

EXTENDING COOL SEASON PRODUCTION OF  
VEGETABLES IN THE HIGH TUNNEL:  
BALANCING HEAT AND LIGHT

by

David Alan Baumbauer

A dissertation submitted in partial fulfillment  
of the requirements for the degree

of

Doctor of Philosophy

in

Plant Sciences and Plant Pathology

MONTANA STATE UNIVERSITY  
Bozeman, Montana

April 2019

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DEDICATION

This dissertation is dedicated to Dr. Donald Mathre, who for over thirty years has supported a wide variety of projects at the Plant Growth Center and Horticulture Farm. Don's love of gardening and teaching is infectious and he is always willing to lend a hand. He has been a true friend and mentor, and I greatly appreciate all that he has done for me, the university and the Bozeman community.

## ACKNOWLEDGEMENTS

I would like to thank my committee: Drs. Burgess, Dougher, Mathre and Talbert for their willingness to serve and oversee this research project.

Allison Rognlie helped grow, harvest, and weighed hundreds of pounds of produce and assisted with the growth chamber portion of the study along with Colleen Schmidt. Allison also waded through thousands of lines of temperature and PAR data, formatting it for analysis. This project wouldn't have gotten done without her. Tyrel Hoferer designed, fabricated and installed the end walls of the high tunnels and was the lead for moving the high tunnels, which is no small feat. All PGC and Horticulture Farm student employees over the past five years participated in the project in some fashion, from high tunnel construction, working soil, harvesting and processing produce. The list of student helpers is long and I appreciate their help and support.

Drs. Lachoweic and Robison-Cox patiently provided statistical advice. Pete Zuck and his colleagues at Johnny's Selected Seeds provided advice on variety selection and provided seeds for the project. My family and friends have provided amazing support for David "going back to school".

The project was supported in part by a grant from the Montana Specialty Crop Block Grant Program "Vegetable Crop Production Strategies for Moveable High Tunnels".

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## ABSTRACT

Montana high tunnel growers face challenges associated with being at a northern latitude and high elevation. The wide seasonal fluctuation in photosynthetically active radiation coupled with wide diurnal temperature swings produces a dynamic growing environment within the high tunnel. This dissertation is comprised of four studies investigating the management of light and temperature and their influences on high tunnel grown crops. Chapter one is an introduction to high tunnels and production strategies. Chapter two discusses the results of the Montana High Tunnel Growers Survey, in which respondents reported that managing the high tunnel environment was their number one challenge. Two thirds of respondents produced crops during the shoulder seasons of spring and fall, a period of time when the climatic conditions are especially dynamic. Chapter three presents the findings on the influences various types of season extension have on light and temperature levels and the impacts they have on the accumulation of growing degree hours, soil degree hours, and daily light integral. While each layer retains heat, moderating the effect of low night air temperatures, it comes at the cost of lower light energy at the crop level. Heat retention performance of high tunnel plus row cover improves as outside air temperature decreases, maintaining crop level air temperature at  $-3^{\circ}\text{C}$  despite an outside air temperature of  $-22^{\circ}\text{C}$ . Chapter four presents the results of seeding date and row cover effects on the yield and days to harvest of six cool season crops. Row cover within the high tunnel only improved crop yields when outside air temperatures were well below the historical average. The early seeding date in the fall resulted in higher yields and fewer days to harvest, indicating that the two weeks difference between August 15<sup>th</sup> and August 30<sup>th</sup> has a large impact on production. Chapter five reports on the influence of low daily light integral has on the production of kale, lettuce, and spinach. While all three responded to increasing light, lettuce had the largest response with a 200% increase in dry weight when the daily light integral increased from 8 to 14  $\text{mol m}^{-2} \text{d}^{-1}$ .

## CHAPTER ONE

### INTRODUCTION

High tunnels are inexpensive, unheated greenhouse-like structures that rely on passive solar heating and natural ventilation to moderate the temperature within the structure. They typically feature a hoop shaped metal frame that supports a single layer of greenhouse grade polyethylene film. High tunnels elevate daytime air temperature, provide some frost protection, warm soils, block wind and precipitation allowing producers to better manage the growing environment, and are widely used in the United States to produce high value fruits, vegetables, and cut flowers. (Blomgren and Frisch, 2007; Carey et al., 2009; Coleman, 2009; Fortier and Bilodeau, 2014). Crops are produced in the ground as opposed to containers, and the tunnels are typically sized to facilitate working the soil with small farm scale equipment. Vegetable crops popular for high tunnel production include warm season vine crops such as tomato and cucumber that are trellised for efficient space utilization, and quick growing baby leaf salad greens such as lettuces, kale, spinach, and Brassica greens. High tunnel production is promoted as being relatively sustainable as it provides a degree of crop protection without consuming much energy. Researchers in New York compared open field production of trellised tomato, high tunnel tomato and greenhouse tomato production on energy consumed. High tunnel tomato production was 2.5 times more efficient than field production and 19 times more energy efficient than greenhouse produced tomato (De Villiers et al., 2009). Over the past twenty years, innovative growers in the northeast states have been utilizing

high tunnels to produce cool season crops during shoulder seasons of early spring and late fall and in some cases year round (Blomgren and Frisch, 2007; Coleman, 2009) and interest in extended season high tunnel production has spread across the northern tier states.

