Water Requirements, Use Efficiency, and Insect Infestation in Brussels Sprouts, and Nitrogen Use Efficiency in Sweet Basil Under Low Tunnels Compared to Open-Field Production

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Abstract

Sustainable vegetable production is one of the most active areas of vegetable research and of concern to all producers. Everyone, both producers and consumers, are concerned with sustainability. Brussels sprouts and sweet basil are high value commodities, but increasing global concerns about water availability, insect-pest problems, and costly fertilizer inputs severely impact the growth and production of these crops. Low tunnels covered with spun-bonded fabric can improve production of vegetables and herbs in Virginia and the U.S. This study investigated the performance of Brussels sprouts and basil grown under low tunnels (LTs), and their relationship with water use efficiency, nitrogen use efficiency, and the level of protection against insect injury. Low tunnels increased yield, number of sprouts, and water use efficiency of Brussels sprout production. In addition, LTs decreased irrigation requirements, irrigation events, leaf feeding injury, and insect populations in comparison to open field. Similarly, LTs increased summer production of sweet basil as measured by fresh weight and biomass. In addition, plant N uptake was greater under the LTs; however, the increase in nitrogen use efficiency was inconsistent.

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General Audience Abstract

Brussels sprouts and sweet basil are economically important cash crops on the East Coast. Brussels sprouts is a Cole crop and an important source of dietary fiber, vitamins (A, C & K), calcium, iron, manganese and antioxidants. Similarly, sweet basil is a member of the mint family and important high-value herb in the U.S. and the world. It is mainly grown for culinary purposes as a dried and fresh spice in the U.S. However, demand for these commodities is increasing. Low tunnels (LTs) covered with spun-bonded fabric can be a practical management tool to increase yield. Results from this study indicate that LTs increase yield of Brussels sprouts and basil, water use efficiency and total nitrogen uptake, while reducing insect pest infestation. Therefore, LTs can be a useful tool to improve sustainability of Brussels sprouts and basil production.

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Chapter 1: Introduction

Sustainable vegetable production is one of the most active areas of vegetable research and a concern to all producers. To be sustainable, vegetable production must be environmentally sound, economically viable, with social justice and equity. Sustainable vegetable production is challenging. It requires more time and effort. Scientists are conducting research to improve sustainability using intensive vegetable management practices. Horticulturists have introduced protected production system to modify crop microenvironment and produce vegetables in a more sustainable way. A wide variety of techniques such as hot beds, glass cloches, cold frame, low and high tunnels, and various types of greenhouses have been used to extend the growing season (Lamont, 2005). Due to the continued research focus on protected vegetable production systems, cultivation of vegetables under row cover is spreading in the United States (Lamont, 2005).

Row covers are transparent or semitransparent plastic film/fabric that is used for the plant protection against cold temperature and insects by vegetable grower (Arancibia, 2018). There are different types of row covers available for vegetable production. Initially, parchment paper was used for covering vegetables followed by utilization of plastic (Lamont 2005). However, air flow and ventilation was problem to the plants covered by the plastic, that lead to development of spun-bonded fabric. Spun-bonded fabrics allow air flow and ventilation, hence, helping to avoid the stressful high temperatures inside the tunnels on sunny day (Arancibia and Motsenbocker, 2008). Spun-bonded low tunnels (LTs) are supported by wire hoops. However, they can also be used as floating row covers without support as a blanket for short-term frost protection, but depending on the thickness longer-term use may cause physical damage and abrasion of plants with yield reduction (Baker et al., 1998).

Production under LTs covered with spun-bonded fabric can be effective for sustainable production of vegetables early and late in the season (Arancibia, 2018). Low tunnels may be more affordable to the farmer than high tunnels and are movable to allow crop rotation with cover crops. Row covers can improve plant growth, earlier harvest, and increase yield if used properly (Gerber et al., 1988; Ibarra et al., 2001). In addition to growth and development, LTs can modify micro-environments such as soil temperature, air temperature, relative humidity, solar radiation, and air movement, which helps to reduce evapotranspiration (ET) and subsequently water stress (Arancibia, 2009, Arancibia, 2018). Among them, temperature is key components for driving the environment's energy status (Lombard and Richardson,1979). The favorable microclimate inside tunnels early in the season increases vegetative growth and crop yield in many crops (Arancibia, 2009 and 2012; Arancibia and Motsenbocker, 2008; Gerber et al., 1988). Therefore, LTs are generally used during the spring to enhance plant growth, biomass accumulation and extend the production season (Soltani et al., 1995).

Irrigation is one of the major factors in vegetable production. Irrigation is often governed by the limited availability of water and labor. Therefore, farmers are concerned about water availability and use efficiency. Water use efficiency (WUE) is defined as the ratio of crop yield to the amount of water applied (Howell, 2001). Water is essential for crop production because the plant needs water for expansive growth and gas exchange. However, more than 90% of the water needed by the plant is lost to transpiration (Morison 2008). In all agriculture systems, lower WUE occurs when soil evaporation is high as compared to plant transpiration in the same field (Gallardo et al., 1996). Water lost through evaporation and transpiration is known as ET. Many vegetables species are shallow rooted and are sensitive to mild water stress (Sammis, 1980; Feigin et al., 1982). There are three approaches for increasing WUE. One approach is breeding and developing drought resistant plants, a second approach is reducing ET, and the third is adequate irrigation management to reduce water loses to deep percolation. Evapotranspiration rate is important for irrigation scheduling (Zotarelli et al., 2013). Higher the ET results in higher water needs by the plant. This means by reducing ET, we are able to reduce the water needed by the plant, hence increased WUE. Numerous factors must be considered while estimating the ET, the amount of solar radiation, crop growth stage, day length, temperature, humidity, and wind speed (Arancibia, 2018; Kemble, 2016). Arancibia (2009) states that LTs can be an effective tool for reducing ET by modifying the microclimate. Reducing ET can reduce the irrigation amount too. Irrigation scheduling can minimize the amount of water needed by crop, maximizing crop yield, and reducing nutrient movement below the root zone. The hypothesis for this study is that LTs reduce ET, so plants will use less water than in an open field, which will increase WUE. Consequently, irrigation is expected to be reduced without yield reduction. It is also expected that yield will increase under LT, so WUE will improve further.

Insect pest control is essential for successful vegetable production. The loss of production due to insect-pests is significant because of reduced yield and production efficiency. An intensive spray program to control insect pests can pose a serious risk to non-target organisms (Mallik and Tesfai, 1985; Pimentel, 2005; Pimentel et al., 1993).

Similarly, continuous application of pesticide into the environment coupled with development of resistant insects suggest that there is a need for alternative eco-friendly methods of insect management. Low tunnels can also provide protection against insect infestations in vegetable production (Adams et al., 1990; Hough-Goldstein, 1987; Natwick and Laemmlen, 1993). The use of LTs and other types of row covers has increased because they act as a barrier for fly-in insects like aphids, cucumber beetles, white flies, while reducing the transfer of insect transmitted diseases (Boisclair and Estevez, 2006; Bextine et al., 2001). The hypothesis is that LTs provide protection against fly-in insects and to those insects that are not already present in the Brussels sprouts or in the soil inside the tunnel. In addition, insect leaf damage is expected to be less in comparison to an open field.

Soil health and fertility are of paramount concern for sustainable vegetable production and have a significant impact on the system's nutrient management. Maintaining soil health and fertility in a sustainable manner is challenging. If consistent tillage is used with little crop biomass incorporation, then the overall soil quality and health deteriorate (Reeve and Drost 2012). In addition, many other soil factors are associated with a nutrient's plant availability such as type of soil particles, textural classification, cation exchange capacity, soil organic matter content, and drainage (Waynandt 2016). Hence, availability of nutrients to the plant may vary from soil to soil. Proper fertilization management strategies are important for sustainable vegetable production. Excess nitrogen availability can promote vegetative growth to the detriment of reproductive growth and yield. Similarly, the risk of nutrient losses to deep percolation is increased. Low soil fertility reduces crop yield, which is not economically favorable for vegetable production. Low tunnels can improve nutrient use efficiency in vegetable production. The hypothesis for this study is that LT enhances plant growth, so crops utilize nutrients more efficiently as compared to conventional open field production system. However, there are no reports on nutrient requirements for crops grown under LT covered with spun-bonded fabric. Many studies have been conducted with LTs to extend the growing season for vegetable production. However, nutrient and water-use efficiency under the LT still need to be investigated. Therefore, investigating the interaction between row covers and nutrients and water requirement is warranted.

Objectives

- To determine water requirements and its use efficiency under LTs in comparison to open-field Brussels sprout production.
- To determine insect infestation and feeding injury under LTs in comparison to open field production of Brussels sprouts.
- To determine nitrogen requirements and use efficiency under LT in comparison to open field for sweet basil production.

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Chapter: 2

Low tunnels reduce irrigation water needs and increase growth, yield and water use efficiency in Brussels sprouts

Additional index words: row cover, temperature, solar radiation, evapotranspiration, irrigation

Abstract

Farmers use low tunnels (LTs) covered with spun-bonded cloth to protect warm-season vegetable crops against cold temperatures and extend the growing season. Cool season vegetable crops may also benefit from LTs by enhancing vegetative growth and development. This study investigated the effect of the micro-environmental conditions under low tunnels (LTs) on Brussels sprouts growth and production as well as water requirements and use efficiency in comparison to open field. Low tunnels increased soil temperature in Spring 2017, but only early in the Fall 2017 and Spring 2018. Similarly, LTs reduced evapotranspiration by 54% to 68% by reducing solar radiation and blocking wind in spite of higher maximum air temperatures. Because of the reduced evapotranspiration, water needs, and irrigation decreased by 24% to 40%. In contrast, LTs enhanced vegetative growth (plant leaf area, plant biomass, and plant height). Sprouts per plant and yield under LT increased by 29% and 46% in Spring 2017, by 22% and 46% in Fall 2017, and by 29% and 22% in Spring 2018 trials, respectively. Considering the increased growth and productivity and the reduced irrigation, LTs increased water use efficiency in relation to yield by 62% to 107% in comparison to open field. Increased total yield, and improved water use efficiency illustrate that LTs may be a useful management tool in sustainable production systems in addition to their traditional role for season extension.

Introduction

Protected production systems are used to modify a crop's microenvironment and extend the growing period earlier in spring or later in fall (Arancibia, 2018; Lamont, 2005). In addition, protected systems enhance vegetative growth and increase productivity, which may improve the sustainability of vegetable production operations. A wide variety of structures such as hotbeds, glass cloches, cold frame, low and high tunnels, and various types of greenhouses have been used as protected systems to extend the growing season (Lamont, 2005). Although farmers use protected cultivation system for warm season vegetables, LT can also be beneficial to cool season vegetables by increasing early vegetative growth, reducing evapotranspiration (ET) and possibly irrigation.

Low tunnels effectively extend the growing season for vegetable production (Arancibia, 2018; Lamont, 2005). Among the different types of covers available to use with LTs, spun-bonded row covers of various thicknesses are most popular. They are semitransparent porous fabrics that allow airflow and ventilation, hence, helping to avoid condensation that may damage the foliage in contact with water (Arancibia, 2018). Low tunnels covered with spun-bonded fabric increase vegetative growth and yield by increasing soil and air temperature (Arancibia, 2018; Arancibia and Motsenbocker, 2008; Gerber et al., 1988; Ibarra et al., 2001; Jolliffe and Gaye, 1995; Nair and Ngouajio, 2010). In addition, LTs are movable, allowing for crop rotation with cover crops in sustainable production systems.

Many vegetables species are shallow rooted and are sensitive to mild water stress (Feigin et al., 1982; Sammis, 1980). Therefore, irrigation is important for vegetable crop production to maintain adequate soil moisture for continuous growth and development. However, more than 90% of the water used by the plant is lost through transpiration (Morison et al., 2008). In most agricultural systems, poor water use efficiency (WUE) occurs when soil evaporation is high as compared to plant transpiration in the same field (Gallardo et al., 1996). Water lost through evaporation and transpiration is known as evapotranspiration (ET), which depends on environmental conditions and plant stage (size). Increased ET rates result in increased water needs by the plant. Factors influencing ET are solar radiation (SR), crop growth stage, day length, air temperature, relative humidity, and wind speed (Allen et al., 1998; Jensen and Allen, 2016; Zotarelli et al., 2010). Therefore, fully grown plants demand larger amounts of water, especially in warm, sunny, and windy days due to the increased ET (Abdrabbo et al., 2010). Under LT however, row cover reduces direct sunlight and blocks the wind, which reduces ET even at higher temperatures (Arancibia 2012; Arancibia, 2009). Therefore, reducing the ET in crops grown under LTs may result in lower irrigation requirements and improved WUE.

The use of LT can be beneficial to extend the harvest season of Brussels sprouts (*Brassica oleracea* L. Group Gemmifera). Brussels sprouts is a cool season, frost tolerant vegetable crop from the family Brassicaceae. It is an important source of dietary fiber, vitamins (A, C & K), calcium (Ca), Iron (Fe), manganese (Mn), and antioxidants (U.S. Department of Agriculture, 2018). The US imported fresh and frozen Brussels sprouts valued at $56 million but exported only $16 million of similar sprout products in 2017 (U.S. Department of Agriculture, 2017). Therefore, the US is under producing Brussels sprouts. Brussels sprouts are produced mainly in fall, but spring production is also possible and extending the harvest season by growing under LT may help increasing local production for direct sale markets, which may reduce imports.

The hypothesis for this study was that LTs create a more favorable environment in both spring and late summer-fall that would increase vegetative growth and yield while reducing ET and irrigation. Therefore, the objectives of this studies were: A) to determine the differences in micro-environmental conditions between LT and open field and their association with irrigation requirement; B) to determine differences in vegetative growth, production, and WUE in Brussels sprouts grown under LT and open field.

Materials and methods

Brussels sprouts, cultivar 'Dimitri', were grown on a Bojac sandy loam soil in the Spring 2017, Fall 2017, and Spring 2018 at the Virginia Tech Eastern Shore Agricultural Research and Extension Center in Painter, Virginia (longitude -75.82114 and latitude 37.58466). All trials were setup in a spilt-plot design with four replications. The main effect (plots) consisted of two plastic mulches (white and black) and the secondary effect (subplot) consisted of treatments with LT and open field. Spun-bonded row cover of 33.8 $g{\cdot}m^{-2}$ (Dewitt, Sikeston, MO) were used for the studies in spring and 16.9 $g{\cdot}m^{-2}$ in fall.

