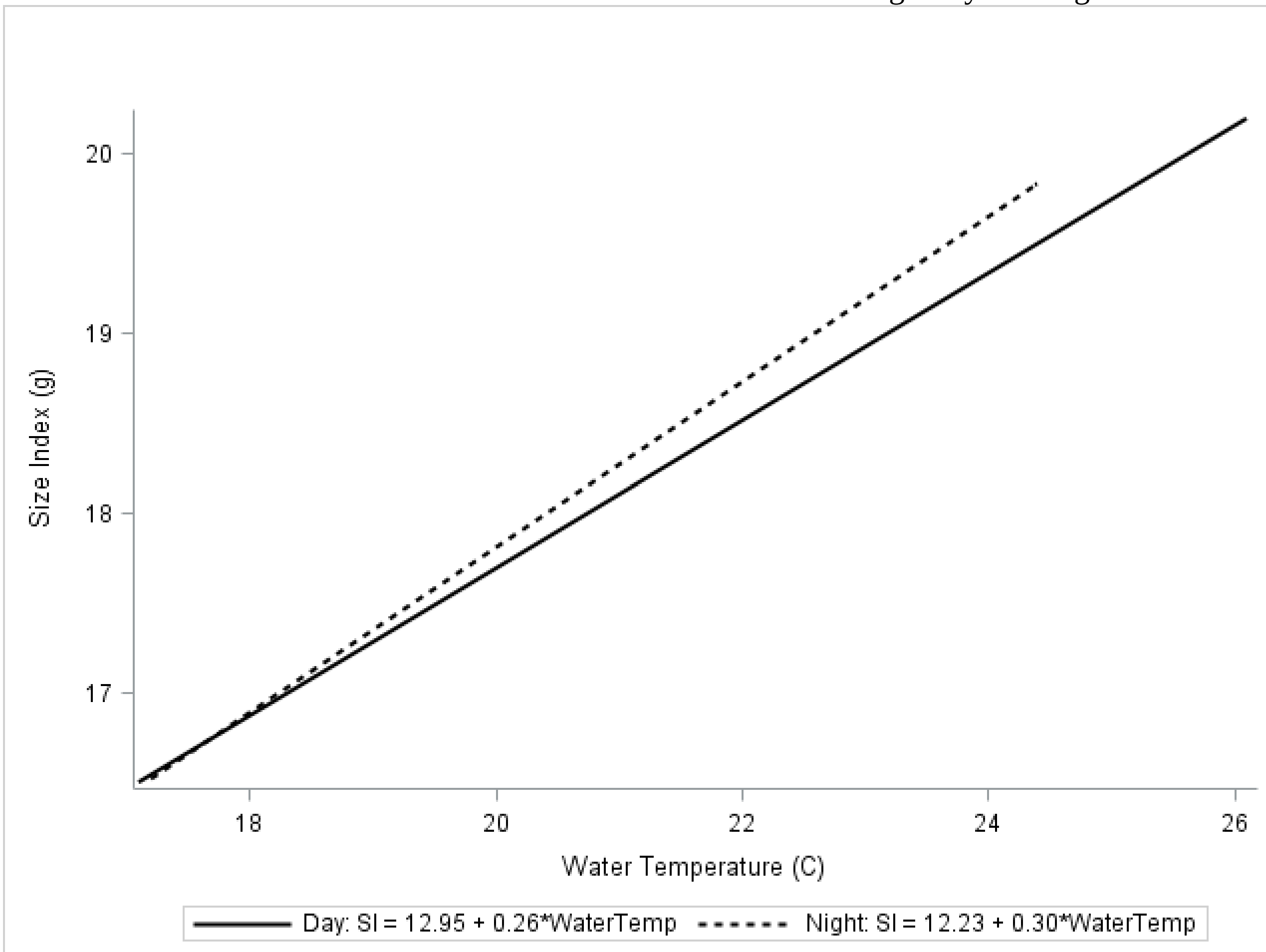


Figure 3. 5. Predicted Head Fresh Weight of *Lactuca sativa* L. 'Rex' Based on Average Day and Night Water Temperature