Between 2009-2014, The USDA-NRCS EQIP high tunnel initiative has granted \$61 million funding the construction of 13,000 high tunnels across the nation (Janke et al., 2017). Montana market growers have taken advantage of the cost share program purchasing of 90 commercial grade high tunnels by 2015. This recent rise in the number of high tunnels in Montana coupled with regional production challenges such as wide diurnal temperature fluctuations due to our high elevation and low light levels during late fall and winter led to the development of the Season Extension Research Project (SERP) at Montana State University and this dissertation topic.

Chapter two presents the results of the Montana high tunnel growers survey in which we sought to determine grower practices and concerns. Thirty-seven growers utilizing 68 high tunnels responded to the survey between February and November of 2015. Fifty-two percent of respondents had four or fewer years of experience growing in high tunnels and 61% were producing cool season crops in addition to warm season crops. Managing the high tunnel air temperature, both overheating in the summer and mitigating low temperatures during fall-winter-spring was the grower's top concern. In order to provide additional protection from low temperatures, over 90% of survey respondents also utilized poly spun bond row cover within their high tunnels. Montana

high tunnel growers are faced with the challenge of balancing heat retention with maximizing light at the crop level.

To determine the influence the secondary layer of row cover had on light transmission and air and soil temperatures, a study was conducted from April 2016 through April 2018. Chapter three reports the results of recording air and soil temperatures and photosynthetic photon flux density (PPFD) at four locations in the SERP plots: outside, outside under a row cover, inside the high tunnel, and inside the high tunnel under a row cover during the months of April and October. These months were chosen as they are transitional months when air temperature might dictate the deployment of a secondary layer of season extension. The micrometeorological data was used to calculate growing degree hours (GDH), soil degree hours (SDH) and daily light integral (DLI). Night temperatures under the row cover in the high tunnel were often several degrees warmer than the high tunnel alone, however DLI was reduced by ~50% under the two layers in October.

Chapter four investigates the high tunnel production of six cool season vegetables during early spring and fall utilizing row cover and varying seeding dates to determine how early and late vegetable production could be carried out in Bozeman, MT. Moveable high tunnels were utilized for this study to facilitate producing three crops (two cool season and one warm season) per year. Fresh weight and days to harvest (DTH) were recorded. Unless air temperature was below normal, this study indicated that light was often more limiting than heat in the production of several of these species.

To explore the minimum amount of light required to produce baby kale, lettuce and spinach greens, a growth chamber study was conducted during 2018. Two chambers were set at a constant temperature and photoperiod and the light level was adjusted to produce a daily light integral (DLI) of 8, 10, 12, and 14 mol m<sup>-2</sup> d<sup>-1</sup>. Crops were grown for 28 days and fresh and dry weight, leaf area, and chlorophyll level were recorded. There was a strong linear response in dry weights in response to increasing DLI, with lettuce having the greatest response of the three species trialed.

Chapter six summarizes the results of the four studies and presents future directions for research at SERP.

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CHAPTER TWO

THE MONTANA HIGH TUNNEL GROWERS SURVEY – IDENTIFYING GROWER  
PRACTICES AND CONCERNS

Contribution of Authors and Co-Authors

Manuscript in Chapter Two

Author: David A. Baumbauer

Contributions: Conceived of the study, performed the study, performed the analyses, interpreted results and wrote the manuscript.

Co-Author: Macdonald H. Burgess

Contributions: Discussed results and implications and edited earlier manuscripts.

Manuscript Information

David A. Baumbauer and Macdonald H. Burgess

HortTechnology

Status of Manuscript:

Prepared for submission to a peer-reviewed journal

Officially submitted to a peer-reviewed journal

Accepted by a peer-reviewed journal

Published in a peer-reviewed journal

American Society of Horticultural Science

The Montana High Tunnel Growers Survey – Identifying Grower Practices and Concerns

David A. Baumbauer<sup>1</sup> and Macdonald H. Burgess

Manager, Plant Growth Center and Assistant Professor

Department of Plant Sciences and Plant Pathology, Montana State University, Bozeman,

MT 59717

<sup>1</sup> Corresponding author. Email address: [baumbauer@montana.edu](mailto:baumbauer@montana.edu)

The survey referenced in this publication was approved by the Montana State University