Seeds were sown in 128 cells trays (Beaver plastic LTD, Canada) in first week of March 2017, last week of June 2017, and first week of March 2018 for the Spring 2017, fall 2017 and Spring 2018 trials, respectively. Trays were 65.5 cm long and 33 cm wide with square cells of 4 cm wide and 6.5 cm depth. Trays were filled with Promix HP mycorrhiza media (Premier Horticulture, Quebec, Canada) (59-69% Canadian sphagnum peat moss plus vermiculite, perlite, dolomitic lime, and a wetting agent). The greenhouse was maintained at 20ºC in early spring and 32ºC during the day in summer. Seedlings were sprinkle irrigated twice a day and fertilized continuously through the irrigation system with a concentration of 50 ppm N with 20N-8.7P-16.6K soluble fertilizer (Plantex, Brampton, Canada) until transplanting. Transplants were hand planted into double row beds on 12 April 2017, 10 August 2017 and 25 April 2018 (Table 1). Planting was on raised beds (0.2 m tall and 0.8 m wide) 1.8 m apart (center to center) with the appropriate plastic mulch (0.003 cm thick and 152.4 cm wide) (Hilex poly Co., North Vernon, IN) and drip irrigation laid between rows under plastic (Aqua Trax, Marshall Avenue EI Cajon, CA). Emitters in the irrigation tape were 30 cm apart and flow rate was 1.89 $L \cdot min^{-1}$ per 30 m tape length. Individual plots were 15 m long and divided into two 6 m subplots (LT and open field) and separated by a 1.5 m alley. In-row planting distance was 0.6 m and rows in the same bed were 0.45 m apart. The LTs were supported by 3 m long PVC hoops bent to form a 1.0 m tall and 1.0 m wide tunnel with sand bags on the sides to hold edges in place. Sand bags weighed 1.5 to 2 kg and 18 bags were used in each subplot. A pre-plant fertilizer (10N-4.4P-8.3K) was incorporated into the plant beds at 112.5 $kg \cdot ha^{-1}$ of N according to Mid-Atlantic Vegetables Guide recommendation for Brussels sprouts (Wyenandt, 2016) using a rotary tiller prior to laying polyethylene mulch in all trials. A one-time side dress at 14.5 $kg \cdot ha^{-1}$ of N was applied through the dripline in all trials. A stock solution of 3.2 kg soluble fertilizer (20N-8.7P-16.6K) was mixed in 20 L water and metered into the drip irrigation system through an injector (Chemilizer Products, Inc., Largo, FL). All other cultural practices followed the Mid-Atlantic Commercial Vegetable Production Recommendations (Wyenandt, 2016).

Environmental parameters and irrigation. Data-loggers (EM50R, Decagon Devices, Pullman, WA) were installed after transplanting in all plots and trials to record micro-environmental conditions throughout the growing period. Sensors were connected directly to data-loggers and hourly data were transmitted via radio frequencies to a central storage station connected to a computer. Soil temperature and moisture were monitored in two replications in the Spring 2017, three replications in the Fall 2017, and four replications in Spring 2018. Air temperature and RH were monitored in two replications in both spring trials, but only one in the fall trial. Soil temperature and moisture sensors (5TM, Decagon Devices) were set at a depth of 15 cm. Air temperature and RH sensors (VP3, Decagon Devices) were 30 cm above ground (plant canopy level) in both treatments as it was necessary to monitor parameters inside the LT. Solar radiation (SR) sensor (Pyranometer, Apogee, North Logan, UT) was above canopy also to fit inside the LT. Wind speed was monitored (Davis Cup Anemometer, Decagon Devices) in the open field, but not under LT as wind under LT was considered undetectable based on previous work (Arancibia 2009; Arancibia 2012). Daily maximum and minimum air temperatures, daily total SR, daily maximum and minimum RH, and daily average wind speed were used to determine ET using the Penman-Monteith Daily equation (Synder and Eching, 2007). Since Brussels sprouts is a medium size crop (>40 cm) at maturity, the ET equation for tall canopies was used. The program also considers date and location (latitude, altitude), and measured the ET based on the Penman-Monteith equation.

Low tunnels were removed 69 days after transplanting (DAT) in Spring 2017 (Table 1), so soil temperature data were separated into early-season (0 to 30 DAT) and mid-season (30 to 69 DAT). In contrast, LTs were removed at harvest in the fall trial, so soil temperatures were separated as early season (0 to 30 DAT), mid-season (31 to 60 DAT), and late season (61 DAT to harvest). In addition, soil temperature was measured from LT installation in Spring 2018. Hence, soil temperature data were separated into early season (14-45 DAT) and mid/late season (46-81 DAT). Air temperature was monitored up to the day before LT removal at 1 to 68 DAT in Spring 2017, 1 to 100 DAT in Fall 2017, and 14-81 DAT in Spring 2018.

Irrigation events based on soil moisture status and total irrigation water applied were determined in Spring (2017, 2018), but not in Fall 2017. Irrigation events were initiated at 40% to 50% deficit of plant available water and amount of water applied depended on amount of water needed to bring soil moisture up to field capacity and volume of the root zone. Based on Part 623 in the National Engineering Handbook (U.S. Department of Agriculture, 2013), soil moisture at field capacity in a sandy loam soil was at 22% volumetric water content, and 50% plant available water deficit was at 16% volumetric water content. Therefore, amounts of applied water was calculated by based on the following formula:

Total volume of water = [(Depth x Width x Dist.) x 6%], Where, Depth is the depth of the root zone, Width is the width of the root zone, Dist. is the length of the subplot, and 6% is the volumetric water content to replenish.

Amount of water applied was determined based on irrigation time and drip tape flow. Irrigation time was calculated by dividing water volume needed by drip tape flow rate. Root zone depth and width was estimated at initial stage, 30 DAT, and 60 DAT for the calculation of total volume of water required to bring 50% water deficit to field capacity.

In initial stage, estimated root zone depth and width was 15 and 30 cm, respectively, hence 43 min irrigation was applied up to 30 DAT. Similarly, estimated root zone depth and width after 30 DAT was 30 and 45 cm, respectively, hence two-hour irrigation was applied. In addition, estimated root zone depth and width after 60 DAT was 45 cm, hence three-hour irrigation was applied.

Plant growth, yield, and water use efficiency. Leaf area per plant, leaf biomass, and specific leaf area were measured by harvesting one plant from each subplot 30 and 60 DAT in both spring and at harvest in fall. The leaf area of all leaves from each plant samples was measured using a leaf area meter (LI-3100 Li. COR. Inc., Lincoln, Nebraska). Then, leaf samples were dried at 70 °C for at least 15 d and weighed to determine leaf biomass. Leaf area was divided by the dry weight to determine specific leaf area.

Prior to harvest, Brussels sprouts were decapitated (removal of the apex) on 20 June 2017 and 27 June 2018 in the spring trials, and on 20 Oct. in fall to promote the development of auxiliary buds (sprouts). Then at harvest, four plants were selected randomly from each subplot to determine plant height (stem length), plant biomass, number of sprouts, and yield. Plant height was measured from the base of the plant to the top of the stem. Number of sprouts per plant and yield of Brussels sprouts were determined by harvesting all mature axillary buds. Maturity and harvest time were determined visually when the majority of sprouts in the plants were above 2.5 cm in diameter (U.S. Department of Agriculture, 2016) and in spring trials, the outer leaves of the sprouts started to open losing firmness (warm conditions).

WUE was determined in relation to growth and production parameters. Yield, number of sprouts, plant biomass, were obtained at the time of harvest from each subplot as described above. Irrigation events and total water applied were monitored throughout the trials as described above. WUE was calculated by dividing the corresponding growth/yield parameter (number of sprouts, yield, and biomass) in each subplot (production area) by the total irrigation water applied to the same production area.

Statistical analysis. The data for the different parameters were analyzed by Minitab 2018 software (Minitab® Statistical Software 2018, State College, Pennsylvania). Analysis of variance (ANOVA) was conducted to evaluate the significance of treatment effects. Mean of each parameter was compared by Fischer's least significant difference (LSD) at 5 % significance. When there was no interaction, mean comparison was done between LT and open field, averaged across mulch color. When there was a difference by mulch then mean comparison was done between white and black mulch too, averaged across LT and open field. Time series plot, trend line, and bar graph were prepared by using Excel 2016 (Microsoft Corp., Redmond, WA).

Results

Environmental parameter and irrigation. Soil temperature was influenced by plastic mulch and LT, and there was no interaction between mulch and LT in all trials. Black plastic mulch increased soil temperature early in the season in all trials (Tables 2, 3, and 4). However, no differences in soil temperature were observed in the mid and late season, except in Spring 2017. Mean, maximum, and minimum soil temperatures under black mulch were greater than white mulch by 1.6, 1.9, and 1.3 °C, respectively, in the early season of Spring 2017 (Table 2). Similarly, mean, maximum, and minimum soil temperatures under black mulch in midseason were greater than white mulch by 0.7, 0.7, and 0.6 °C, respectively. In the fall trial, mean, maximum, and minimum soil temperatures under black mulch early in the season were 1.8, 2.6, and 0.9 °C greater than under the white plastic mulch, respectively (Table 3). Early in the season in Spring 2018, mean, maximum, and minimum soil temperature under black mulch were also 1.0, 1.4, and 0.6 °C greater than under the white plastic mulch, respectively (Table 4).

Low tunnels also increased soil temperature in comparison to open field early in the growing season in all trials, except for mean and maximum temperature in the Spring 2018 (Tables 2, 3 and 4). In the Spring 2017, LT increased mean, maximum, and minimum soil temperatures early in the growing season by 1.2, 0.9, and 1.5 °C, respectively (Table 2). Early in the growing season in the fall, LT increased mean, maximum, and minimum soil temperature by 0.8, 0.6, and 1.3 °C, respectively (Table 3). However, only minimum temperature increased under LT by 0.8 °C early in the season in Spring 2018 trial (Table 4). Soil temperatures in mid and late-season of the fall trial were the same between tunnels and open field, except for minimum temperature. Low tunnel increased minimum soil temperature in the mid and late-season by 0.2 and 0.6 °C, respectively. In mid/late-season of the Spring 2018, mean soil temperature increased under LT by 0.5 °C, but maximum soil temperature decreased by 1.0 °C (Table 4).

Low tunnels increased maximum air temperature throughout the growing period in comparison to open field in all trials, but no differences were detected for mean and minimum air temperature (Table 5). Maximum air temperature under tunnels in Spring 2017 and Spring 2018 trials were greater than open field by 4.2 and 8.6 °C, respectively (Table 5). Although air temperature in the Fall 2018 was monitored in one replication only, the difference in average maximum temperature between LT and open field appears to be similar to the spring trials.

Daily SR, RH, and wind speed were monitored between LT and open field to estimate ET mainly. Based on the combined data from the three trials, the average daily SR under the LT and in the open field were 12.0, and 17.5 $MJ \cdot d^{-1}$, respectively, a 31% reduction by the row cover. The average maximum RH under the LTs from the three trials was 92%, 4% greater than in open field. Daily average minimum RH under LT and open field from the three trials were 57%, and 56%, respectively. Similarly, the average wind speed in open field from the three trials was 0.58 $m \cdot s^{-1}$ in comparison to undetectable wind inside the tunnel (Arancibia, 2009; Arancibia, 2012).

Daily air temperature, RH, SR, and wind speed were used to determine the daily ET (tall canopy) under LT and open field. Low tunnel decreased the daily ET in comparison to open field conditions throughout the treatment period in all trials (Fig. 1). Average daily ET under LT and in the open field in the Spring 2017 were 1.64 and 4.06 mm, respectively (60% ET reduction). In the Fall 2017, ET under LT and in the open field were 1.1 and 3.47 mm, respectively (68% ET reduction). Similarly, in Spring 2018, average daily ET under LT and in the open field were 2.35 and 5.08 mm, respectively (54% ET reduction). The overall ET reduction under LT in all three trials was 60%.

Low tunnels reduced the irrigation needs of Brussels sprouts in both spring trials. There were no differences in irrigation events between black and white mulch as well as no statistical interaction between LT and mulch. Fig. 2 shows the progression of soil moisture (volumetric water content) and irrigation events throughout the growing period for one replication under LT and in the open field. In the first month of both trials, soil moisture stayed above 50% deficit most likely due to sensors location outside/beneath root zone (small plants) and heavy rainfall, so irrigation was mainly applied for plant establishment and fertilization. Low tunnel reduced the number of irrigation events necessary to replenish soil moisture in the Spring 2017 from 15 in the open field to 7 under the LT (53% reduction) (Fig. 3). In the Spring 2018, LT reduced the irrigation events from 11.4 in the open field to 6.8 under LT (40% reduction). Consequently, LT reduced the total amount of irrigation water applied by 40% (from 106 $L \cdot m^{-1}$ in the open field to 64 $L \cdot m^{-1}$ under the LT) and 24% (from 157 $L \cdot m^{-1}$ in the open field to 120 $L \cdot m^{-1}$ under the LT) in the Spring 2017 and Spring 2018, respectively (Fig. 3). In addition, a linear relationship was found between the combined (both trials) cumulative irrigation and cumulative ET under the LT (r=0.89, P-value<0.0001) as well as in the open field (r=0.88, P-value<0.0001) (Fig. 4).

Growth, production, and water use efficiency. Overall, LT increased growth and production of Brussels sprouts in all trials (Tables 6, 7, and 8). In contrast, the color of the plastic mulch had no effect on plant growth and yield, and there was no interaction between mulch color and tunnels for any parameter. In Spring 2017, LT increased leaf area by 73% and 52% at 30 and 60 DAT, respectively, in comparison to open field (Table 6). Similarly, leaf area under LT at harvest was 44% greater than the open field in the fall. In Spring 2018, LTs increased leaf area by 71% and 67% at 30 and 60 DAT, respectively. Low tunnel also increased leaf biomass by 55% and 31% at 30 and 60 DAT, respectively, in the Spring 2017, by 42% at harvest in the fall, and by 51% and 21% at 30 and 60 DAT, respectively, in the Spring 2018 (Table 6).

Specific leaf area was same under LT and in the open field at 30 DAT in the Spring 2017, and at harvest in the Fall 2017. In contrast, specific leaf area under the LT at 60 DAT in the Spring 2017, and at 30 and 60 DAT in Spring 2018 trial were 27%, 12%, and 37 % greater than open field, respectively (Table 7). Plants under LT were also taller than in the open field in all trials. Plant height at harvest was 45%, 43%, and 62% taller under the tunnels than open field in the Spring 2017, Fall 2017, and Spring 2018, respectively (Table 7). In addition, the overall growth under LT as determined by total plant biomass increased by 26% and 37% in the Spring 2017 and 2018, respectively, in comparison to open field (Table 8).

Low tunnels increased the number of sprouts per plant, which resulted in greater yield than in the open field. Plants grown under LT produced 15.4 (29%), 14.1 (22%), and 12 (29%) more sprouts in the Spring 2017, Fall 2017, and Spring 2018, respectively (Table 8). The average sprout weight in the Spring 2017 was 0.4 g greater under LT in comparison to open field, however, the weight was no greater in the Fall 2017 and Spring 2018 trials (Table 8). Because of the increased number of sprouts per plant, yield increased by 1.28 (46%), 3.44 (46%), and 0.65 $Mg \cdot ha^{-1}$ (22%) under LT in the Spring 2017, Fall 2017, and Spring 2018, respectively, in comparison to open field (Table 8). However, when comparing the weight of the sprouts in the spring trials with the fall trial, spring sprouts were significantly lighter (49%) than in the fall trial.

WUE was determined with respect to yield, number of sprouts, and biomass, and all increased under the LT in both spring trials (Table 9). In contrast, there was no differences in WUE between black and white mulches, and no interaction between mulch and LT except for the sprout-WUE in the Spring 2017. LT increased yield-WUE and biomass-WUE by 107% and 82%, respectively, in comparison to open field in the Spring 2017 (Table 9). Similarly, in the Spring 2018, yield-WUE, sprouts-WUE, and biomass-WUE under LT were 62%, 70%, and 81% greater than the open field, respectively. Sprouts-WUE in the Spring 2017 also increased under LT in both black (97%) and white (70%) mulch in comparison to open field, but sprouts-WUE was greater under LT and black mulch than LT and white mulch.