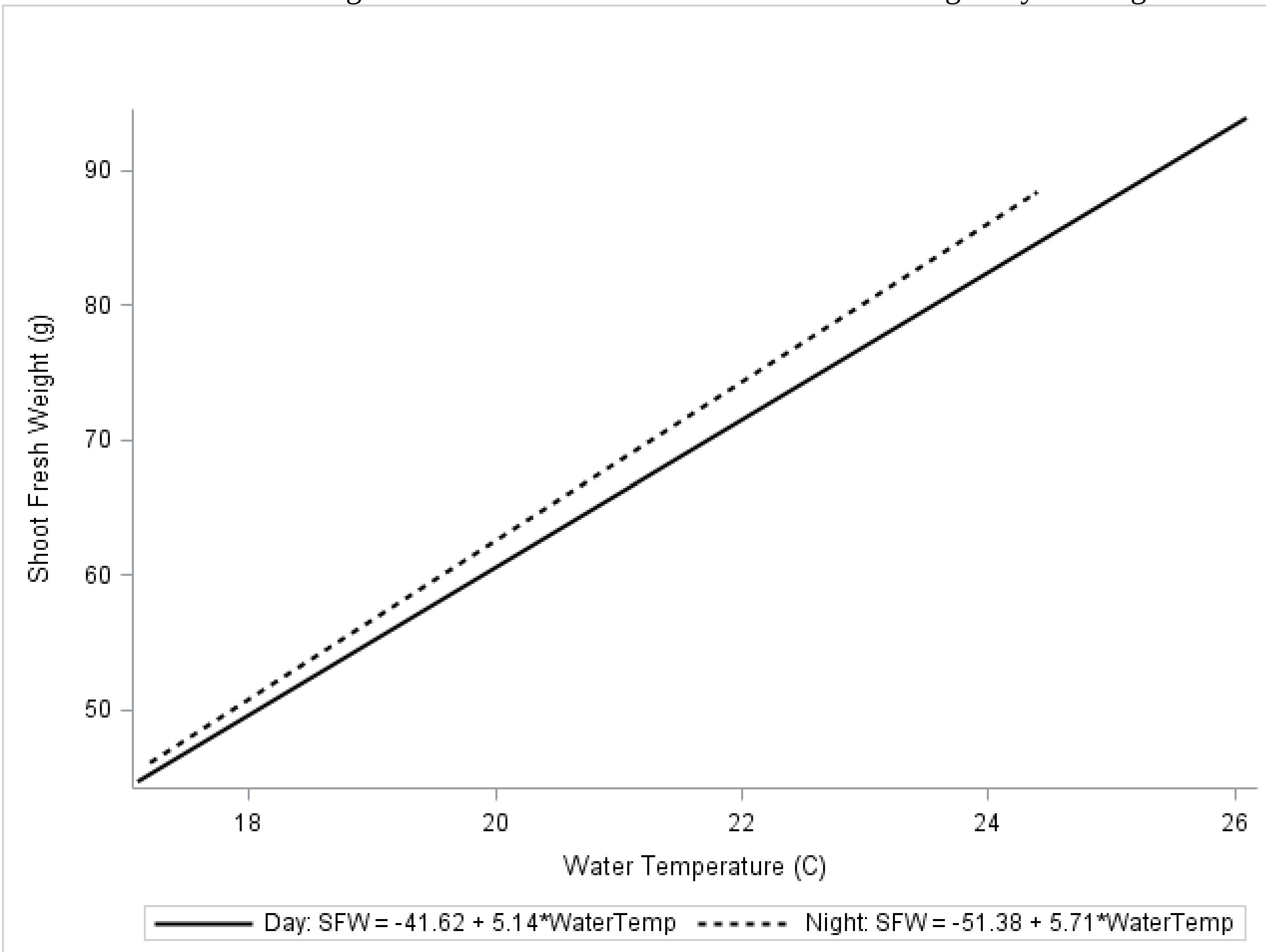