Institutional Review Board on December 31<sup>st</sup>, 2014 (IRB# DB123114-EX)

Category: Research Reports

*Additional Index words.* Cool season vegetable production, market gardening, season extension

*Abstract.* Thirty-seven Montana high tunnel growers utilizing 68 high tunnels participated in a survey designed to determine grower practices, markets utilized, and challenges experienced. Fifty-two percent of survey respondents had four or less years of experience and 90% claimed certified organic status or followed organic practices. All respondents produced high tunnel vegetables and 74% also produced some combination of cut flowers, herbs and small fruit. Montana high tunnel growers utilized a variety of wholesale and direct marketing opportunities to sell their produce, with 71% selling at farmers markets with restaurant sales and community supported agriculture programs tied at 41%. Sixty-one percent of respondents utilized their high tunnels to grow cool-season crops during the shoulder seasons of early spring and late fall. When queried about challenges, managing the high tunnel environment gathered the highest number of responses.

#### Introduction

With the sharp increase in high tunnel adoption by US producers, especially by small acreage market gardeners (Carey et al., 2009), new choices and challenges in vegetable production have arisen. High tunnel growers must make a variety of management decisions to optimize production: Crop selection and scheduling, fertility and irrigation, pest management, and management of the high tunnel environment all play a vital role in the success of the grower. High tunnel growers often experience wide

diurnal air temperature fluctuations within the tunnels, especially on sunny days and clear nights (Wien, 2009). Maintaining soil fertility without the buildup of salts is a concern given the intensive nature of high tunnel production (Reeve and Drost, 2012, Rudisill et al., 2015, Knewton et al., 2012). Insect and disease pressure may be accentuated in the high tunnel environment due to warmer temperatures and increased relative humidity (O'Connell et al., 2012, Warren et al., 2015). Ingwell et al reported higher numbers of aphids, whiteflies, and hornworms in the high tunnel than field plots (Ingwell, 2017). Understanding these options and preparing to overcome these challenges is critical to production and profitability.

Regional and state wide surveys of high tunnel growers have been conducted in the Central Great Plains (Knewton et al., 2010), Virginia (Foust-Meyer, 2014) and in Maine (Fitzgerald and Hutton, 2012). A Montana high tunnel grower's survey was warranted due to the different climate faced by Montana producers. Compared to coastal or low-elevation locations, Montana high tunnel growers face the additional challenges of greater diurnal temperature fluctuations associated with high elevation locations (Figure 2.1), a short growing season, cold climate (USDA hardiness zones 3-5) strong winds and low light intensity and duration during fall and winter months. Strong demand for locally grown vegetables has encouraged many Montana growers to add high tunnels and other season extension technologies to their operations. In the 2012 Census of Agriculture, 83 Montana farms reported production of greenhouse vegetables and fresh cut herbs, valued at \$1,335,438 which was an 80% increase in operations and a 40% increase in sales from the 2007 Census of Agriculture. In the 2014 USDA Organic Survey, 28 Montana farms

reported production of organic vegetables under protected cultivation comprising 366,283 square feet of area. These figures represent the spectrum of protected cultivation from greenhouses with full environmental control to unheated and naturally ventilated high tunnels, but illustrate an increased importance of season extension to Montana producers. United States Department of Agriculture (USDA) Natural Resources Conservation Service's (NRCS) Environmental Quality Incentives Program (EQIP) program has reduced the financial hurdle for many growers wishing to add high tunnels to their operations. In Montana, ninety-five tunnels were purchased with assistance of the EQIP program in the five year period of 2010-2014 (P.F. Hensleigh, personal communication). Froust-Meyer and O'Rourke reported that nationwide, latitude was the strongest predictor of NRSC-EQIP high tunnels adoption; counties at high altitudes had higher participation in the EQIP high tunnel program than counties at lower altitudes (Foust-Meyer, 2014).

Montana high tunnel growers seeking assistance are hampered by a lack of a statewide grower's organization as occurs in many states such as Maine, Iowa, and Kansas, and limited university research and outreach efforts (Carey et al., 2009). In an effort to address the needs of Montana high tunnel growers, the Season Extension Research Program (SERP) was founded at Montana State University in the fall of 2014. To determine the initial research focus for the program, a survey was developed to identify the current practices and challenges of Montana high tunnel growers.