Discussion

Environmental parameters and irrigation. Black mulch and LT increased soil temperature, but plant size, shading, and soil depth were influencing factors. The increase in soil temperature under black plastic mulch is well documented by previous researchers and supported by the results in the Spring 2017 and early in the Fall 2017 and Spring 2018 (Table 2, 3, and 4) in this study (Arancibia and Motsenbocker, 2008; Lamont, 2005; Soltani et al., 1995). Black plastic mulch absorbs more solar energy in comparison to white plastic mulch resulting in warmer soil early in the season. In the fall trial and Spring 2018 trial, however, a slight increase in soil temperature under black mulch was detected only early in the season when plants were small with little shading. The similar temperatures across treatments late in the season were most likely due to less solar radiation and the shading effects of large mature plants.

Similarly, the effects of LT on soil temperature were observed mainly early in the season with small increases in mean, maximum, and minimum temperatures (Table 2, 3, and 4). Later in the season, fewer differences in soil temperatures were observed most likely because of increased plant shading and the placement depth of the soil temperature sensors. In this study, soil temperature sensors were 15 cm deep in the soil. Similar studies with muskmelon, tomato, and cucumber where the sensors were also 15 cm deep, showed no differences in soil temperature between LT and open field (Tillman et la., 2015; Wolfe et al., 1995). In contrast, in studies that reported differences in soil temperatures, the sensors were 5 cm deep (Arancibia and Motsenbocker, 2008; Nair and Ngouajio, 2010) or 10 cm deep (Ibarra-Jiménez et al., 2004; Ibarra et al., 2001; Soltani et al., 1995).

Row covers modified the microenvironment inside LTs, which reduced ET. The increase in maximum air temperatures under the LT in comparison to open field (Table 5) agrees with previous reports (Arancibia and Motsenbocker, 2008; Ibarra et al., 2001; Nair and Ngouajio, 2010; Tillman et al., 2015). Furthermore, the reduction in SR under tunnels in this study is also in agreements with previous reports and it is specified by the manufacturers of the row covers (Arancibia, 2009; Arancibia 2012; Nair and Ngouajio, 2010; Tillman et al., 2015). It is worth noting that the thickness of the row cover material influences light transmission. The small increase in the maximum RH in this study is inconsistent with previous reports where there were no differences in RH, so spun-bonded row covers had little or no effect on RH (Arancibia, 2009; Arancibia 2012). In addition, the maximum RH occurred mainly at night when ET is very low or zero. Therefore, in spite of the increase in maximum air temperature, the reduced light intensity and lack of wind under the tunnel significantly reduced ET in comparison to open field (Fig. 1; Arancibia, 2009; Arancibia 2012).

Less ET under the LT reduced the crop's water needs and irrigation requirements in comparison to open field. The reduced ET under the LT decreased the rate of soil moisture loss, so it took longer for soil to dry to 50% plant available water content (Fig.

2). Since soil moisture dictated the time to irrigate, less irrigation events were necessary throughout the growing period to replenish the soil moisture and the total amount of applied water was reduced (Fig. 3). However, the relationship between cumulative ET and the cumulative irrigation were different between LT and open field (Fig. 4), suggesting that plant size and the rate of soil moisture loss, and/or other factor(s) are influencing these relationships. To our knowledge, this is the first report that demonstrates the that LTs reduce irrigation needs in comparison to open field.

Growth, production, and WUE. LT enhanced vegetative growth and yield, and improved WUE. In this study, LT increased vegetative growth of Brussels sprouts as measured by plant leaf area, leaf biomass, plant biomass, and plant height in all trials in comparison to open field (Table 6,7, and 8). These results agree with previous reports indicating that row covers enhance vegetative growth and production of vegetable crops (Arancibia and Motsenbocker, 2008; Ibarra-Jiménez et al., 2004; Ibarra et al., 2001; Jolliffe and Gaye, 1995; Nair and Ngouajio, 2010; Soltani et al., 1995; Tillman et al., 2015). However, differences in specific leaf area between LT and open field were inconsistent among trials. Differences were not evident at 30 DAT in the Spring 2017 trial and at harvest in the fall trial but increased at 60 DAT in the Spring 2017 trial, and 30 and 60 DAT in Spring 2018 trial (Table 7). Soltani and collaborators (1995) also found inconsistencies in specific leaf area in samples taken overtime during plant growth and over the years, but concluded that in general row cover increases specific leaf area. Therefore, the micro-environmental conditions under the LT increase leaf area mainly by increasing leaf biomass and that the increase in specific leaf area (reduced density) plays a secondary role.

The favorable micro-environmental conditions under the LT enhanced vegetative growth and increased yield in Brussels sprouts. Most reports have attributed the larger plants and yield of vegetable crops grown under row covers to the increased temperatures and growing degree-days accumulated under the LT than the open field (Arancibia and Motsenbocker, 2008; Ibarra et al., 2001; Nair and Ngouajio, 2010; Soltani et al., 1995; Tillman et al., 2015). However, based on the results of this study, reduced ET and water stress appear to have contributed to the increase in vegetative growth and production in addition to temperatures (Fig. 1; Table 6, 7, and 8).

The greater yield under LT was predominantly due to more sprouts per plant than sprout size. Most sprouts were over 2.5 cm in diameter at harvest and differences in weight between tunnels and open field were inconsistent suggesting that LT has no effect on sprouts size. However, there was a difference in sprout weight between the fall trial (heavier and denser) compared to the spring trials. Heavier sprouts in the fall were due to the cooler temperatures during sprout development in contrast to the warmer temperatures in the spring trials. Optimal temperature for sprouts development range between 5 and 18 °C (Welbaum, 2015). Therefore, Brussels sprouts for spring production should be planted much earlier in the spring to improve quality.

The increase in yield and reduction in irrigation contributed to the improved WUE under the LT. The modification of the microenvironment under the LT reduced ET and crop irrigation needs while increasing growth and productivity (Fig. 2, Table 8). Therefore, the ratio of increased growth and reduced applied water demonstrates that LT increases WUE. This is the first report to our knowledge presenting evidence that LTs reduce irrigation needs and increase WUE.

Conclusions

Low tunnels modified the microenvironment by increasing soil and air temperatures and reducing ET in comparison to open field plots; which resulted in increased vegetative growth and yield of Brussels sprouts. In addition, less ET, LT reduced the rate of soil moisture loss and irrigation needs and likely reduced water stress on sunny and/or windy days. Therefore, the combined effect of reduced irrigation and increased yield improved WUE of Brussels sprouts grown using LT.

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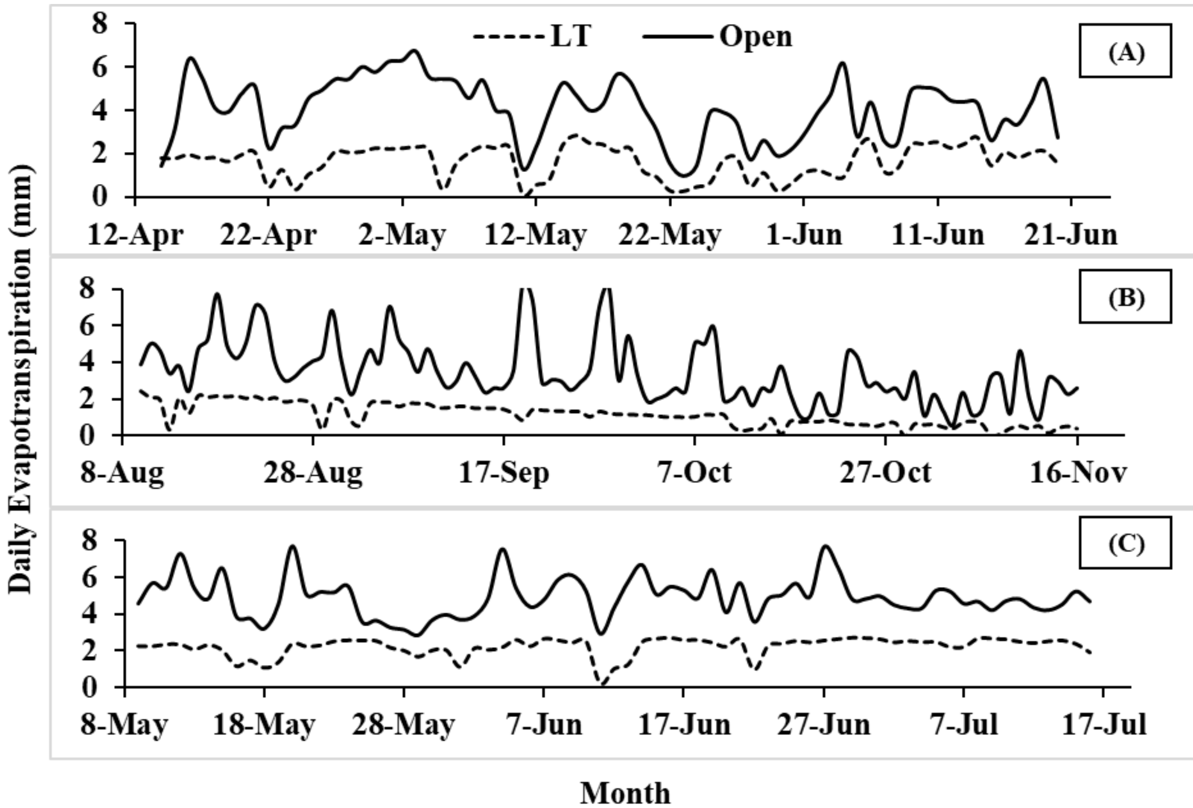

Fig. 1: Daily evapotranspiration (ET) at canopy levels in Brussels sprouts grown under low tunnel (LT) and open field. A= Spring 2017, B= Fall 2017, and C= Spring 2018.

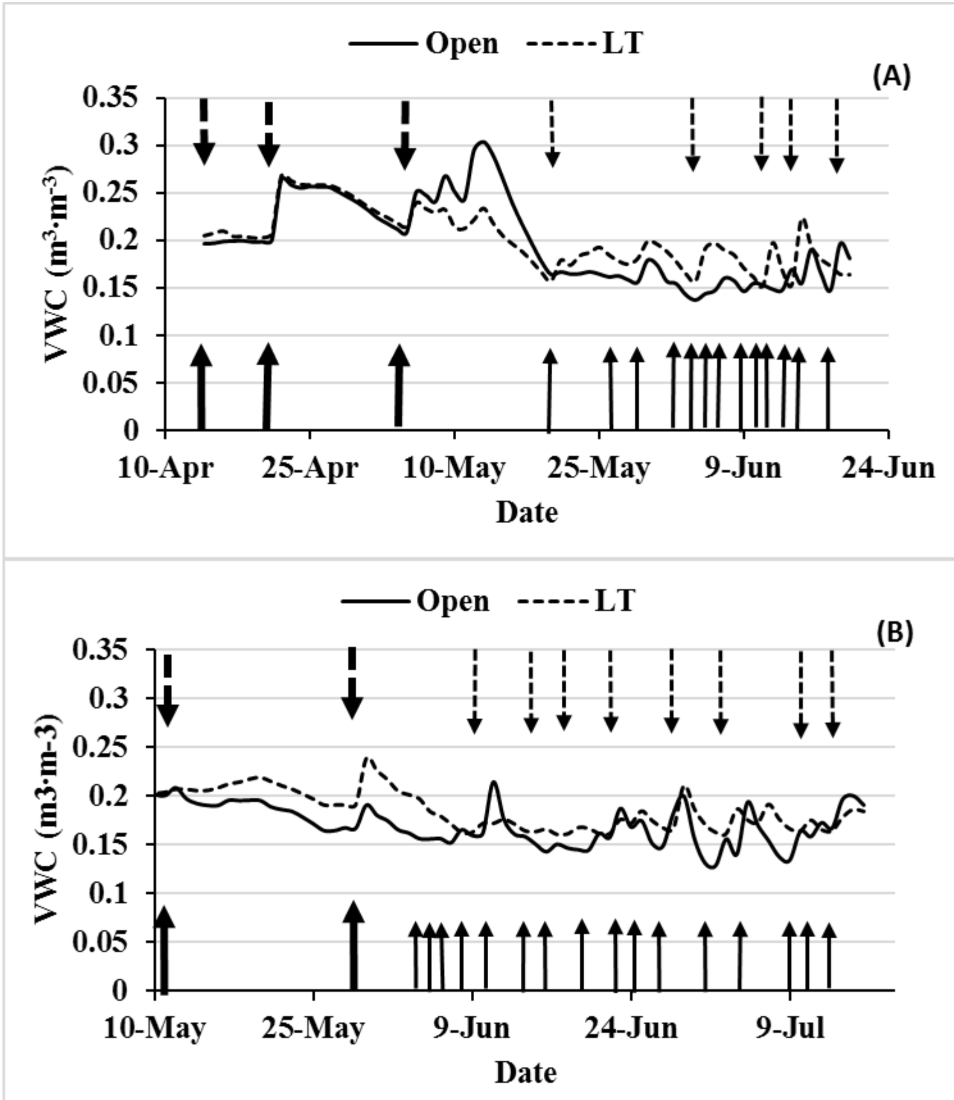

Fig. 2. Daily minimum volumetric water content (VWC), and irrigation events in Brussels sprouts grown under the low tunnel (LT) and open field (Open). A= Spring 2017, B= Spring 2018. Data presented is from one replication in each trial. Arrows corresponds to irrigation events. Darker arrow corresponds to irrigation events for plant establishment and fertilizer application applied to all subplots.

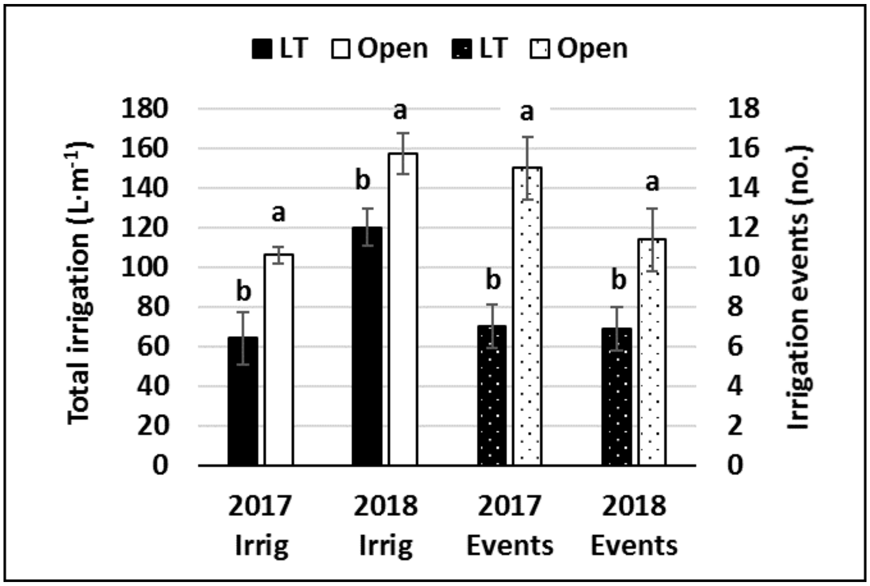

Fig. 3: Total irrigation water applied and irrigation events in Brussels sprouts grown under low tunnel (LT) in comparison to open field (Open). Spring 2017 and 2018. Mean total irrigation water applied (Irrig) and mean irrigation events within a year followed by different letters are significantly different from each other by Fischer's least significantly difference at $P \leq 0.05$. Bars in each column correspond to the standard error of the mean.