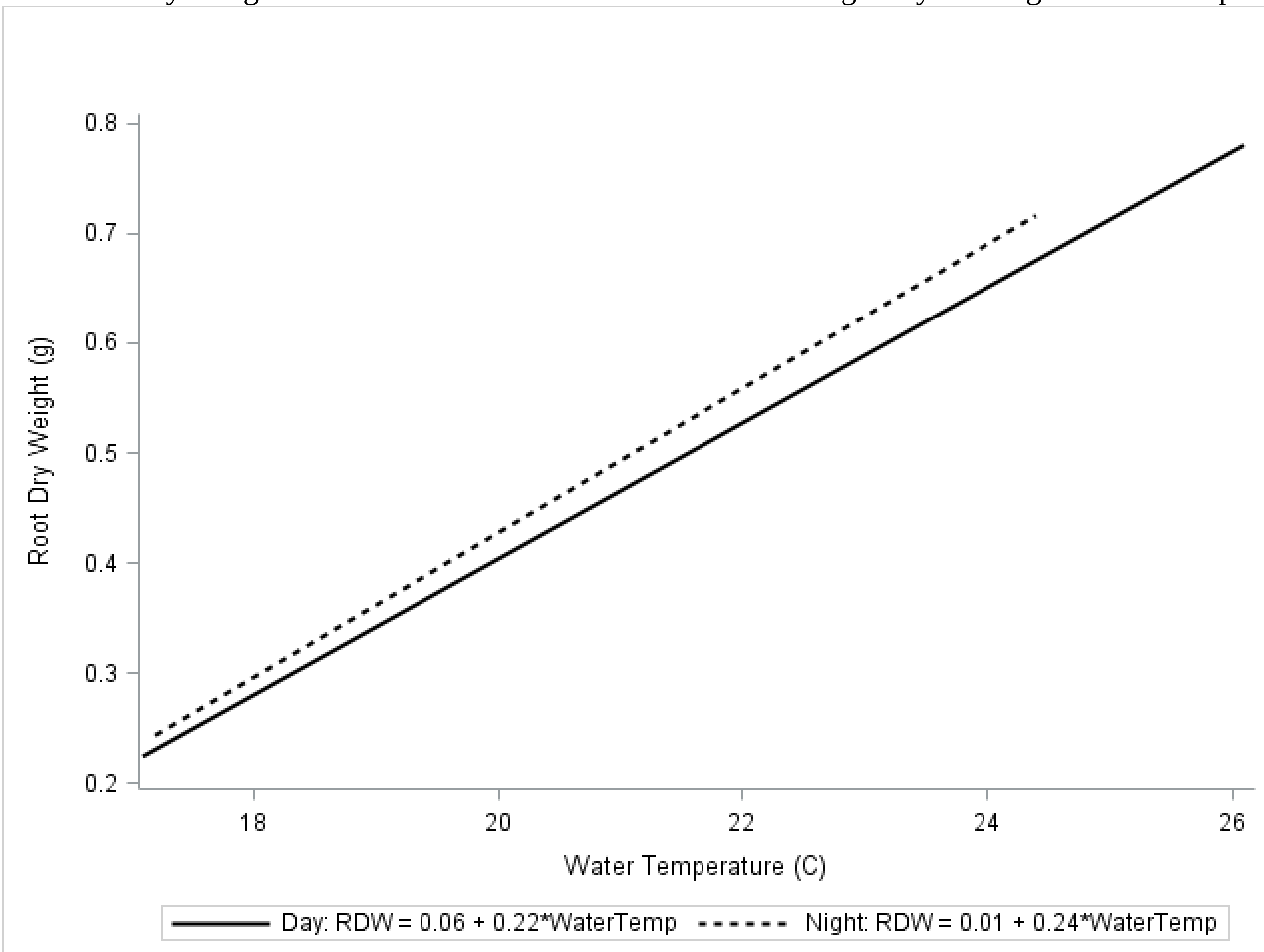