#### Materials and Methods

A survey of high tunnel growers in Montana was conducted in 2015. Thirty-three survey questions were developed focusing on farm demographics, crops grown, markets

utilized, high tunnel systems in use, soil fertility practices, and pest management practices (Appendix A). Questions were developed to seek out grower concerns and determine where growers get information. A pilot survey was distributed to four growers to determine clarity of the questions. Potential participants were identified from internet searches of Montana farmer's markets vendors and regional grower's organizations. Extension agents and research center personnel from areas with a concentration of vegetable growers also assisted in providing grower contact information. Fifty-one e-mail addresses associated with Montana market gardeners were identified through this process. Qualtrics (Provo, UT), a web based survey program, was used to generate the survey and the survey's URL was distributed to participants via e-mail. The survey was promoted in newspapers and state wide agriculture publications via a press release written and distributed by Montana State University's communication services department. While the press release did not generate additional requests from growers to participate in the survey, it was hoped that the publicity would encourage those producers that were already contacted by e-mail to participate. No reminders were sent and no incentives to complete the survey were offered. Five paper copies of the survey were distributed at a Ravalli County extension hosted greenhouse grower meeting in October, 2015. Survey results were collected from March 3<sup>rd</sup>, 2015 through November 18<sup>th</sup>, 2015. Thirty-two growers completed the online survey for a 63% response rate, and all five paper surveys were completed. Not all participants answered every question, so percentages reported in the results and discussion sections are based on the number of

responses to each question. The results presented here are descriptive summary statistics including means and percentages of respondents.

### Results and Discussion

The 37 respondents were from 15 counties, located primarily in the western third of Montana. Seventy-four percent farmed on five acres or less. Forty-eight percent had five years or less of market gardening experience while 52% had five or more years of experience. Fifty-two percent of respondents had four or less years of high tunnel growing experience. Growers were asked to describe their production practices. Thirty-two percent were certified organic while 6% were transitional organic. Fifty-three percent described their operation as organic without certification or participating in other sustainable farming certificate programs. The remaining 9% chose conventional practices (Figure 2.2).

When queried on what crops were grown in their high tunnels, all respondents answered vegetables, while half included herbs in their product mix. Forty-three percent also produced berries or other fruit and 31% grew flowers in their high tunnels. Growers were asked to list their top three most economically important warm season and cool season crops. Tomatoes were listed in the top three warm season crops by all respondents, a similar response as the Knewton et al. (Great Plains) and Fitzgerald and Hutton (Maine) surveys reported. Peppers were the second most important (52% of growers reporting) and cucumbers third at 35%. The most important cool season crops included: Salad mix and greens (85%), spinach (37%) and carrots (26%). This was an

open response question, so the grower's choice of crop names required the authors to combine lettuce, salad mix, baby greens and mesclun into one group.

Farmers markets were the top listed market by 71% of participating growers. Community supported agriculture (CSA) programs and sales to restaurants were 47% and grocery stores were markets for 44% of respondents (Figure 2.3). Wholesale distributors were listed among the 'others' category and the recent rise in the number of these enterprises in the state could increase market possibilities in the near future (Neely, 2007).

Thirty-six percent of growers reported using their high tunnels primarily for the production of warm season crops and 61% utilized their high tunnels for both warm and cool season crops. One grower reported their primary high tunnel use was to grow cool season crops.

Thirty-three growers reported having traditional stationary high tunnels, while eight growers reported having moveable high tunnels. Total square footage of stationary high tunnels ranged from 360 square feet to 10,000 square feet. Moveable high tunnel total square footage ranged from 100 square feet to 2160 square feet. Growers with moveable tunnels were evenly divided between zero, one, and two moves per year, although one grower reported moving their high tunnel three or more times per year.

High tunnels that were subsidized through the NRCS EQIP program prior to 2014 did not allow electricity or supplemental heating and cooling systems to be utilized (NRCS, 2013). These constraints might have influenced the features selected by high tunnel purchasers during the first three years of the EQIP program. Seventy-nine percent

of the growers used one layer of polyethylene greenhouse film plastic while 15% used two layers with inflation. Seventy-three percent of the high tunnels utilized end wall vents and 82% had roll up side walls. One grower utilized roof vents. Twenty-four percent of the growers used shade cloth to aid with cooling.

Light quantity is lower within the high tunnel. Borrelli et al reported photosynthetic photon flux densities (PPFD) were 27% lower inside the high tunnel than outside at Pullman, WA and 36% lower in a Vancouver, WA high tunnel during winter production (Borrelli et al., 2013). Poly spun bond row covers also lower light quantity. Researchers in Spain reported PPFD levels under poly spun bond row cover varied from 85% to 65% of outside levels depending on dust and moisture levels on the row cover. (Gimenez et al, 2002). There are few reports in the literature of the effect on PPFD when spun polyester row covers are used within the high tunnel. Ninety-four percent of Montana growers surveyed utilized spun polyester row cover within the high tunnel to protect their crops. This high level of row cover use within the high tunnel reduces light quantity, but may be practiced due to a presumption of needed crop protection from the highly variable temperature swings. Appropriate conditions for the deployment of row covers and which species would benefit from the added expense of row cover was identified as information needed by growers taking this survey. Thirty-five percent of growers incorporated plastic mulch into their high tunnel production system. Seventy-nine percent did not utilize supplemental heat sources while 12% installed a fossil fuel powered unit heater. Nine percent reported incorporating some form of solar heat storage within their high tunnels.