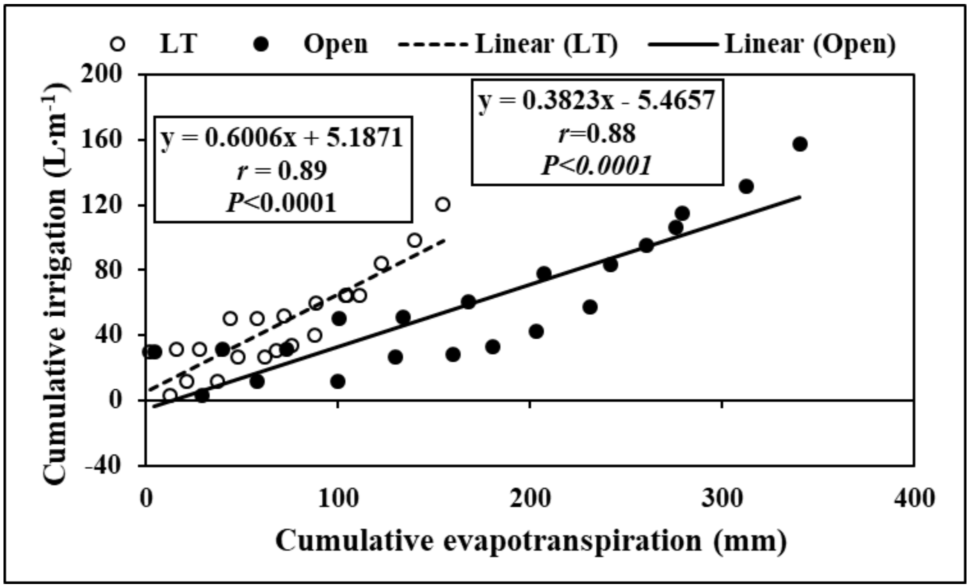

Fig. 4. Relationship between cumulative evapotranspiration and cumulative irrigation in Brussels sprouts grown under low tunnel (LT) and open field (Open). Each point corresponds to weekly measurement from both Spring 2017 and Spring 2018 trials. *r* is a correlation coefficient.

Table 1: Schedule of planting, tunnel installation, tunnel removal, and harvest of Brussels sprouts in Spring and Fall 2017 trials.

	Trials		
	Spring 2017	Fall 2017	Spring 2018
Transplant	12-Apr	10-Aug	25-Apr
LT installation [z]	12-Apr (0 DAT [y])	10-Aug (0 DAT)	9-May (14 DAT)
Decapitation	20-Jun (69 DAT)	20-Oct (71 DAT)	27-Jun (63 DAT)
LT removal	20-Jun (69 DAT)	19-Nov (101 DAT)	16-Jul (82 DAT)
Harvest	3 & 10 July (82 DAT & 89 DAT)	19-Nov (101 DAT)	29-Jul (95 DAT)

[z] LT= Low tunnel

[y] DAT= days after transplanting

Table 2: Mean, maximum, and minimum soil temperature (15 cm below surface) in Brussels sprouts production under low tunnel and open field conditions. Spring 2017.

Treatment	Early season [z]			Midseason [z]		
	Mean	Maximum	Minimum	Mean	Maximum	Minimum
	………………(°C)………………			…………….(°C)…………….		
Mulch						
Black	21.0 a [y]	23.3 a	19.0 a	22.4 a	23.8 a	21.3 a
White	19.4 b	21.4 b	17.7 b	21.7 b	23.1 b	20.7 b
Low Tunnel						
Open	19.6 a	21.9 a	17.6 a	21.9	23.4	20.8
Low tunnel	20.8 b	22.8 b	19.1 b	22.2	23.5	21.2
P-value						
Mulch	0.004	0.007	0.004	0.024	0.018	0.012
Low Tunnel	0.016	0.041	0.009	0.353	0.989	0.130
M x LT [y]	0 .670	0.154	0.071	0.885	0.274	0.277

[z] Early season= 14 April to 15 May (2 to 33 DAT [x]), Midseason= 16 May to 20 June (34 to 69 DAT).

[y] Means within each column followed by different letters are significantly different from each other using Fischer's least significant difference at $P \leq 0.05$.

[x] M=mulch, LT= Low tunnel.

[w] DAT= days after transplanting.

Table 3: Mean, maximum, and minimum soil temperature (15 cm below surface) in Brussels sprouts production under low tunnel and open field conditions. Fall 2017.

Treatment	Early season [z]			Midseason [z]			Late season [z]		
	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum
	...………….(°C)……………			…………….(°C)………….			………..(°C)…………….		
Mulch									
Black	28.2 a[y]	30.9 a	25.8 a	23.9	25.5	22.6	17.5	18.6	16.5
White	26.4 b	28.3 b	24.9 b	22.8	23.8	22.0	17.0	17.8	16.3
Low tunnel									
Open	26.9 b	29.3 b	24.7 b	23.4	24.8	22.2 b	17.0	18.1	16.1 b
Low Tunnel	27.7 a	29.9 a	26.0 a	23.4	24.5	22.4 a	17.4	18.3	16.7 a
P-value									
Mulch	0.001	<0.0001	0.038	0.120	0.096	0.185	0.338	0.255	0.658
Low tunnel	0.002	0.036	<0.0001	0.783	0.130	0.004	0.116	0.393	0.023
M x LT [x]	0.924	0.57	0.306	0.823	0.993	0.662	0.747	0.957	0.480

[z] Early season= 10 August to 10 Sep (0 to 31 DAT [w]), midseason= 11 Sep to 10 Oct. (32 to 61 DAT), and Late season= 11 Oct. to 16 Nov. (62 to 98 DAT).

[y] Means within each column followed by different letters are significantly different from each other using Fischer's least significant difference at $P \leq 0.05$.

[x] M=mulch, LT= low tunnel.

[w] DAT= days after transplanting.

Table 4: Mean, maximum, and minimum soil temperature (15 cm below surface) in Brussels sprouts production under low tunnel and open field conditions. Spring 2018.

Treatment	Early season [z]			Mid and late season [z]		
	Mean	Maximum	Minimum	Mean	Maximum	Minimum
	……………..(°C)……………..			…………..(°C)……………		
Mulch						
Black	24.9 a [y]	26.7 a	23.1 a	27.1	28.6	25.8
White	23.9 b	25.3 b	22.5 b	26.5	27.9	25.3
Low tunnel						
Open	24.1	26.1	22.4 b	26.6 b	28.8 a	25.5
Low tunnel	24.6	26.0	23.2 a	27.1 a	27.8 b	25.6
P-value						
Mulch	0.015	0.039	0.021	0.083	0.13	0.087
Low tunnel	0.058	0.774	0.001	0.045	0.03	0.435
M x LT [x]	0.603	0.901	0.256	0.807	0.999	0.435

[z] Early season= 9 May to 9 June (14 to 45 DAT [w]), mid and late season= 10 June to 16 July (46 to 82 DAT).

[y] Means within each column followed by different letters are significantly different from each other by Fischer's least significant difference at $P \leq 0.05$.

[x] M=mulch, LT= low tunnel.

[w] DAT= days after transplanting.

Table 5: Mean, maximum, and minimum air temperature (30 cm above surface) in Brussels sprouts production under low tunnel and open field conditions. Spring 2017, Fall 2017, and Spring 2018.

Treatment	Spring 2017			Fall 2017 [z]			Spring 2018		
	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum
	…………(°C)…………			…………..(°C)…………..			…………..(°C)…………..		
Low Tunnel	21.7	30.4 a [y]	15.1	20.9	30.2	15.0	27.8	38.7 a	19.5
Open	20.7	26.2 b	15.5	19.2	24.6	14.3	24.5	30.1 b	19.6
P-value	0.303	0.009	0.669				0.057	0.022	0.808

[z] Fall 2017 trial: one air temperature sensor for each low tunnel (LT) and open field in the Fall 2017 trial.

[y] Means within a column followed by different letters are significantly different from each other by Fischer's least significant difference at $P \leq 0.05$.

Table 6: Leaf area, and leaf biomass in Brussels sprouts grown under Low tunnel and open field conditions. Spring 2017, Fall 2017, and Spring 2018.

	Leaf area					Leaf biomass				
	Spring 2017		Fall 2017	Spring 2018		Spring 2017		Fall 2018	Spring 2018	
	30 DAT [z]	60 DAT	Harvest	30 DAT	60 DAT	30 DAT	60 DAT	Harvest	30 DAT	60 DAT
Treatment	……………………..(cm^2)…………………………….					………………………(g)………………………………..				
Low tunnel	4454 a[y]	26152 a	26648 a	4383 a	14813 a	28.3 a	203 a	250 a	29.0 a	142 a
Open	2576 b	16602 b	18486 b	2564 b	8895 b	18.3 b	155 b	176 b	19.2 b	117 b
P-value										
Mulch	0.335	0.541	0.719	0.8	0.679	0.484	0.972	0.861	0.456	0.771
Low tunnel	0.021	<0.0001	<0.0001	0.015	0.002	0.049	0.016	0.003	0.049	0.048
M x LT [x]	0.098	0.105	0.788	0.765	0.348	0.053	0.351	0.192	0.891	0.304

[z] DAT= days after transplanting.

[y] Means within a column followed by different letters are significantly different from each other by Fischer's least significant difference at $P \leq 0.05$.

[x] M=mulch, LT= Low tunnel.

Table 7: Specific leaf area, and plant height in Brussels sprouts grown under low tunnel and open field conditions. Spring2017, Fall 2017, and Spring 2018.

	Specific leaf area					Plant height		
	Spring 2018		Fall 2017	Spring 2018		Spring 2017	Fall 2017	Spring 2018
	30 DAT [z]	60 DAT	Harvest	30 DAT	60 DAT	Harvest	Harvest	Harvest
Treatment	……………………..($cm^2 \cdot g^{-1}$)………………………					……………….(cm)………………….		
Low tunnel	158	100 a [y]	107	152 a	104 a	67.7 a	66.7 a	50.3 a
Open	145	80 b	106	136 b	76 b	46.7 b	46.6 b	31.0 b
P-value								
Mulch	0.483	0.438	0.785	0.057	0.96	0.796	0.342	0.276
Low tunnel	0.247	0.047	0.962	0.001	<0.001	<0.0001	<0.0001	<0.0001
M x LT [x]	0.295	0.063	0.225	0.452	0.563	0.181	0.237	0.857

[z] DAT= Days after transplanting

[y] Means within a column followed by different letters are significantly different from each other by Fischer's least significant difference at $P \leq 0.05$.

[x] M=mulch, LT= Low tunnel.

Table 8: Yield, number of sprouts per plant, sprout weight, and plant biomass in Brussels sprouts grown under low tunnel and open field conditions. Spring 2017, Fall 2017, and Spring 2018.

	Yield			Sprouts per plant			Sprout weight			Plant biomass	
	Spring 2017	Fall 2017	Spring 2018	Spring 2017	Fall 2017	Spring 2018	Spring 2017	Fall 2017	Spring 2018	Spring 2017	Spring 2018
Treatment	………..(Mg·ha^{-1})………..			…………(No)…………			…………(g)…………			……..(g)……..	
Low tunnel	4.1 a [z]	10.8 a	3.3 a	68.8 a	77.3 a	53.8 a	3.3 a	7.7	4.2	269 a	292 a
Open	2.8 b	7.4 b	2.7 b	53.4 b	63.2 b	41.8 b	2.9 b	6.7	4.3	213 b	213 b
P-value											
Mulch	0.072	0.975	0.992	0.441	0.445	0.606	0.148	0.689	0.94	0.837	0.089
Low tunnel	0.001	0.047	0.045	<0.0001	0.005	<0.0001	0.02	0.335	0.883	0.049	0.005
M x LT [y]	0.331	0.912	0.892	0.353	0.182	0.634	0.533	0.074	0.909	0.524	0.178

[z] Means within a column followed by different letters are significantly different from each other by Fischer's least significant difference at $P \leq 0.05$.

[y] M=mulch, LT= Low tunnel

Table 9: Water use efficiency (WUE) with respect to yield, plant biomass, and sprouts in Brussels sprouts production under low tunnel and open field conditions. Spring 2017 and Spring 2018.

	Yield WUE		Biomass WUE		Sprouts WUE			
Treatment	Spring 2017	Spring 2018	Spring 2017	Spring 2018	Spring 2018			Spring 2017
	…….($g \cdot L^{-1}$)……..		…….($g \cdot L^{-1}$)…….		($No \cdot L^{-1}$)			($No \cdot L^{-1}$)
Low Tunnel	7.41 a [z]	5.19 a	8.87 a	8.33 a	1.55 a	Black	LT	2.54 a
Open	3.57 b	3.21 b	4.87 b	4.61 b	0.91 b		Open	1.29 c
						White	LT	2.04 b
							Open	1.20 c
P-value						*P*-value		
Mulch	0.128	0.533	0.224	0.282	0.553	Mulch		<0.0001
Low Tunnel	<0.0001	0.003	0.002	0.007	0.003	Low Tunnel		<0.0001
M x LT [y]	0.266	0.725	0.073	0.566	0.725	M x LT		0.005

[z] Means within a column followed by different letters are significantly different from each other by Fischer's least significant difference at $P \leq 0.05$.

[y] M=mulch, LT= low tunnel.

Chapter: 3

Low tunnels covered with spun-bonded fabric reduce insect feeding injury in Brussels sprouts.

Additional index words: row cover, feeding injury index, harlequin bug, aphid, lepidopteran.

Abstract

Low tunnels (LTs) covered with spun-bonded fabric (row cover) are mainly used for season extension in vegetable crops. Low tunnels can act as a physical barrier against fly-in insect and other pests that are not present in the soil. This study demonstrated an additional benefit of low tunnels beyond season extension by reducing insect infestation, leaf feeding injury, and insecticide applications. Infestations of lepidopteran insects and harlequin bugs were reduced under LT compared to open field. However, aphid's infestation was observed under LT in fall 2017. Low tunnels reduced lepidopteran insects by 1.1 to 3.3 individuals per five plant in comparison to open field. Similarly, Harlequin bugs under LT were reduced by 7.5 to 18.1 individuals per five plants compared to open field. In addition, mean insect feeding injury index (0 to 4) in the LT was 1.13, 0.55, and 0.53 less than open field in Spring 2017, Fall 2017, and Spring 2018, respectively. Low tunnels also reduced the number of insecticide application necessary to control insect populations. Fewer insect infestations and feeding injury, and reduced insecticide applications indicate that low tunnel can be a management tool to improve sustainability in vegetable production systems.