Figure 3. 6. Predicted Root Dry Weight of *Lactuca sativa* L. 'Rex' Based on Average Day and Night Water Temperature



Conclusion

The purpose of this work was to provide information to growers to improve hydroponic lettuce production in the Southeastern United States. Growers struggle with some of the aspects of growing lettuce in the Southeast, like higher than optimal temperatures and high energy costs. Through the experiments in this thesis, we addressed these problems and worked to provide solutions for growers.

Heat tolerance of *Lactuca sativa* L. varieties grown hydroponically and consumer sensory evaluation of heat tolerant hydroponic lettuce

Lettuce is a cool season crop (Ryder, 1999) and therefore does not perform well in the summer in the southeast. There have been breeding efforts to provide growers with heat-tolerant and/or slow-bolting cultivars. A few of those cultivars were trialed in our heat tolerant study to test how they would do in a very hot greenhouse in the southeast. The greenhouse was located at Auburn University (32.5970 °N, 85.4880 °W) and average air temperatures during the trial period were 33 and 24.5 °C for day and night, respectively.

Butterhead lettuce is the most common greenhouse lettuce, but growers are looking for more options in types, such as romaine and other specialty type lettuces. Twenty cultivars labeled for heat tolerance and/or slow-bolting were selected to be in the study. Eleven Romaine cultivars were ‘Aerostar’, ‘Coastal Star’, ‘Flashy Trout Back’, ‘Green Forest’, ‘Green Towers’, ‘Jericho’, ‘Monte Carlo’, ‘Parris Island’, ‘Salvius’, ‘Sparx’, and ‘Truchas’, two Bibb cultivars were ‘Bambi’ and ‘Buttercrunch’, three Butterhead cultivars were ‘Adriana’, ‘Rex’, and ‘Skyphos’, and four Summercrisp cultivars were ‘Magenta’, ‘Muir’, ‘Nevada’, and ‘Teide’. They were trialed in a Deep Water Culture system and rated for tipburn and bolting. For the romaine group 'Monte Carlo' had a lower bolting rating than 'Green Towers' and 'Jericho', while 'Monte Carlo' and 'Truchas' had lower tipburn ratings than 'Green Towers' and 'Jericho'. For the summer crisp group 'Muir' had the highest bolting rating while 'Nevada' had the lowest. 'Muir' also had the highest tipburn rating. Bolting and tipburn ratings were not significant among cultivars for the bibb and butterhead groups.

Medians were reported for cultivar tipburn and bolting ratings. Nine of the twenty cultivars trialed were moved on to a study evaluating consumer preference of heat tolerant hydroponic lettuce. Cultivars were chosen because of their lower median ratings for both tipburn and bolting. Selected cultivars were 'Adriana', 'Aerostar', 'Monte Carlo,' 'Nevada', 'Parris Island', 'Rex', 'Salvius', 'Skyphos', and 'Sparx'. A sensory evaluation was done with students, faculty, and staff of Auburn University. They were asked to rating the lettuce on Bitterness, Crispness, Overall Texture, Overall Flavor, and Marketability. Bitterness did not correlate to Crispness, but Marketability correlated with Crispness, Bitterness, Overall Texture, and Overall Flavor. Out of the nine cultivars in the study, only two of them we would not recommend. 'Skyphos' and 'Adriana' had low marketability ratings and therefore are not good options even if they perform well in the southeast.

Further research could be done to trial more cultivars for heat tolerance. Using different methods of evaluating heat tolerance at the chemical level would help strengthen results of what cultivars are heat tolerant. Testing how the much the chemical properties change during the trial could give us a quantitative measurement.

In further research, including color and/or appearance in a consumer survey would help give a complete picture of what consumers prefer. 'Skyphos' had a red color and 'Adriana' had a floppy appearance. Both of these cultivars did not receive high marketability ratings from the consumers. A study quantifying buyer preferences for greenhouse-grown lettuce asked chefs to taste test 20 cultivars of lettuce. In the feedback it was said that the chefs would be less likely to buy lettuce with a red coloring because they knew their customers would think something was wrong with the lettuce. This is where asking about appearance and color in consumer preference would be useful. Evaluating these characteristics could provide more information on what characteristics consumers prefer in lettuce.

Influence of heating nutrient solution on greenhouse-grown hydroponic lettuce

Hydroponic lettuce production is increasingly popular in the southeastern United States, but one of the disadvantages of this type of lettuce production in the costs. Labor is the most expensive single cost for greenhouse production while energy is the second (Frantz et al., 2010). Determining methods of reducing energy costs, while keeping production yields high is essential for keeping greenhouse lettuce growers competitive in local, regional, and national markets. Energy costs, therefore represent the largest single factor that can be reduced in order to be competitive in these markets.