Survey responses regarding fertility were based on a grower's practice on a minimum of a biennial basis. Sixty-one percent of high tunnel growers surveyed utilized the services of a commercial soil analytical laboratory while an additional 16% used on farm DIY soil test kits. The combined methods of soil testing was 77% and was considerably higher than reported in the Knewton survey (55%) and the Fitzgerald and Hutton survey (48%). Farm-made compost was the most common soil amendment, used by 81% of high tunnel growers. Twenty-three percent of surveyed growers utilized a commercially produced compost product and just over half of growers reported using farmyard manures. Sixty percent of growers reported using fertilizers derived from animal by-products, 30% used plant based fertilizers and 40% used mineral powders such as gypsum, sulfur and greensand. Forty-four percent of growers reported using commercially formulated multi-element fertilizers, urea, and other commercial nitrogen fertilizers. It is not possible to distinguish Organic Materials Review Institute (OMRI) approved fertilizers from conventional fertilizers given the design of the survey. This would be a topic of inquiry for future surveys of high tunnel grower practices.

Eighty-eight percent of growers surveyed reported practicing crop rotation in their high tunnel production schedule compared to 50% reported by Knewton et al. Cover crops are one technique used by growers to counteract the degradation of soil quality within the high tunnel (Scotti, 2015) and 13% of survey respondents frequently used cover crops in their high tunnels while 50% occasionally incorporated cover crops into their production schedule. Drip irrigation was by far the most common irrigation method

with 63% of growers reporting. Nineteen percent hand watered and 6% utilized sprinkler irrigation.

Growers were asked to identify pest issues based on summer versus spring/fall growing seasons in an attempt to determine if there was seasonality of pest problems. Weeds were the top summer pest for 38% of the growers while insects were the top pest for 24% of growers. When the grower's second most important summer pest issue was included, weeds ranked highest at 57% and insects second at 54%. Diseases and vertebrate pests were third and fourth at 27% and 24%. Top spring/fall pest issues were fairly evenly divided among the four categories. When second choices were included, weeds once again was the top choice with 54% combined votes. Insects, diseases and vertebrate pests were evenly divided when grower's top two choices were combined. Sixty percent of growers practiced weekly monitoring for pests. Half of the growers utilized biocontrol agents to manage pests while 23% utilized OMRI approved pesticides. A third of the growers screened high tunnel vents and doors to exclude pests.

Growers were asked to list their top three challenges with high tunnel production. The authors grouped the challenges into the following broad categories: Environmental control issues (heating and cooling), pest management issues (weeds, insects, diseases, and vertebrate pests) and plant nutrition and soil fertility issues. Forty-four percent of respondents listed challenges in the environmental control category with excess heat and lack of ventilation as the most common concern. Pest management issues were the top challenge for 22% of growers, while 15% listed concerns that fell into the soil fertility

and plant nutrition category. Grower challenges with crop scheduling and determining rotations were the fourth most common listed issue.

Survey participants were asked to select from a menu of common sources of high tunnel information. The top three sources included: Other farmers (61%), trade publications (52%) and county or state extension services at 48%. When asked to rank seven broad categories according to area of greatest need for information, growers selected information on growing specific crops as the most pressing (33% of respondents) with pest management, nutrient management and marketing essentially tied for second most important topic.

Montana high tunnel growers face challenges associated with climate and access to regionally appropriate expertise. Through the use of a high tunnel grower's survey, the authors identified areas of interest to focus a research agenda, specifically addressing managing the high tunnel environment, especially the use of secondary row covers, weed management and trialing crops suitable for cool season production.