Introduction

Insect pest control is essential for successful vegetable production. Therefore, eco-friendly methods are needed to manage insects and improve sustainability. Destructive insect pests of Brussels sprouts (*Brassica oleracea var gemmifera L.*) in Virginia include several lepidopterans such as diamondback moth (*Plutella xylostella*), cabbage looper (*Trichoplusia ni*), yellow stripe armyworm (*Spodoptera ornithogalli*), cabbage worm (*Pieris rapae*), and bugs such as harlequin bug (*Murgantia histrionica*) (Kemble, 2017; Wyenandt, 2016). The lepidopteran larvae are the most common insects that feed on Brussels sprout foliage (Wallingford et al., 2012). The loss of production due to insect pest is significantly high because of the costs incurred and reduced yield, which reduces production efficiency. An eco-friendly method that reduces pest feeding injury and insecticide applications may improve production efficiency and minimize the potential environmental hazard. An intensive spray regimen can pose a serious risk to non-target organisms (Mallik and Tesfai, 1985; Pimentel, 2005; Pimentel et al., 1993). Similarly, continuous applications of pesticides into the environment coupled with development of resistant insects suggests that there is a need for alternative eco-friendly methods of insect management (Mueller et al., 2006).

Low tunnel can help to exclude large insects such as butterflies and moths among others (Arancibia, 2018; Millar and Isman, 1988; Rekika et al., 2008). Therefore, LTs have potential to improve the sustainability of the production system by reducing insect populations, feeding injury, and insecticide applications. Low tunnels covered with spun-bonded cloths, which are semitransparent and porous allowing for air to flow, can increase crop vegetative growth and yield by improving the microenvironment under tunnel (Arancibia, 2018; Arancibia and Motsenbocker, 2008; Gerber et al., 1988; Ibarra et al., 2001; Jolliffe and Gaye, 1995; Nair and

Ngouajio, 2010). In addition, the use of row covers as an effective insect management technique has increased because they act as a barrier for fly-in insects like aphids, cucumber beetles, whitefly, while reducing the transfer of insect transmitted diseases (Bextine et al., 2001; Boisclair and Estevez, 2006). Most of the research studies have used floating row cover as an insect barrier tools (Orozco-Santos et al., 1995; Orozco et al., 1994; Perring et al., 1989). However, physical damage and abrasion of the plants are common with floating row cover that ultimately causes yield reduction (Baker et al., 1998).

Our management strategy was to reduce reliance on insecticide spray for Brussels sprout by rows with LT covered with spun-bonded fabric to exclude insect. Row covers were placed over the plants supported by hoops and secured with plastic sacs along the edges. The hypothesis was that LTs provide protection against fly-in insects and to those insects that are not already present on the plant or in soil inside the tunnel. In addition, insect feeding injury in the leaf is expected to be less in comparison to open field. The objectives of this study were: 1) to determine the level of protection LTs provide against insect infestation and 2) to compare leaf feeding injury by insect in LT and open field.

Materials and methods

Brussels sprouts, cultivar ‘Dimitri’, were grown on a Bojac sandy loam soil in Spring 2017, Fall 2017, and Spring 2018 at the Virginia Tech Eastern Shore Agricultural Research and Extension Center in Painter, Virginia (longitude -75.82114 and latitude 37.58466). All trials were setup in a spilt-plot design with four replications. The main effect consisted of two polyethylene mulches (white and black) and the secondary subplot effect consisted of treatments with LT and open field. Spun-bonded fabric of 33.8 $g{\cdot}m^{-2}$ (Dewitt, Sikeston, MO) were used for the studies in the spring and 16.9 $g{\cdot}m^{-2}$ in the fall.

Seeds were sown in 128 cells trays (Beaver plastic LTD, Canada) the first week of March 2017, last week of June 2017, and first week of March 2018 for the Spring 2017, Fall 2017 and Spring 2018 trials, respectively. The trays were 65.5 cm long and 33 cm wide with square cells of 4 cm wide and 6.5 cm depth. Trays were filled with Promix HP mycorrhiza media (Premier Horticulture, Quebec, Canada) (59-69% Canadian sphagnum peat moss plus vermiculite, perlite, dolomitic lime, and wetting agent). The greenhouse was maintained at 20 ºC in early spring and 32 ºC during the day in the summer. Seedlings were sprinkle irrigated twice a day and fertilized continuously through the irrigation system with a N concentration of 50 ppm with 20N-8.7P-16.6K soluble fertilizer (Plantex, Brampton, Canada) until transplanting. Transplants were hand planted into double row beds on 12 April 2017, 10 August 2017 and 25 April 2018 (Table 1). Planting was on raised beds (0.2 m tall and 0.8 m wide) 1.8 m apart (center to center) with appropriate plastic mulch (0.003 cm thick and 152.4 cm wide) (Hilex poly Co., North Vernon, IN) and drip irrigation laid between rows under plastic (Aqua Trax, Marshall Avenue EI Cajon, CA). Emitters in the irrigation tape were 30 cm apart and flow rate was 1.89 $L \cdot min^{-1}$ per 30 m tape length. Individual plots were 15 m long, and divided into two 6 m subplots (LT and open field), separated by a 1.5 m alley. In-row planting distance was 0.6 m and rows in the same bed were 0.45 m apart. Low tunnels were supported by 3 m long PVC hoops bent to form a 1.0 m tall and 1.03 m wide tunnel with sand bags on the sides to hold edges in place. The weight of sand bags was 1.5 to 2 kg and 18 bags were used in each subplot. Low tunnels were installed in 12 April, 10 August, 9 May and removed in 20 June, 19 November, 16 July in Spring 2017, Fall 2017, and Spring 2018, respectively (Table 1). A pre-plant fertilizer (10N-4.4P-8.3K) was incorporated into the plant beds at 112.5 $kg \cdot ha^{-1}$ of N based on Mid-Atlantic Vegetables Guide recommendation for Brussels sprouts (Wyenandt, 2016), using a rotary tiller prior to laying polyethylene mulch in all trials. A one-time side-dress at 14.5 kg·ha^{-1} of N was applied through the dripline in all trials. A stock solution of 3.2 kg soluble fertilizer (20N-8.7P-16.6K) was mixed in 20 L water and metered into the drip irrigation system through an injector (Chemilizer Products, Inc., Largo, FL). All other cultural practices followed the Mid-Atlantic Commercial Vegetable Production Recommendations (Wyenandt, 2016).

Insects and insecticide application. Five plants per subplot were visually inspected for insect infestation and feeding injury to determine protection level provided by LT. Plots were not sprayed until feeding injury was visible and insect infestation was determined. Then, plots with and without LT were sprayed differently according to insect thresholds (Wyenandt, 2016). The threshold used for controlling lepidopteran and other harmful insects were 20%, 30%, and 5% of plants infested in early, mid, and sprouts formation stages, respectively. Insecticide were applied also specifically when aphids and sooty mold were detected. In Spring 2017, the number of insect present was recorded on 31 May (50 DAT) and treatments were sprayed with Xentari at 2.5 Kg·ha^{-1} and Coragen at 354 ml·ha^{-1} to control lepidopteran insects (Table 2). Then, the feeding injury was determined once affected leaves had expanded. In the fall, insects were counted on 20 Aug. (10 DAT), 15 Sep. (36 DAT), and 31 Oct. (82 DAT). Insecticides applied on 20 Aug. were Lamda (266 ml·ha^{-1}), Coragen (295 ml·ha^{-1}), and Belay (295 ml·ha^{-1}) to control lepidopteran and other insects (Table 2). Voliam xpress (665 ml·ha^{-1}) was applied on 15 Sept, and Volian xpress (590 ml·ha^{-1}) + 0.25% Induce was applied on 31 Oct. to control lepidopteran and other insects also (Table 2). In addition, Movento (370 ml·ha^{-1}) + 0.25% Induce was applied to control aphids under low tunnels. Insecticides Coragen (370 ml·ha^{-1}) and Mustang Maxx (296 ml·ha^{-1}) were applied in the open field plots on 31 May (36 DAT) and 5 July (71 DAT), respectively (Table 2).

Insects feeding injury. Insect feeding injury was determined by the number of injured leaves per plant and by the visual estimation of the severity of the feeding injury. One plant per subplot was randomly selected at 60 DAT in both spring trial and at harvest in the fall trial and all leaves analyzed for severity (percent leaf area lost). The insect feeding injury index consisted of five levels based on the visual estimation of the severity: Level 0 = no feeding injury; level 1 = <5% of leaf area lost; level 2 = 5% to <15% leaf area lost; level 3 = 15% to <30% leaf area lost; and level 4 = ≥30% leaf area lost (Figure 1). Then, the mean insect feeding injury (MIFI) for each sample plant was determined by the following formula:

$$MIFI = [(0 \cdot n_0) + (1 \cdot n_1) + (2 \cdot n_2) + (3 \cdot n_3) + (4 \cdot n_4)] \div N$$

Where MIFI is the mean insect feeding injury; n_0, n_1, n_2, n_3, and n_4 are the number of leaves with injury level 0, 1, 2, 3, and 4, respectively; and N is the total number of leaves per plant.

Statistical analysis. The data for the different parameters were analyzed by Minitab 2018 software (Minitab® Statistical Software 2018, State College, Pennsylvania). Analysis of variance (ANOVA) was conducted to evaluate treatment effect significance. Replication was treated as a random factor with mulch and low tunnels treated as fixed factors. When there was no interaction, means were compared between LT and open field, averaged across mulch color. Mean of each parameter was compared by Fischer's least significant difference (LSD) at 5 % level of significance.

Results

Insects and insecticide application. The main insect pests present were lepidopteran larvae (diamondback moth, cabbage looper, and imported cabbageworm) in Spring 2017, lepidopteran, harlequin bugs, and aphids in Fall 2017, and lepidopteran larvae and harlequin bugs in Spring 2018. Lepidopteran and harlequin bugs were typically below threshold under LT (Table 3), but aphids were found under LT late in the season in the fall. In contrast, lepidopteran and harlequin bugs were above thresholds in the open field treatment. Overall, there was no difference in number of insects' population in all sampling date between mulches and there was no interaction between tunnels and mulch treatments (Table 3). In Spring 2017, there were 3.0 more lepidopteran insects per five plants in the open field compared to LT at 50 DAT (Table 3). In fall, there were 13.8, 7.5 and 12.7 more harlequin bugs per five plant in the open field than under LT at 10, 36, and 82 DAT, respectively (Table 3). Similarly, there were 1.1, 3.0, and 3.3 more lepidopterans per five plants in the open field than under LT at 10, 36, and 82 DAT, respectively. However, aphid infestations were observed only under LT at 82 DAT in the fall (data not presented). In Spring 2018, there were 2.9 more lepidopteran and 18.1 more harlequin bugs per five plants in the open field than under LTs at 36 and 71 DAT, respectively (Table 3). Based on the threshold, insecticides were applied only one time in both LT and open field plots in Spring 2017 at 50 DAT. In the fall, insecticides were applied three times in the open field, but only one time under LT specifically for aphids. Similarly, in Spring 2018 insecticides were applied two times in the open field but not under LT.

Insect feeding injury. Insect injury was also decreased in plants under LT in all trials. Plants under LT had fewer injured leaves and the feeding symptoms were less severe (percent of the feeding area) than in the open field. The number of injured leaves and the severity of the feeding injury were measured by MIFI; which was reduced by 77%, 24%, and 93% under LT in comparison to the open field in Spring 2017, Fall 2017, and Spring 2018, respectively (Table 4). There was no difference in MIFI between mulches and there was no interaction between tunnels and mulch treatments.

Discussion

Low tunnels covered with spun-bonded fabric decreased insect populations in comparison to uncovered plants. The fabric provided a physical barrier blocking insect migration to the plants and reduced insect densities and feeding injury. This is consistent with other reports in broccoli, summer squash, cabbage, and melon that reported reduced insect populations under row covers (Adams et al., 1990; Hough-Goldstein, 1987; Natwick and Laemmlen, 1993). Insect populations under LT were mostly below threshold for insecticide application in contrast to the open field (Table 3). Therefore, there were less insecticide applications to the crop under LT and most of the applications were to the open field plots. However, aphid infestations were detected only under tunnels in Fall 2017 and prompted an insecticide application. In this case, fabric likely prevented natural predators from reaching and controlling aphid populations, or alternatively reduced UV light that inhibits aphid development (Hori et al., 2014). In addition, fewer insects reached the crop inside the LT; which resulted in less leaf injury compared with unprotected plants. The results of this study are consistent with the decreasing injury in crisphead lettuce grown under row covers (Rekika et al., 2009). Furthermore, the greater feeding injury in the open field suggested that more frequent insecticide applications would be needed to reduce injury to the same level as under LT.

Conclusion

Low tunnels reduced insect populations and feeding injury that resulted in fewer insecticide applications. Fewer insecticide application can save additional cost required to buy insecticide to the grower. Similarly, this management tool is eco-friendly, and can minimize potential environment hazard. Therefore, LT can be a practical management tool for protecting the crop against insect pest infestations and minimizing environment pollution.

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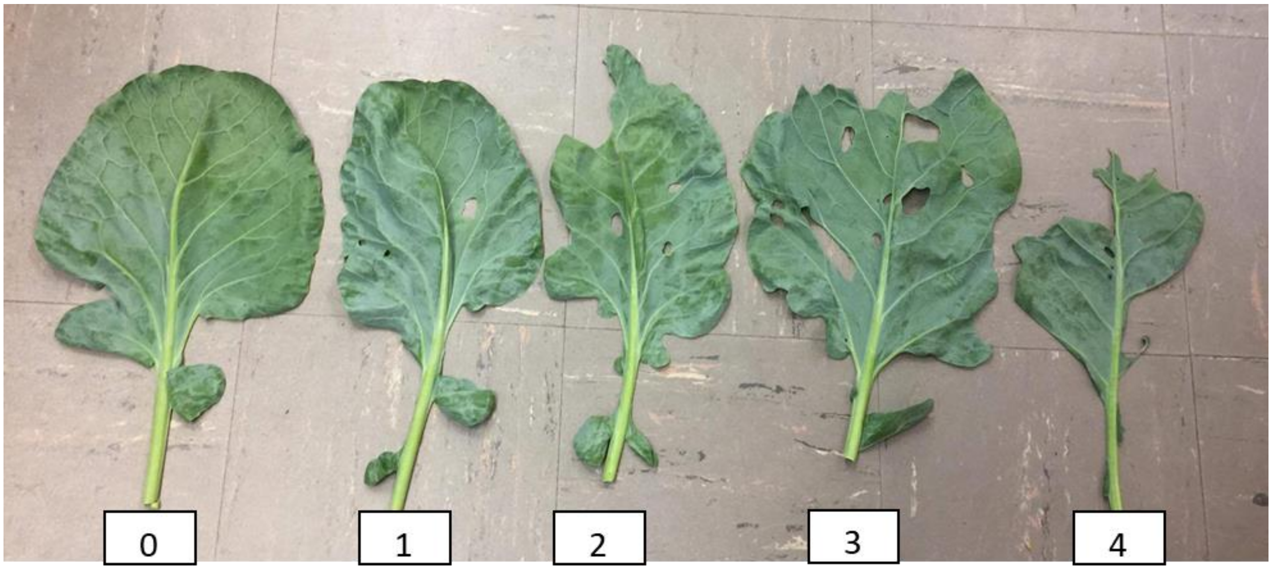

Figure 1: Visual estimation of leaf injury level in Brussels sprouts production under low tunnel and open field conditions. Spring 2017, Fall 2017, and Spring 2018. 0 = no feeding injury, 1 = <5% of leaf area lost, 2 = 5% to <15% leaf area lost, 3 = 15% to <30% leaf area lost, 4 = ≥30% leaf area lost.

Table 1: Schedule of planting, tunnel installation, and tunnel removal of Brussels sprouts in spring and fall trials.