Heating nutrient solution is used by growers to decrease production time and production costs. An experiment was conducted to determine effects of heating the nutrient solution on lettuce growth in Deep Water Culture during the winter in a greenhouse in the southeast.

Seedlings of *Lactuca sativa* ‘Rex’ L were grown in nutrient solutions contained in one of twelve, 42.5-L plastic boxes. Nutrient solutions were either unheated (control), continuously heated to a target temperature of 16 °C, or continuously heated to a target temperature of 22 °C using aquarium heaters. Size index (SI), head fresh weight (HFW), and root dry weight (RDW) were recorded at harvest. Plants grown in 22.2 °C had a higher SI and HFW than those grown in unheated tanks, but were similar to 16.7 °C. There was a 26.6 % increase in HFW from unheated to 22.2 °C. Size index (SI), head fresh weight (HFW), and root dry weight (RDW) of lettuce plants increased linearly as actual temperature increased. Results also indicated that night temperature was more important for size.

The results of this study are promising for growers, but further research needs to be done to evaluate if the heaters are economical. Ideally, using heaters would be used instead of heating the greenhouse air, or they would allow the grower to greatly reduce heating the greenhouse air. Research should be done that includes a wider range of nutrient solution temperatures. This would give a better idea of at what point increasing nutrient solution would have a detrimental effect on lettuce in Deep Water Culture.

Night temperature seemed to be more important for size than day temperature. There could be a few different reasons why we got this result, but further research could help to explain. Setting up an experiment where only the nutrient solution is heated at night could be a first start at finding the reason.

Hopefully, with this research and future related research, lettuce production in the southeast can be improved by finding more suitable cultivars and finding ways to reduce production costs.

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Appendix

Abstract

On 29 October 2015 two plants from each of twenty different lettuce cultivars, grown hydroponically in Deep Water Culture, were harvested and placed in individual plastic bags in a cooler filled with ice. They were transported to three, separate locations and were tasted by five different Auburn, AL-area chefs who rated each cultivar for bitterness, overall flavor, crispness, texture, and marketability. Lettuce types included Romaine, Butterhead/Bibb, and Summercrisp. Cultivars selected for the study were marketed as heat tolerant and/or slow-bolting and included 'Nevada', 'Rex', 'Adriana', 'Skyphos', 'Muir', 'Green Towers', 'Teide', 'Truchas', 'Jericho', 'Flashy Trout Back', 'Sparx', 'Parris Island', 'Salvius', 'Coastal Star,' 'Magenta,' 'Monte Carlo', 'Bambi', 'Aerostar', 'Green Forest', and 'Buttercrunch'. There were no differences in organoleptic qualities or marketability between cultivars. There were no differences in ratings among cultivars within types, but differences existed between lettuce types. Bitterness and flavor ratings were higher for Bibb type than Butterhead and Summercrisp types, but were similar for Romaine. Crispness ratings were higher for Bibb and Romaine types than for Butterhead and Summercrisp types. Texture ratings were higher for Bibb and Romaine types than Butterhead, but were similar to Summercrisp. There were no differences in marketability between varieties, but marketability was strongly correlated with flavor, crispness, and texture ratings. Bitterness did not affect marketability.

Introduction

Butterhead/Bibb is the most commonly grown hydroponic lettuce type (Tyson et al., 2013). Hydroponic lettuce growers in the Southeast need good recommendations of varieties and cultivars to expand their markets. For example, Romaine lettuce is in high demand and is considered a cool season lettuce variety in field production (Dufault et al., 2009). However, specific information regarding heat tolerance in hydroponic systems is unavailable in the literature. Growers need information regarding other types of lettuce, including Romaine. This project is an extension of a variety trial to determine the most heat-tolerant cultivars in hydroponic systems. Through this research we will be able to provide lettuce growers valuable information that will improve their marketing efforts.