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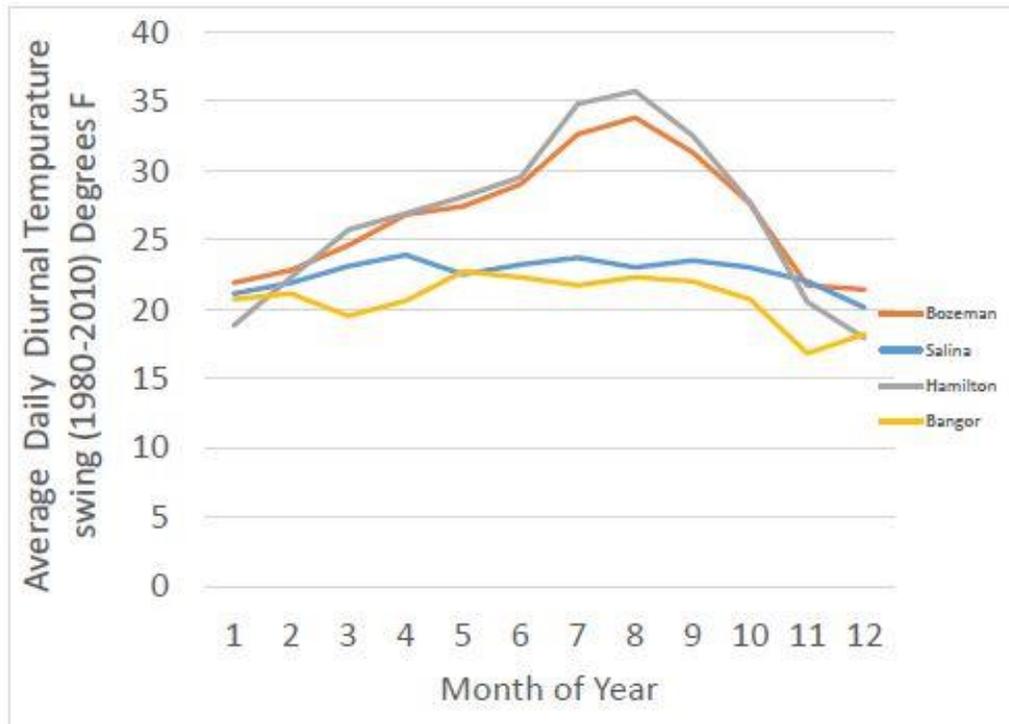


Figure 2.1. Comparison of monthly average diurnal temperature fluctuations at two Montana locations (Bozeman and Hamilton) with Salina, KS and Bangor, ME. The Kansas and Maine locations reflect areas referenced in Knewton et al., 2010 and Fitzgerald and Hutton, 2012. Temperature data from the National Climatic Data Center.

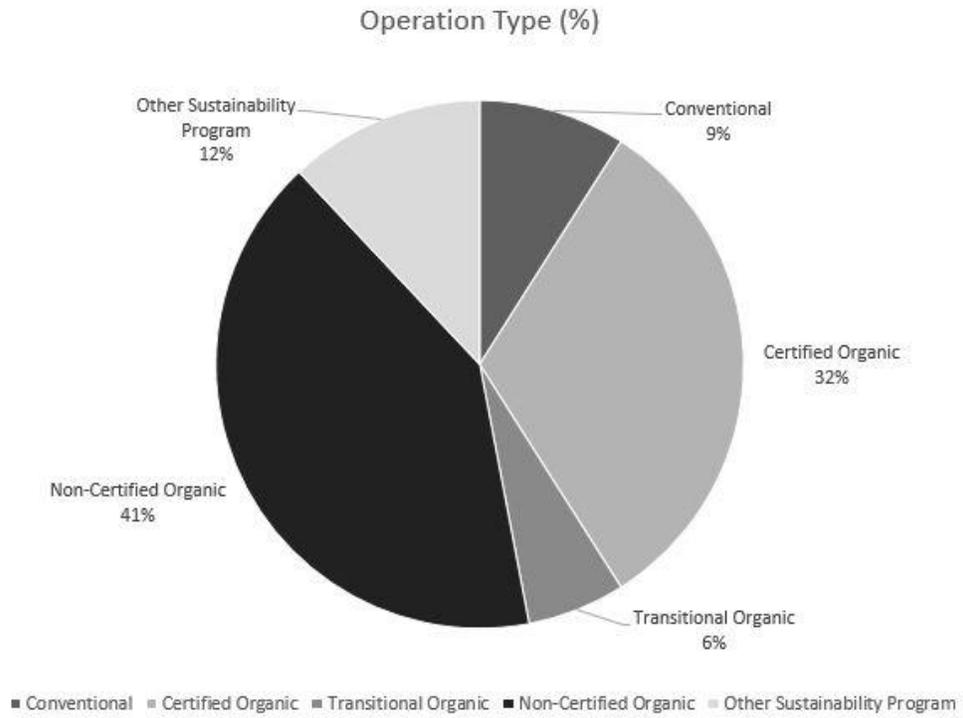


Figure 2.2. Montana high tunnel grower survey participants self-identify by production system.