	Trials		
	Spring 2017	Fall 2017	Spring 2018
Transplant	12-Apr	10-Aug	25-Apr
LT installation [z]	12-Apr (0 DAT [y])	10-Aug (0 DAT)	9-May (14 DAT)
LT removal	20-Jun (69 DAT)	19-Nov (101 DAT)	16-Jul (82 DAT)

[z] LT= Low tunnel

[y] DAT= days after transplanting

Table 2: Insecticide name, application time, rate, and targeted pest in Brussels sprouts grown under the low tunnel (LT) and open field (Open). Spring 2017, Fall 2017, and Spring 2018.

Date	Days	Insecticide name	Rate	Unit	Open	LT [z]	Trial	Targeted pest
31-May	50 DAT [y]	Xentari	2.5	$Kg{\cdot}ha^{-1}$	Yes	yes	spring 2017	lepidop. [x]
		Coragen	354	$ml{\cdot}ha^{-1}$	Yes	yes	spring 2017	lepidop.
20-Aug	10 DAT	Lamda	266	$ml{\cdot}ha^{-1}$	Yes	no	Fall 2017	lepidop.
		Coragen	295	$ml{\cdot}ha^{-1}$	Yes	no	Fall 2017	lepidop.
		Belay	295	$ml{\cdot}ha^{-1}$	Yes	no	Fall 2017	H. bug [w]
15-Sep	36 DAT	Voliam xpress	665	$ml{\cdot}ha^{-1}$	Yes	no	Fall 2017	H. bug/lepidop.
31-Oct	82 DAT	Voliam xpress + 0.25% induce	590	$ml{\cdot}ha^{-1}$	Yes	no	Fall 2017	H. bug/lepidop.
		Movento + 0.25% induce	370	$ml{\cdot}ha^{-1}$	No	yes	Fall 2017	Aphid
31-May	36 DAT	Coragen	370	$ml{\cdot}ha^{-1}$	Yes	no	Spring 2018	lepidop.
5-Jul	71 DAT	Mustang maxx	296	$ml{\cdot}ha^{-1}$	Yes	no	Spring 2018	H. bug

[z] LT= low tunnel

[y] DAT= Days after transplanting

[x] Lepidop. = Lepidopteran

[w] H. bug= Harlequin bug

Table 3: Mean number of insect per five plant in Brussels sprouts production under the low tunnel and open field conditions. Spring 2017, Fall 2017, and spring 2018.

	Number of insect (5 plant) [z]								
	Spring 2017	Fall 2017						Spring 2018	
	50 DAT [y]	10 DAT		36 DAT		82 DAT		36 DAT	71 DAT
Treatment	Lepid. [x]	Lepid.	H. bug [w]	Lepid.	H. bug	Lepid.	H. bug	Lepid.	H. bug
Low tunnel	0.72 b [v]	0.13 b	0.50 b	0.00 b	0.12 b	0.13 b	0.10 b	0.65 b	0.00 b
Open	3.74 a	1.25 a	14.25 a	0.13 a	7.50 a	3.38 a	13.3 a	3.57 a	18.1 a
P-value									
Mulch	0.19	0.1	0.586	0.653	0.892	0.628	0.949	0.93	0.821
Low tunnel	0.008	0.047	0.02	<0.0001	<0.0001	0.008	<0.0001	0.007	<0.0001
M x LT [u]	0.795	0.215	0.487	0.475	0.534	0.348	0.521	0.996	0.821

[z] Threshold: 20%, 30%, 5% of plants infested with any insect-pest species at early and mid-growth stage, and at sprouts formation stage, respectively.

[y] DAT= Days after transplanting

[x] Lepid. = Lepidopteran

[w] H. bug= Harlequin bug

[v] Means within a column followed by different letters are significantly different from each other by Fischer's least significant difference at $P \leq 0.05$.

[u] M=mulch, LT= low tunnel.

Table 4: Mean insect feeding injury (MIFI) in Brussels sprouts production under the low tunnel and open field conditions. Spring 2017, Fall 2017, and Spring 2018.

	MIFI [z]		
	Spring 2017	Fall 2017	Spring 2018
Treatment	60 DAT [y]	harvest	60 DAT
Low tunnel	0.33 b [x]	1.71 b	0.04 b
Open	1.46 a	2.26 a	0.57 a
P-value			
Mulch	0.075	0.083	0.602
Low tunnel	<0.0001	0.005	0.003
M x LT [w]	0.34	0.939	0.732

[z] MIFI: 0 to 4; 0 = no feeding injury; 1 = > 0% to <5% of leaf area lost; 2 = 5% to <15% leaf area lost; 3 = 15% to <30% leaf area lost; and 4 = ≥30% leaf area lost.

[y] DAT= Days after transplanting

[x] Means within a column followed by different letters are significantly different from each other by Fischer's least significant difference at $P \leq 0.05$.

[w] M=mulch, LT= low tunnel.

Chapter: 4

Nitrogen requirement and use efficiency under low tunnel sweet basil production.

Additional index words. Row cover, N uptake, apparent N recovery, leaf N content

Abstract

Nitrogen (N) use efficiency (NUE) is important in a sustainable vegetable production system and has significant impact on the system's nutrient management. Low tunnel (LT) enhances vegetative growth, but N requirement may differ from open field for optimal growth and yield, and therefore, NUE. This study was conducted in a Bojac sandy loam soil at the Eastern Shore Agricultural Research and Extension Center (AREC) in Painter, Virginia. The objective was to determine differences in N requirement for optimal growth and yield, uptake, and use efficiency in basil grown under LT compared to open field. The experimental design was a split plot with four replications. The main effect was N fertilizer rate (0, 37, 74, 111, 148, and 185 $kg{\cdot}ha^{-1}$) and the secondary effect (subplots) was LT covered with spun-bonded row cover and no cover (open field). Total fresh weight yield and dry biomass increased with low tunnel by 61% and 58% in 2017 and by 50% and 48% in 2018, respectively. Overall, optimum fresh weight and biomass was obtained at 111 $kg{\cdot}ha^{-1}$ of N. Mixed results were found for NUE, so overall, LT may or may not increase NUE. Plant height and stem diameter were greater under LT than open field; however, they were not affected by N fertilizer rate. Leaf N concentration decreased under LT, but total plant N uptake increased because of increased biomass. In conclusion, LT increased production of sweet basil.

Introduction

Protected production systems (low and high tunnels) modify the crop's microenvironment and extend growing season earlier in spring or later in fall (Lamont, 2005). However, protected systems may also enhance vegetative growth and increase productivity of warm-season vegetable crops in the summer (Arancibia, 2018). Spun-bonded row covers as low tunnels (LT) or as floating blankets create a mini-greenhouse effect by modifying microenvironment; which increases plant growth and production (Arancibia and Motsenbocker, 2008; Ibarra et al., 2001; Nair and Ngouajio, 2010; Soltani et al., 1995; Tillman et al., 2015). Row covers also protect against insects (Arancibia, 2018; Bextine et al., 2001; Qureshi et al., 2007). There has been extensive research regarding use of row covers for season extension in vegetable production, but nutrient requirements and use efficiency still need to be addressed.

Soil quality and nitrogen use efficiency (NUE) are important parameters in sustainable vegetable production and have a significant impact on the system's nutrient management and cycling. The system's NUE is important because of N fertilizers' cost and potential losses that lead to pollution when plants do not use all applied N (Hirel et al., 2007; Sutton et al., 2013; Tamang et al., 2017). Furthermore, optimum N applications reduce pollution risk via leaching, especially in sandy-textured soils where intensive vegetable production often occurs (Fleming et al., 2013; Gai et al., 2016; Stenberg et al., 1999; Zotarelli et al., 2009). Adequate N fertilizer plays an important role in plant growth and development, yield, and formation and quality of the end product (Lemaire and Gastal, 2009). Under N deficiency plants often exhibit stunted and chlorotic growth along with reduce yield and/or degraded fruit quality. Therefore, a major task for N fertilizer application is to provide the right rate to optimize growth and yield in a sustainable vegetable production system.

Sweet basil (*Ocium basilicum* L.) is a member of the mint family and an important high-value herb in U.S. and the world. Basil is mainly grown for culinary purposes in the U.S. either as fresh or dried spice (Simon et al., 1990). Fresh basil production in the U.S. increased significantly in recent years due to higher dollar value and an important source of income for some vegetable and herb growers (Dekalb et al., 2014; Homa et al., 2014; Wyenandt et al., 2015). Approximately 4400 ha of basil were grown in the U.S. in 2010, but this production was not sufficient to fulfill U.S. basil demand (Wyenandt et al., 2015). About 20% (US$60 million) of fresh sweet basil was imported from Colombia, Israel, Mexico, and Peru (Wyenandt et al., 2015). However, importing basil from other countries is difficult due to disease and pest introductions couple with shipping cost (Wyenandt et al., 2015). Therefore, buyers are more interested in marketing basil from domestic growers. In the case of Virginia, there is little basil production, but great interest by vegetable farmers because of high value and demand in nearby markets. Hence, there is potential to increase domestic sweet basil production to meet the market demand and quality. Extending production season and increasing fresh basil yield by using row covers as LTs may increase production and economic sustainability of the local industry.

Vegetable farmers use LT as protected systems in early spring, but there is little to no information on growth and production during the summer or optimal nutrient needs to sustain enhanced growth and production. Possible interactions between LT and N might occur and needs to be investigated. We postulated that: 1) Because LT enhances plant growth more consistently, crops utilize N more efficiently as compared to conventional open field production system and 2) Crops grown under LT require more N to sustain greater biomass production. Therefore, the objectives of this study are: 1) To compare growth and production parameters in basil grown under LTs and open field and 2) To compare N uptake and NUE at increasing N application rates between LTs and open field systems.

Materials and Methods:

This study was conducted at the Virginia Tech Eastern Shore Agricultural Research and Extension Center (ESAREC) in Painter, Virginia (longitude -75.82114 and latitude 37.58466). Experiments were conducted during the summer in 2017 and 2018. Soil type was Bojac sandy loam. Bojac sandy loam has approximately 59% sand, 30% silt and 11% clay in the Ap (plowed A) horizon (0-46 cm) (Felming et al., 2013).

Experimental design. Each year the experimental design was a split plot with four replications in a factorial arrangement. The main effect (plots) was N rate at 0, 37, 74, 111, 148, 185 $kg{\cdot}ha^{-1}$ and the secondary effect (subplots) was low tunnel with spun-bonded row cover (33.8 $g{\cdot}m^2$, Dewitt, Sikeston, MO) and no cover (open field). Potassium and phosphorous were applied based on soil analysis according to soil test recommendation for Virginia (Maguire and Heckendorn, 2015) and Mid-Atlantic vegetables guide (Wyenandt, 2016).

Plot establishment and planting. 'Eleonara' basil was sown in 128 cells trays (Beaver plastic LTD., Canada) in mid-March 2017 and last week of March 2018 and grown under greenhouse conditions. Trays were 65.5 cm long and 33 cm wide with square cells of 4 cm wide and 6.5 cm depth filled with Promix HP mycorrhiza media (Premier Horticulture, Quebec, Canada) (59-69% Canadian sphagnum peat moss plus vermiculite, perlite, dolomitic lime, and wetting agent). Greenhouse was maintained at 25 ºC. Seedlings were sprinkle irrigated twice a day and fertilized continuously through irrigation system with 20N-8.7P-16.6K soluble fertilizer (Plantex, Brampton, Canada) at N concentration of 50 ppm until transplanting.

The research field was conventionally tilled. Fertilizer was broadcasted at a rate of 112 $kg \cdot ha^{-1}$ K_2O (EC Fertilizer, Troonstrat, Brussels, Belgium) and 224 $kg \cdot ha^{-1}$ gypsum (23% Ca, 19% S) based on soil test results that indicated K and Ca level were below optimum level (Wyenandt, 2016). Nitrogen per treatment (plot) in the form of urea (46% N) was applied and thoroughly mixed into soil with a rototiller before raising bed and laying plastic mulch. Beds were spaced 1.8 m apart (center to center) with black plastic mulch (0.003 cm thick and 152.4 cm wide) (Hilex poly Co., North Vernon, IN) and drip tape (Aqua Trax, Marshall Avenue EI Cajon, CA) under the mulch. Emitters in the irrigation tape were 30 cm apart and flow rate was 1.89 $L \cdot min^{-1}$ per 30 m tape length. Transplants were hand planted into single row beds on 3 May 2017 and 25 May 2018. Individual plots for each N rate were 15 m long, and divided into two 6 m subplots (LT and open field), separated by a 1.5 m alley. In-row planting distance was 0.6 m corresponding to a population density of 9260 plant per ha. Low tunnels were supported by 3 m long PVC hoops bent to form a 1.0 m tall and 1.03 m wide tunnel with sand bags on the sides to hold the edges in place. The weight of sand bags was 1.5 to 2 kg and 18 bags were used in each subplot. All other cultural practices beside fertilizer management were done according to the Southeastern U.S. Vegetable Crop Handbook (Kemble, 2016).

Plant production parameter: Two plants per subplot were tagged to measure plant height, stem diameter, fresh weight, and biomass. Plant parameters were measured at each harvest, which was determined by initial development of inflorescence. Plant height was measured from the plant base to the top of the stem in the first three harvests. Stem diameter was measured at the base of the plant by using a Vernier caliper in the first two harvest.

In the 2017 trial, plants were harvested five times at 30, 60, 85, 101, and 123 days after transplanting (DAT), and in the 2018 trial, plants were harvested four times at 30, 52, 75, and 99

DAT. At the first harvest, plants were cut 20 and 25 cm above ground in the open field and LTs, respectively. Plants were taller under LTs and there was a need to leave similar foliage as in the open field for further growth. For subsequent harvests, the newly grown shoots were carefully cut 2 cm from the base to allow regrowth for the next harvest. Fresh weight was taken and then plant material was dried at 70°C for at least 15 d until a constant weight was achieved to determine total dry matter (biomass) production.

Nitrogen uptake and use efficiency. Twenty fully developed young mature leaves were collected from each subplot. Total plant biomass samples and leaf samples were dried at 70°C for at least 15 d. Dried samples were ground using a grinding mill to pass a 2 mm screen. Total N content was determined by dry combustion (10 mg sample) using the Elementar cube (Vario EL cube Elementar, Elementar Americas, Inc., Mt. Laurel, NJ) (Bremner, 1996). Total N uptake (aboveground) was determined by multiplying plant N content by total plant dry biomass. In addition, plant fresh weight, plant dry biomass and total plant N uptake were used to determine fresh weight and dried biomass NUE along with apparent N recovery efficiency (ANRE) by the following formulas (Ye et al., 2007):

$$NUE_X = [Yield_X +N - Yield_X -N] / N \text{ application}$$

$$ANRE = (N \text{ uptake} +N - N \text{ uptake} -N) / N \text{ rate} \times 100$$

Where $_X$ corresponds to fresh weight or biomass and +/-N refers to with or without N application, respectively.

Statistical analysis. Data for different parameters were analyzed by R-studio 2016 (R core 2016, Vienna, Austria). First, analysis of variance (ANOVA) of the overall model for each year (spilt plot) was conducted to evaluate the significant effect of each factor, and their interaction on all parameters. Replication was treated as a random factor, and N rate and LT were treated as fixed factors. Means of each parameter was also compared by Fischer's least significant difference (LSD) at 5% level of significance.