Finding out consumer preferences for food is important when deciding what to produce. Producing food that is not liked and not wanted would result in profit losses. Consumer preference surveys, or sensory evaluations have been done for a multitude of foods and products. There have been sensory evaluation studies done on transgenic tomatoes (Lim et al., 2014) all the way to mayonnaise prepared with ostrich egg (Abu-Salem and Abou-Arab, 2008). Finding what consumers desire in lettuce, crispness, bitterness level, can help give an idea of what growers should produce.

Sensory characteristics such as appearance, aroma, texture, and taste will affect consumer preferences of produce, whether consciously or subconsciously. Biological instinct is to find sweet tasting food more desirable than bitter tasting foods. Although, as we age we may be able to desire bitter tasting foods due to "acquired taste." The idea of being able to acquire taste for a certain food indicates that other factors can affect preferences, like beliefs and expectations of a food (Clark, 1998). Most consumers expect lettuce to be crisp (Barrett et al., 2010) and in general consumers expect lettuce to not be bitter (Simonne et al., 2002), but these expectations can change.

Finding what consumers desire in lettuce, crispness, bitterness level, can help give an idea of what growers should produce.

Materials and Methods

Heat tolerance of Lactuca sativa L. varieties grown hydroponically

On 18 September 2015, 13 seeds each cultivar of lettuce were sown in flats of 104 Oasis® Horticubes (OASIS® Grower Solutions, Kent, Ohio), covered with clear plastic humidity domes, and placed on a greenhouse bench. After germination, seedlings were irrigated with municipal water (Auburn, AL) every other day for seven days followed by irrigation with a complete nutrient solution containing 150, 80, 200, 150, and 35 mg L^{-1} N, P, K, Ca, and Mg, respectively every other day for another seven days. Fertilizers used included Gramp's Original hydroponic lettuce fertilizer (Ballinger, TX) 8-15-36, calcium nitrate 15.5-0-0, and magnesium sulfate 10% Mg. Lettuce plants were then transplanted on 2 October 2015 into one of four identical raft culture hydroponic pools located in a separate greenhouse. Plants were grown for 30 d and harvested on 29 October 2015.

Quantifying buyer preferences for greenhouse-grown lettuce

On 29 October 2015 twenty different lettuce cultivars, grown hydroponically in Deep Water Culture, were harvested and placed in individual plastic bags in a cooler filled with ice. They were transported to three, separate locations and were tasted by five different Auburn, AL-area chefs who rated each cultivar for bitterness, overall flavor, crispness, texture, and marketability (Fig. A.1). Eleven Romaine cultivars selected were ‘Aerostar’, ‘Coastal Star’, ‘Flashy Trout Back’, ‘Green Forest’, ‘Green Towers’, ‘Jericho’, ‘Monte Carlo’, ‘Parris Island’, ‘Salvius’, ‘Sparx’, and ‘Truchas’. Five Butterhead/Bibb cultivars selected were ‘Adriana’, ‘Bambi’, ‘Buttercrunch’, ‘Rex’, and ‘Skyphos’. And four summercrisp cultivars selected were ‘Magenta’, ‘Muir’, ‘Nevada’, and ‘Teide’. The lettuce heads were all laid out in front of the chefs and each of the heads were placed on a white plate that had a number on it to signify which cultivar was on the plate. The numbers were:

List of Cultivars:

1. Nevada-Summer Crisp
2. Rex-Butterhead
3. Adriana-Butterhead
4. Skyphos-Butterhead
5. Muir-Summer Crisp
6. Green Towers-Romaine
7. Teide-Summer Crisp
8. Truchas-Romaine
9. Jericho-Romaine
10. Flashy Trout Back-Romaine
11. Sparx-Romaine
12. Parris Island-Romaine
13. Salvius-Romaine
14. Coastal Star-Romaine
15. Magenta-Summer Crisp
16. Monte Carlo-Romaine
17. Bambi-Bibb
18. Aerostar-Romaine
19. Green Forest-Romaine
20. Buttercrunch-Bibb

Results

There were no differences among cultivars or varieties for Bitterness (Table A.1). There were no differences among cultivars within varieties for Flavor, Crispness, Texture, and Marketability. Bibb had a higher flavor rating than Butterhead and Summercrisp, but was similar to Romaine. Bibb and Romaine had a higher Crispness than Butterhead and Summercrisp. Bibb and Romaine had a higher texture rating than Butterhead, but was similar Summercrisp. Bibb had a higher marketability rating than Butterhead and Summercrisp, but was similar to Romaine.