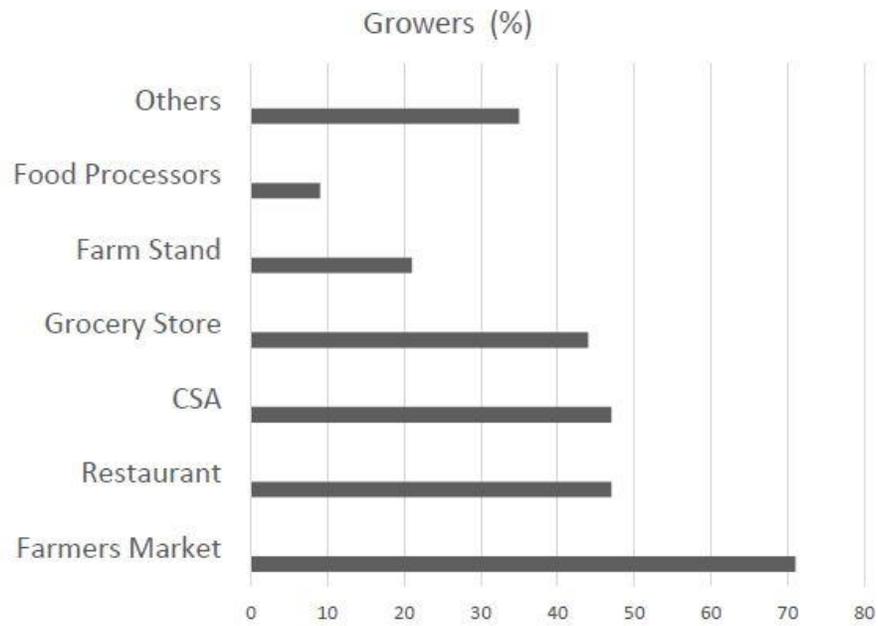


Figure 2.3. Montana high tunnel grower survey participants reported on their top three markets. Other markets include: custom orders, wholesaler distributors and barter.

CHAPTER THREE

ROW COVER INFLUENCES LIGHT TRANSMISSION, AIR AND SOIL  
TEMPERATURES IN THE HIGH TUNNEL  
DURING SPRING AND FALL

Contribution of Authors and Co-Authors

Manuscript in Chapter Three

Author: David A. Baumbauer

Contributions: Designed the study, interpreted the results and wrote the manuscript

Co-Author: Macdonald H. Burgess

Contributions: Managed the data logger, discussed results and implications and edited earlier manuscripts.

Manuscript Information

David A. Baumbauer and Macdonald H. Burgess

Journal of Agricultural and Forest Meteorology

Status of Manuscript:

- Prepared for submission to a peer-reviewed journal
- Officially submitted to a peer-reviewed journal
- Accepted by a peer-reviewed journal
- Published in a peer-reviewed journal

Elsevier

Keywords: season extension, growing degree hours, soil degree hours, daily light integral

## Abstract

To assist high tunnel growers on cool season crop scheduling and when row cover deployment is warranted, hourly averages of photosynthetically active radiation (PAR), air and soil temperatures were recorded at four locations: outside, outside under row cover, inside the high tunnel and inside the high tunnel under row cover. Growing degree hours (GDH), soil degree hours (SDH), and daily light integral (DLI) were calculated from the hourly averages. GDH and SDH were highest in the high tunnel plus row cover location for both months, but DLI was the lowest with the two layers blocking 46% of the light in April and 56% in October. GDH and SDH were more positively influenced by the addition of row cover in the high tunnel in April than October. Outside plus row cover and high tunnel without row cover were similar in GDH, SDH and DLI, except when the outside plus row cover was covered in snow, moderating temperature fluctuation and greatly lowering DLI. This information may be used by high tunnel producers to make management decisions regarding crop scheduling and row cover deployment when growing in the shoulder seasons.

## 1.1 Introduction

Vegetable farmers in the northern United States depend on high tunnels and poly spun bond row covers to protect crops from cold temperature damage and extend the growing season (Birnbaum, 2013; Blomgren and Frisch, 2007; Coleman, 2009; Fortier and Bilodeau, 2014). As demand for local food increases, more northern tier high tunnel growers are producing crops in the ‘shoulder seasons’ of early spring and late fall. To

moderate cold air temperatures, 94% of surveyed Montana high tunnel growers also utilize spun-bonded row covers within their high tunnels (Baumbauer, 2019).

Temperature dictates rate of development while light energy dictates above ground biomass production (Heins et al., 1998; Krug, 1991; Liu and Heins, 2002). Table 3.1 lists the long term (1981-2010) average monthly daily light integral (DLI) and average daily and average minimum air temperature for the shoulder season months of March-May and September-November in Bozeman, MT (45.6770° N, 111.0429° W, elevation 1491 meters). The temperature data was collected from a weather station located on the Montana State University campus, 1.7 km east of the study site ([www.ncdc.noaa.gov](http://www.ncdc.noaa.gov)).

Table 3.1. Average monthly daily light integral (DLI) and minimum and average air temperatures for spring and fall months in Bozeman, MT.