Results

Plant production. With a couple exceptions, there were no significant interactions between N rate and LT for all parameter. Low tunnels increased sweet basil plant growth (averaged across N rates) in both trials, except for stem diameter at 60 DAT in 2017 (Figure 1). Plant height and stem diameter were the same among the N rates in all sampling dates. In contrast, LT increased plant height by 74%, 33%, and 28% at 30, 60, and 85 DAT, respectively, in the 2017 trial, and by 50%, 32%, and 36% at 30, 52, and 75 DAT, respectively, in the 2018 trial (Figure 1). Tunnels also increased stem diameter by 29% at 30 DAT in the 2017 trial, and by 25% and 12% at 30 and 52 DAT, respectively, in the 2018 trial. Stem diameter at 60 DAT in the 2017 trial was the same between LT and open field.

Overall, LT increased basil fresh weight and plant dry biomass production (averaged across N rate) compared to open field in both years (Tables 1, 2, 3, and 4). Plant fresh weight increased by 167%, 72%, 29% and 89% in the first, second, third, and fifth harvest in the 2017 trial, respectively, and by 108%, 23%, 41%, and 54% in the first, second, third, and fourth harvest in the 2018, respectively. However, in the fourth harvest of the 2017 trial, LT increased yield at N application rate of 111 $kg{\cdot}ha^{-1}$ and above (Table 1). Low tunnel also increased plant dry biomass by 183%, 72%, 16%, 46%, and 69% in the first, second, third, fourth, and fifth harvest, respectively, in the 2017, and by 145%, 22%, 33%, and 47% in the first, second, third, and fourth harvest, respectively, in the 2018 (Tables 3 and 4). Consequently, LT increased total yield of fresh basil by 65% and 50% in comparison to open field in 2017 and 2018, respectively, and total dry biomass production by 58% and 48% in 2017 and 2018, respectively (Table 5).

Nitrogen rate also influenced total plant fresh weight (averaged of LT and open field) in both years and there was no interaction with LT (Table 5). Total fresh weight in 2017 increased with N rate until 111 $kg{\cdot}ha^{-1}$, but fresh weight was the same above this N rate. In 2018, total fresh weight also increased until 111 $kg{\cdot}ha^{-1}$, but then decreased at 185 $kg{\cdot}ha^{-1}$. In addition, there were differences in the overall plant fresh weight among the N rates in most harvests, except harvest five (2017). Optimum fresh weight varied each year and harvest. Similarly, total plant dry biomass production responded to N rate in both years in a similar pattern as fresh weight for both years (Tables 5). In addition, there were differences in plant biomass among the N rates in most harvests, except harvest five (2017). However, the optimum dry biomass varied each year and harvest (Tables 3 and 4).

The optimum N application rate was determined as the lowest N application rate in which yield was the greatest or among the top ones without significant differences (Table 5). Since there was no interaction between LT and N rate, optimal N rate was determined averaging LT and open field. Overall, optimum N rate was 111 $kg{\cdot}ha^{-1}$ with fresh basil production of 1613 $g{\cdot}plant^{-1}$ (14936 $kg{\cdot}ha^{-1}$) in 2017, and 1208 $g{\cdot}plant^{-1}$ (11186 $kg{\cdot}ha^{-1}$) in 2018, respectively. Similarly, 111 $kg{\cdot}ha^{-1}$ was the optimum N rate for dry biomass production with 187 $g{\cdot}plant^{-1}$ (1732 $kg{\cdot}ha^{-1}$) in 2017, and 126 $g{\cdot}plant^{-1}$ (1167 $kg{\cdot}ha^{-1}$) in 2018, respectively.

Leaf N status, plant N uptake and NUE. Overall, there were no significant interactions between N rate and LT for all the parameter, except for plant N content in 2018 (Table 6, 7, & 8). Low tunnel decreased the leaf N concentration (averaged across N rate) in all three sampling dates in both years (Table 6). In the 2017 trial, LT decreased leaf N concentration by 20%, 24%, and 12% in comparison to open field at 30, 60, and 85 DAT, respectively. Similarly, in the 2018, LT decreased leaf N concentration by 24%, 10%, and 15% at 30, 52, and 75 DAT, respectively. In contrast, leaf N concentration in response to N rate (averaged for LT and open field) was significant in the second and third harvest, but not in the first harvest in both years. Nitrogen concentration in leaves ranged from 2.5% to 5.6% and the overall average N concentration was 4.0% and 4.8% under the LT and open field conditions, respectively.

Similarly, LT decreased plant N concentration (averaged across N rate) by 12% and 13% in the 2017 and 2018 trial, respectively, although there was an interaction in 2018 (Table 7). Nitrogen content in plant samples ranged from 3.6% to 6.0% and the overall average plant N content was 4.3% and 4.9% under the LT and open field conditions, respectively. The LT decreased plant N concentration at all application rates except at 185 $kg{\cdot}ha^{-1}$ N application rates in 2018. The N concentration in response to N rate, however, was significant in 2017, but there were no responses in 2018. In the 2017 trial, the optimum N application rate was also at 111 $kg{\cdot}ha^{-1}$ N.

Above ground plant N uptake increased in basil grown under LTs in comparison to open field (Table 7). Plant N uptake ranged from 3.7 $g{\cdot}plant^{-1}$ (34.3 $kg{\cdot}ha^{-1}$) and 7.4 $g{\cdot}plant^{-1}$ (68.5 $kg{\cdot}ha^{-1}$) in both years. Average plant N uptake under LT and open field (averaged across N rate) were 6.7 g (62.0 $kg{\cdot}ha^{-1}$) and 4.7 g (43.5 $kg{\cdot}ha^{-1}$), respectively, in 2017, and 5.9 g (54.6 $kg{\cdot}ha^{-1}$) and 4.5 g (41.6 $kg{\cdot}ha^{-1}$), respectively, in 2018. Therefore, LT increased N uptake in basil by 43% and 31% in 2017 and 2018, respectively. Similar to fresh weight and biomass production, plant N uptake increased with N rate until 111 $kg{\cdot}ha^{-1}$ in both years, stayed the same with greater N rates in 2017, but decreased in 2018. In addition, optimum N application rate for N uptake in basil was 111 $kg{\cdot}ha^{-1}$.

Fresh weight NUE, dry biomass NUE, and ANRE responded inconsistently to LT treatment (averaged across N rate) (Table 8). Fresh weight NUE ranged between 8.4 $g \cdot g^{-1}$ of N and 46.2 $g \cdot g^{-1}$ of N in both years, biomass NUE ranged between 1.0 $g \cdot g^{-1}$ of N and 5.4 $g \cdot g^{-1}$ of N, and ANRE ranged between 7.5% and 22.5%. Fresh weight and biomass NUE were 116% and 81% greater, respectively, under the LTs than the open field in 2017, but they were the same in 2018. ANRE was also the same under the LTs and open field in both trials. Similarly, N rate had no effect on fresh weight NUE, biomass NUE, and ANRE in 2017. In contrast, fresh weight NUE, biomass NUE, and ANRE were greatest at 111 $kg \cdot ha^{-1}$, but no different from lower N rates in 2018. NUE and ANRE decreased at greater N rates. Therefore, the optimum N rate for NUE and ANRE in 2018 is also 111 $kg \cdot ha^{-1}$.

Discussion

Using LTs increased sweet basil vegetative growth and production as measured by plant height, stem diameter, fresh weight, and biomass. Results of this study supported many studies with specialty crops that reported an increase in vegetative growth and yield of biomass and yield under row covers or LTs (Chapter 2; Arancibia, 2018; Arancibia and Motsenbocker, 2008; Gerber et al., 1988; Ibarra et al., 2001b; Lamont, 2005; Nair and Ngouajio, 2010; Soltani et al. 1995). The overall increase in sweet basil production in terms of fresh weight and biomass under LT was 57.5% and 53%, respectively. Increased productivity of sweet basil under the tunnels indicated an additional benefit of using LT in the summer. This agreed with a report indicating a yield increase in summer squash grown under row cover during the summer (Gordon et al., 2008). The LT creates a mini-greenhouse effect by increasing air temperature, reducing wind, and reducing solar radiation (shading); which results in less evapotranspiration and water stress (Arancibia, 2018). A more favorable microenvironment resulted in greater growth and production of specialty crops like Brussels sprouts, cucurbits, watermelon, bell peppers (Chapter 2; Arancibia, 2012; Arancibia, 2009; Arancibia, 2018; Arancibia and Motsenbocker, 2008; Gerber et al., 1988). In addition, less pest infestations were found in basil grown under LT (data not present); which is consistent with utilization of row cover as a LT or floating blanket to reduce insect infestations (Adams et al., 1990; Andersen et al., 2006; Bextine et al., 2001; Rekika et al., 2008; Rekika et al., 2009).

In general, N rate increased fresh sweet basil yield and dry biomass in both LTs and open field. Total fresh weight and dry biomass yield was top or among the top ones at 111 $Kg·ha^{-1}$ N indicating that this was the optimum N rate for basil production under LT and open field conditions. These results are consistent with other studies that showed a positive basil response with N fertilizer application in open field conditions (Biesiada and Kuś, 2010; Bufalo et al., 2015; Sifola and Barbieri, 2006). Similar to our results, N fertilizer improved fresh basil yield and aboveground dry biomass and did not affect plant height (Sifola and Barbieri, 2006). In addition, the recommended N application rate for sweet basil in Southeastern U.S. under open field is 111 kg $N·ha^{-1}$ (Kemble, 2016). Hence, this study demonstrated that vegetative growth and production of sweet basil inside LTs increased with N rate in a similar pattern as in the open field.

Leaf and total plant N concentration decreased under the LT in comparison to open field (Tables 8 and 9). One possible explanation is the dilution effect of N compounds in plant tissue due to faster and enhanced vegetative growth under LTs promoted by favorable microclimatic conditions (by increasing air temperature, and reducing wind and solar radiation) and increasing heat index (Chapter 2; Arancibia, 2009; Nair and Ngouajio, 2010; Soltani et al., 1995). Lemaire and Gastal (1997) also concluded that leaf N concentration declines as plant growth increases.

Another likely explanation is a reduced N flow due to reduced evapotranspiration under LT. Reduced flow is supported by reports indicating that shade reduces leaf N concentration (Lemaire and Gastal, 1997; Lemaire et al., 1991; Malagoli et al., 2005).

Leaf and plant N concentration responded to increasing N rate (Table 6 and 7); however, plant N content was not different in the 2018 trial. In the case of leaf N content, lack of response during first harvest was likely due to available N already in the soil (Average nitrate content before planting was 21.5 and 9.6 $mg\cdot kg^{-1}$ of soil in 2017 and 2018, respectively) used for initial plant growth. Some N residue might be already present in the soil which lead to better N uptake to the control plants too. By midseason, soil N in control plots were used and plants then responded to N fertilizer applications. Optimum leaf N content in basil ranges from the 4.0% to 6.0% (Bryson et al., 2014). In our study, leaf N content was within the optimum in both LT and open field in the first harvest in 2017 and in all harvest 2018. However, leaf N content in the second and third sampling under the LT, and third sampling under the open field in 2017 trial were below optimum.

Total plant N uptake was greater under the LTs in comparison to open field in both years (Table 7). Higher vegetative growth under the LT lead to more aboveground plant N uptake in spite of having less plant N concentration. Nitrogen application rate also affected plant N uptake (Table 7). Similar to yield of fresh sweet basil, the optimum N application rate was 111 $kg\cdot ha^{-1}$ N. This result supports the optimum N rate determined by yield results (Tables 5) and the Southern vegetable recommendations for N fertilization in basil (Kemble, 2016).

The response in NUE was inconsistent. The relatively large yield of fresh basil and biomass without N application (control) under the LT in 2018; which was subtracted from the yield at each N application rate, reduced relative yield that was used to determine NUE.

Therefore, the small difference between LT and open field may have obscured the increase in NUE. Results of this study partially support the hypothesis that LT would increase NUE in sweet basil production and additional trials are needed to test the hypothesis.

Similarly, N fertilizer influence on NUE was inconsistent (Table 8). However, the reduction in NUE with increasing N rate in the open field in 2018 is in agreement with other studies that found decreasing NUE with increasing N application rate in wheat and rice (Gauer et al., 1992; Ye et al., 2007). Therefore, results support theories that NUE is influenced by both plant N demand and N applied through fertilizer (Šturm et al., 2010).

ANRE was not influenced by LT in both sampling dates. Furthermore, ANRE in response to N application rates were inconsistent. Overall, our results are in contrast with Ye et al. (2007) that reported increasing ANRE with increasing N application rate in sandy soil in rice.

Conclusion

This study showed potential of using LTs throughout the summer to increase sweet basil vegetative growth and yield. Although LT increased N uptake, the increase in NUE in comparison to open field was inconsistent. In addition, N uptake increased with N application rate until 111 $kg{\cdot}ha^{-1}$, which was determined to be the optimal N rate for basil production. In conclusion, LTs are an additional management tools to increase yield and land productivity of specialty crops.

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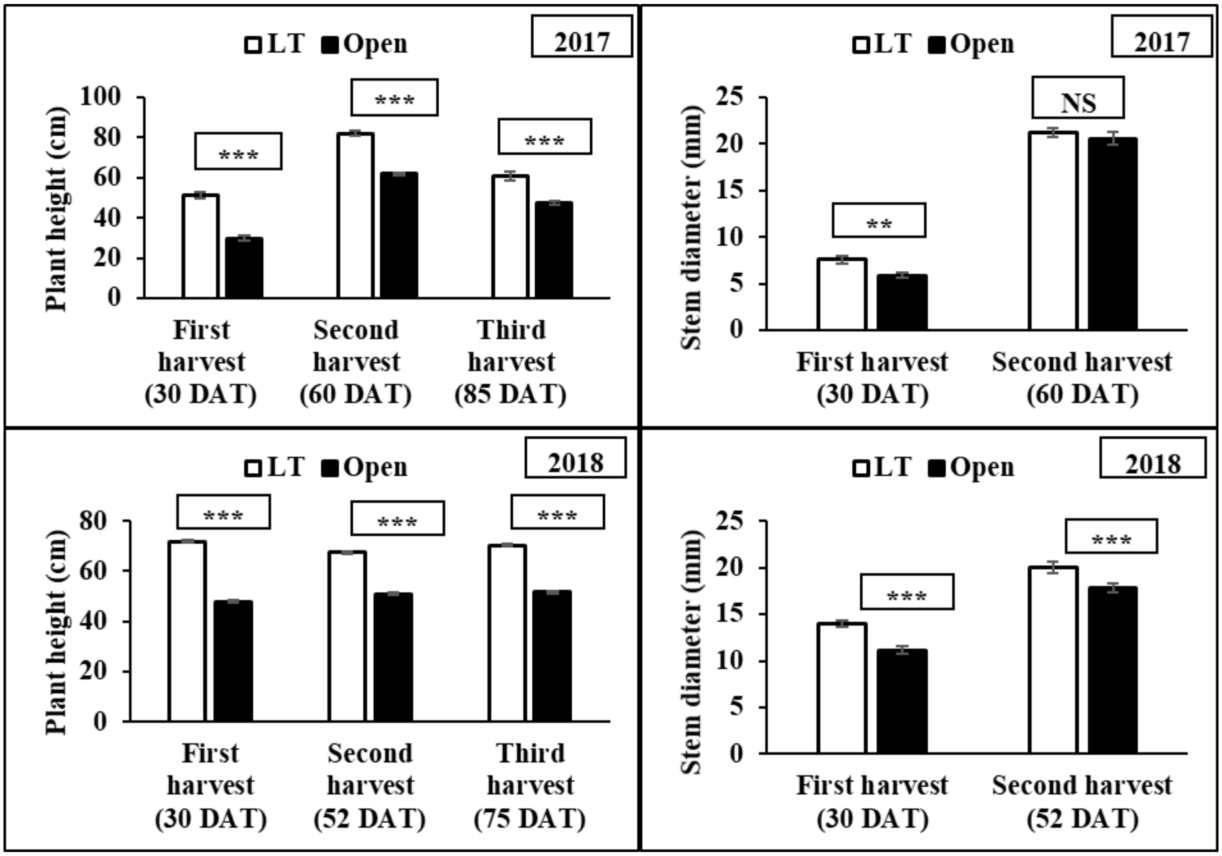

Figure 1: Plant height and stem diameter in sweet basil grown under low tunnel and open field conditions. Summer 2017 & 2018. DAT= Days after transplanting. The data represent means ± SE (n = 24) of the mean. NS, **, *** non-significant, and significantly difference at $P < 0.01$, 0.001, respectively.