Bitterness and Crispness were not correlated. Bitterness did not affect Marketability (Table A.2).

Discussion

Results for the chef preference did not find differences between cultivars for Crispness, Bitterness, Flavor, Texture, and Marketability. This may have been because the chefs were presented with 20 cultivars. Twenty cultivars are a lot of samples to process and differentiate between. When narrowing the samples to nine for the *Using Sensory Evaluation to Assess Consumer Preferences for Hydroponically-grown Lettuce* study, this was not a problem.

Results for chef preference indicate that bitterness did not affect marketability. This may have been due to chefs, who are better trained in food, preferring lettuce with more taste. The chefs also stated that they knew that lettuce that had a red coloring or had specks would not be well liked by their customers. There were also chefs that stressed the importance of testing dressings on the lettuce samples to see how they interacted texturally and taste-wise.

In future experiments, it would be beneficial to narrow down the amount of samples presented to chefs, have more chefs taste test, and possibly add a separate survey dealing with dressings.

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Table A. 1. Differences among varieties in chef preference study

Varieties[z]	Bitterness[y]	Flavor[x]	Crispness[w]	Texture[v]	Marketability[u]
Bibb	NS[t]	4.5a[s]	4.0a	4.0a	5.0a
Butterhead		3.0b	3.0b	2.0b	3.0b
Romaine		3.5ab	4.0a	4.0a	4.0ab
Summer Crisp		3.0b	3.0b	3.0ab	4.0b

[z] No differences among cultivars within varieties for Flavor, Crispness, Texture, and Marketability.

[y] Bitterness was rated on a scale from 1 to 5 with 1 being not bitter and 5 being bitter.

[x] Flavor was rated on a scale from 1 to 5 with 1 being poor flavor and 5 being excellent flavor.

[w] Crispness was rated on a scale from 1 to 5 with 1 being not crisp and 5 being very crisp.

[v] Texture was rated on a scale from 1 to 5 with 1 being poor texture and 5 being excellent texture.

[u] Marketability was rated on a scale from 1 to 5 with 1 being not likely to buy and 5 being likely to buy.

[t] No differences among cultivars or varieties for Bitterness

[s] Reported are medians. Estimated cultivar differences using the simulated method at α=0.05.

Table A. 2. Correlations between criteria for chef preference evaluation

	Flavor[x]	Crispness[w]	Texture[v]	Marketability[u]
Bitterness[y]	20.71[t]	1.25	4.66	0.03
	***[z]	NS	*	NS
Flavor		29.56	36.74	14.18
		***	***	***
Crispness			57.32	28.17
			***	***
Texture				25.97
				***

[z]NS = non significant; P≤ 0.05 (*), P ≤ 0.01 (**), P ≤ 0.001(***).

[y] Bitterness was rated on a scale from 1 to 5 with 1 being not bitter and 5 being bitter.

[x] Flavor was rated on a scale from 1 to 5 with 1 being poor flavor and 5 being excellent flavor.

[w] Crispness was rated on a scale from 1 to 5 with 1 being not crisp and 5 being very crisp.

[v] Texture was rated on a scale from 1 to 5 with 1 being poor texture and 5 being excellent texture.

[u] Marketability was rated on a scale from 1 to 5 with 1 being not likely to buy and 5 being likely to buy.

[t] Reported are medians. Estimated cultivar differences using the simulated method at α=0.05.

Figure A. 1. The scale presented to chefs

Please rate each lettuce for the following:

Bitterness:	1 – not bitter	5 – very bitter
Overall flavor:	1 – poor flavor	5 – excellent flavor
Crispness:	1 – not crisp	5 – very crisp
Overall texture:	1 – poor texture	5 – excellent texture
Marketability:	1 – not likely to buy	5 – very likely to buy

Lettuce 1

Bitterness	1	2	3	4	5
Overall Flavor	1	2	3	4	5
Crispness	1	2	3	4	5
Overall Texture	1	2	3	4	5
Marketability	1	2	3	4	5