Table 1: Plant fresh weight in sweet basil grown under low tunnel (LT) and open field (Open) at increasing level of N application. Summer 2017.

Treatment	Harvest 1 (30 DAT [z]) (g·plant^{-1})	Harvest 2 (60 DAT) (g·plant^{-1})	Harvest 3 (60 DAT) (g·plant^{-1})	Harvest 4 (101 DAT) (g·plant^{-1})		Harvest 5 (123 DAT) (g·plant^{-1})
N rate				LT	Open	
0	47 b [y]	346 d	270 c	174 bc	108 c	236
37	86 ab	485 bc	326 bc	139 b	134 bc	195
74	94 ab	433 cd	378 abc	200 b	153 bc	257
111	97 ab	540 ab	453 a	287 a	155 bc	301
148	102 a	455 bc	407 ab	353 a	200 b	402
185	135 a	587 a	457 a	318 a	174 bc	327
Tunnel						
LT	136 a	600 a	431 a	245		374 a
Open	51 b	348 b	333 b	154		198 b
P-value						
N rate	0.047	<0.0001	0.015	0.001		0.138
LT	<0.0001	<0.0001	0.006	<0.0001		<0.0001
N x LT [x]	0.688	0.079	0.290	0.028		0.704

[x] DAT= Days after transplanting

[y] Means within each column (as well as horizontal comparison in harvest 4) followed by different letters are significantly different from each other by Fischer's least significant difference at $P \leq 0.05$.

[x] N= nitrogen rate, LT= Low tunnel

Table 2: Plant fresh weight in sweet basil grown under low tunnel (LT) and open field (Open) conditions at different level of N application. Summer 2018.

Treatment	Harvest 1 (30 DAT [z]) (g·plant^{-1})	Harvest 2 (52 DAT) (g·plant^{-1})	Harvest 3 (75 DAT) (g·plant^{-1})	Harvest 4 (99 DAT) (g·plant^{-1})
N rate				
0	151 c [y]	206 b	219 c	202 c
37	171 bc	232 b	274 abc	207 c
74	208 ab	261 ab	267 bc	227 bc
111	262 a	325 a	351 a	270 ab
148	212 ab	262 ab	327 ab	276 a
185	219 ab	255 b	274 abc	206 c
Tunnel				
LT	275 a	283 a	334 a	281 a
Open	133 b	231 b	237 b	182 b
P-value				
N rate	0.010	0.019	0.043	0.005
LT	<0.0001	0.007	<0.0001	<0.0001
N x LT [x]	0.076	0.666	0.778	0.174

[z] DAT= Days after transplanting

[y] Means within each column followed by different letters are significantly different from each other by Fischer's least significant difference at $P \leq 0.05$.

[x] N= nitrogen rate, LT= Low tunnel

Table 3: Plant dried biomass in sweet basil grown under low tunnel (LT) and open field (Open) conditions at different level of N application. Summer 2017.

Treatment	Harvest 1 (30 DAT [z]) (g·plant^{-1})	Harvest 2 (60 DAT) (g·plant^{-1})	Harvest 3 (60 DAT) (g·plant^{-1})	Harvest 4 (101 DAT) (g·plant-1)	Harvest 5 (123 DAT) (g·plant^{-1})
N rate					
0	5.5 c [y]	43.3 d	27.5 c	15.2 c	28.6
37	11.3 b	60.6 bc	29.4 bc	14.1 c	24.4
74	12.1 b	54.1 cd	41.8 ab	18.5 bc	31.1
111	11.5 b	67.6 ab	50.7 a	22.9 ab	34.0
148	14.5 ab	56.9 bc	42.6 ab	27.7 a	43.4
185	18.2 a	73.3a	49.3 a	25.4 a	35.8
Tunnel					
LT	18.1 a	75.0 a	43.2 a	24.5 a	41.3 a
Open	6.4 b	43.5 b	37.2 b	16.7 b	24.4 b
P-value					
N rate	0.002	<0.0001	0.005	0.001	0.254
LT	<0.0001	<0.0001	0.036	<0.0001	<0.0001
N x LT [x]	0.209	0.089	0.07	0.055	0.873

[z] DAT= Days after transplanting

[y] Means within each column followed by different letters are significantly different from each other by Fischer's least significant difference at $P \leq 0.05$.

[x] N= nitrogen rate, LT= Low tunnel

Table 4: Plant dried biomass in sweet basil grown under low tunnel (LT) and open field (Open) conditions at different level of N application. Summer 2018.

Treatment	Harvest 1 (30 DAT [z]) (g·plant^{-1})	Harvest 2 (52 DAT) (g·plant^{-1})	Harvest 3 (75 DAT) (g·plant^{-1})	Harvest 4 (99 DAT) (g·plant^{-1})
N rate				
0	13.7 c [y]	26.3 b	18.8 c	18.3 c
37	15.2 bc	29.2 b	23.1 bc	20.2 c
74	19.6 abc	32.7 ab	24.3 abc	21.6 c
111	23.6 a	40.8 a	31.3 a	30.8 a
148	19.3 abc	30.9 b	27.5 ab	27.0 b
185	19.1 abc	32.7 ab	24.4 abc	21.3 c
Tunnel				
LT	26.2 a	35.3 a	28.5 a	27.6 a
Open	10.7 b	28.9 b	21.3 b	18.7 b
P-value				
N rate	0.027	0.037	0.036	<0.0001
LT	<0.0001	0.013	<0.0001	<0.0001
N x LT [x]	0.107	0.870	0.958	0.798

[z] DAT= Days after transplanting

[y] Means within each column followed by different letters are significantly different from each other by Fischer's least significant difference at $P \leq 0.05$.

[x] N= nitrogen rate, LT= Low tunnel

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Table 5: Total plant fresh weight and dried biomass in sweet basil grown under low tunnel (LT) and open field (Open) conditions at different level of N application. Summer 2017, 2018.

	Total fresh weight		Total dry biomass	
	2017	2018	2017	2018
Treatment	($g·plant^{-1}$)	($g·plant^{-1}$)	($g·plant^{-1}$)	($g·plant^{-1}$)
N rate				
0	1040 d [z]	778 d	120 d	77 d
37	1228 cd	884 cd	140 cd	88 cd
74	1338 bc	963 bc	158 bc	98 bc
111	1613 ab	1208 a	187 ab	126 a
148	1643 a	1077 ab	185 ab	105 b
185	1751 a	953 bc	202 a	97 bc
Tunnel				
LT	1787 a	1173 a	202 a	118 a
Open	1085 b	782 b	128 b	80 b
P-value				
N rate	<0.0001	0.001	<0.0001	<0.0001
LT	<0.0001	<0.0001	<0.0001	<0.0001
N x LT [y]	0.073	0.289	0.100	0.738

[z] Means within each column followed by different letters are significantly different from each other by Fischer’s least significant difference at $P \leq 0.05$.

[y] N= nitrogen rate, LT= Low tunnel

Table 6: Leaf N content in sweet basil grown under low tunnel (LT) and open field (Open) conditions at different level of N application. Summer 2017 and 2018.

	2017			2018		
Treatment	Harvest 1 (30 DAT[z]) (%)[y]	Harvest 2 (60 DAT) (%)	Harvest 3 (60 DAT) (%)	Harvest 1 (30 DAT) (%)	Harvest 2 (52 DAT) (%)	Harvest 3 (75 DAT) (%)
N rate						
0	4.5	2.9 b[x]	2.5 b	5.4	4.6 b	4.7 b
37	4.4	3.6 a	2.7 b	5.2	4.6 b	4.8 b
74	4.4	3.7 a	3.1 a	5.4	4.8 ab	5.2 ab
111	4.5	3.9 a	3.2 a	5.4	4.6 b	5.3 a
148	4.7	3.8 a	3.4 a	5.6	5.0 a	5.4 a
185	4.6	3.9 a	3.2 a	5.5	5.2 a	5.1 ab
Tunnel						
LT	4.0 b	3.2 b	2.8 b	4.7 b	4.6 b	4.7 b
Open	5.0 a	4.1 a	3.2 a	6.1 a	5.0 a	5.5 a
P-value						
N rate	0.740	<0.0001	<0.0001	0.512	0.032	0.010
LT	<0.0001	<0.0001	<0.0001	<0.0001	0.001	<0.0001
N x LT[w]	0.597	0.194	0.631	0.590	0.071	0.053

[z] DAT= Days after transplanting

[y] %= percentage of leaf N from 10 mg sample

[x] Means within each column followed by different letters are significantly different from each other by Fischer's least significant difference at $P \leq 0.05$.

[w] N= nitrogen rate, LT= Low tunnel

Table 7: Plant N content and total plant N uptake in sweet basil grown under low tunnel (LT) and open field (Open) conditions at different level of N application. Summer 2017, 2018.

	Plant N content				Plant N uptake	
	2017	2018			2017	2018
Treatment	(%) [z]	(%)			(g·plant^{-1})	(g·plant^{-1})
N rate		LT	Open			
0	3.6 cd [y]	4.6	5.8	* [x]	3.7 d	3.7 d
37	3.6 d	5.0	5.7	*	4.2 cd	4.5 cd
74	3.8 bc	4.9	5.9	*	5.4 bc	5.1 bc
111	3.9 ab	5.2	5.9	*	6.5 ab	6.7 a
148	4.1 a	5.4	6.0	*	7.0 a	5.8 b
185	4.0 ab	5.4	5.7	NS	7.4 a	5.3 bc
Tunnel						
LT	3.6 b	5.1			6.7 a	5.9 a
Open	4.1 a	5.8			4.7 b	4.5 b
P-value						
N rate	<0.0001	0.134			<0.0001	<0.0001
LT	<0.0001	<0.0001			<0.0001	<0.0001
N x LT [w]	0.719	0.04			0.076	0.322

[z] %= percentage of plant N content from 10 mg sample.

[z] Means within each column followed by different letters are significantly different from each other by Fischer's least significant difference at $P \leq 0.05$.

[y] NS and * non-significant and significant at $P \leq 0.05$ by Fischer's least significant difference, horizontal comparison.

[x] N= nitrogen rate, LT= Low tunnel

Table 8: Fresh weight and biomass NUE, and apparent nitrogen recovery efficiency(ANRE) in sweet basil grown under low tunnel (LT) and open field conditions at different level of N application. Summer 2017, 2018.

	Fresh weight NUE		Dry Biomass NUE		ANRE	
	2017	2018	2017	2018	2017	2018
Treatment	($g \cdot g^{-1}$) [z]	($g \cdot g^{-1}$)	($g \cdot g^{-1}$)	($g \cdot g^{-1}$)	(%) [y]	(%)
N rate						
37	45.6	25.5 ab [x]	4.8	2.6 ab	13.0	18.5 ab
74	36.1	22.4 ab	4.5	2.5 ab	20.4	16.9 abc
111	46.2	34.7 a	5.4	4.0 a	22.5	24.3 a
148	36.5	18.1 b	3.9	1.7 b	20.0	12.3 bc
185	34.4	8.4 b	4.0	1.0 b	18.0	7.5 c
Tunnel						
LT	54.4 a	22.4	5.8 a	2.1	20.9	16.4
Open	25.2 b	21.3	3.2 b	2.6	16.6	15.4
P-value						
N rate	0.446	0.042	0.136	0.043	0.604	0.020
LT	0.006	0.831	0.042	0.358	0.220	0.733
N x LT [w]	0.910	0.076	0.896	0.068	0.203	0.200

[z] $g \cdot g^{-1}$= Fresh and dry biomass yield of basil (g) per g of N application.

[y] %= percentage of plant N uptake per g of N application.

[y] Means within each column followed by different letters are significantly different from each other by Fischer's least significant difference at $P \leq 0.05$.

[w] N= nitrogen rate, LT= Low tunnel

Chapter 5: Summary and Conclusion

Low tunnels (LTs) covered with spun-bonded fabric has generally been used in early spring as well as late summer for season extension and protection against insect pests. The purposed of this study was to determine the effect of LTs on water requirements and use efficiency as well as nitrogen uptake and use efficiency since there was no information on these subjects. Insect damage and feeding injury under LTs was also investigated in comparison to open field.

In the study with Brussels sprouts, water requirement was less under LTs than open field, but it was not affected by the color of plastic mulches (black vs white). In addition, yield of Brussels sprouts was greater under LTs. The increased yield and reduced irrigation led to greater water use efficiency under LTs in comparison to open field. The reduced irrigation was due to the less evapotranspiration resulting from reduced solar radiation (shading effect) and no detectable wind, in spite of greater maximum air temperature under the tunnel. Hence, LTs can be a management tool for sustainable production of Brussels sprouts in areas with limited water availability.

Number of insect pests and leaf feeding injury was less under the LTs than open field plots. Hence, fewer insecticide applications were needed under the tunnels than in the open field plots. Therefore, LTs are another tool to manage insect infestations and reduce feeding injury in sustainable vegetable production.

Similarly, LTs increased fresh weight, biomass, plant height, stem diameter, plant N uptake of sweet basil. However, leaf N content was greater in open field plots. Additionally, LTs partially increased fresh and biomass NUE. Fresh weight and biomass were also positively affected by N fertilizer application. The rate of 111 kg·ha^{-1} N was optimum for the growth and production of sweet basil under both LTs and in the open field.

From all outcomes, LTs covered with spun-bonded fabric can be a viable tool to reduce irrigation, increase water use efficiency, and protect against insect pest injury. In addition, LT may increase N use efficiency, but other factors appear to play a role also. Finally, an economic assessment is needed to determine whether the increased yield, reduced irrigation, and reduced insecticide applications will pay for the increased cost of LTs.

Appendix A

Figure 1: Planting, and growth difference in Brussels sprouts grown under low tunnels and open field condition. Eastern Shore, AREC, Painter. 2017-18.

Figure 2: Decagon devices (left) and sensor (5TM) used for the measurement of soil moisture as well as environmental parameter. Eastern Shore, AREC, Painter. 2017-18.

Figure 3: Planting (left) and growth and development (right) of sweet basil in low tunnels and open field. Eastern Shore, AREC, Painter. 2017-18.