	March	April	May	September	October	November
DLI (mol m <sup>-2</sup> d <sup>-1</sup> ) <sup>a</sup>	24.6	36.3	43.1	32.8	20.9	11.3
Min. temperature (°C) <sup>b</sup>	-4.9	-1.1	3.3	5.0	-0.1	-5.8
Ave. temperature (°C) <sup>b</sup>	1.9	6.3	7.6	13.7	7.6	0.3

<sup>a</sup>. U.S. Daily Light Integral Map (Logan and Faust, 2018)

<sup>b</sup>. [www.ncdc.noaa.gov](http://www.ncdc.noaa.gov)

April and October are transition months, as night time temperatures below freezing become less common after April and more common after September. While the monthly average and minimum air temperatures are similar for April and October, April has far more light energy, with an average DLI 15.4 mol m<sup>-2</sup> d<sup>-1</sup> greater than October.

High tunnels moderate low outside air temperatures, especially during daylight hours by trapping solar radiation. High tunnel air temperatures can be 10°C to 30°C higher during the day and up to 5°C warmer at night (Wien, 2008). However, during

clear nights air temperature within the high tunnel may drop below outside air temperature due to long wavelength radiative heat loss through the polyethylene plastic film (Ogden et al., 2009; Wien, 2008). The type of plastic film and the number of layers used to cover the high tunnel impacts the amount of heat retention, Ward and Bomford reported that a high tunnel in Kentucky covered with two layers of infrared reflecting greenhouse film provided 4.3°C of frost protection and elevated the daily minimum air temperature up to 7.4°C (Ward and Bomford, 2011).

A layer of row cover suspended above the crop canopy in the high tunnel offers additional night time heat retention. When air in the high tunnel cools, condensation forms on the row cover helping to trap long wave radiant energy emitted by plants and soil (Biernbaum, 2013). Wien et al. reported that the night time air temperature in late April was 10°F warmer under row cover in a Pennsylvania high tunnel when compared to the high tunnel alone (Wien, 2008). Drost et al. reported that the temperature under a row cover deployed in a Northern Utah high tunnel was 3°C to 5°C warmer at night than in the high tunnel without row cover during the period of October through March (Drost et al., 2017). Ward and Bomford reported an additional 3.1°C of frost protection and 4.9°C elevated daily minimum air temperature under the row cover in a high tunnel on the coldest monitoring days (Ward and Bomford, 2011).

Soil temperature can have a significant effect on the growth rate of plants with a growing point at or near the soil surface. Wurr et al. reported that the mean soil temperature was closely related to the early relative growth rate of Butterhead lettuce while mean air temperature was not related (Wurr et al., 1981). Salomez and Hofman

developed an accurate predictive model for greenhouse grown Butterhead lettuce based on soil temperature and short-wave radiation (Salomez and Hofman, 2007).

Light intensity and duration are typically less than ideal for plant growth in the early spring and fall season for northern latitude vegetable growers. High tunnels block from 35% to 65% of the incoming solar radiation depending on the seasonal sun angle, type and age of plastic film, and high tunnel structure material (Biernbaum, 2013; Blomgren and Frisch, 2007; Coleman, 2009; Faust and Logan, 2018). Poly-spun row covers transmit 65%-85% of light depending on seasonal sun angle, dust accumulation and water vapor condensation on the inner surface (Gimenez et al., 2002). When used together, the combination of high tunnel and row cover can greatly reduce the light energy at the crop level.

Glenn et al reported the light compensation point for lettuce and spinach was less than  $1 \text{ mol m}^{-2} \text{ d}^{-1}$ , but a minimum of  $8 \text{ mol m}^{-2} \text{ d}^{-1}$  was required to produce market quality heads (Glenn et al., 1984). Lower light intensity impacts leafy crops such as spinach and lettuce by increasing crop production time (Torres and Lopez, 2010). Leafy greens grown under lower light intensities are often etiolated and have thinner leaves with a larger leaf area index (LAI) (Gimenez et al., 2002; Glenn et al., 1984) and may also develop higher leaf nitrate and oxalate acid levels, which are harmful phytochemicals (Bian et al., 2015). Without the addition of supplemental lights, northern latitude high tunnel growers depend on growing low light tolerant varieties, increasing crop spacing to reduce light competition and scheduling crops to produce much of their

above ground growth before the DLI drops below a critical level (Coleman, 2009; Nelson, 2012).

The objective of this study was to determine the effect greenhouse grade polyethylene plastic film and spun-bonded polypropylene row cover have on PAR levels, air and soil temperatures during the shoulder season months of April and October in a northern latitude, high elevation location such as Bozeman, MT. Impacts caused by season extension on DLI, growing degree hours (GDH) and soil degree hours (SDH) may be used by producers to make management decisions regarding which species to grow, crop scheduling and when to deploy row cover within the high tunnel.

## Materials and Methods

### 2.1 Site description

The Season Extension Research Program (SERP) site is located at the Montana State University Horticulture Farm in Bozeman, Montana, and consists of six 9 meter by 14.6 meter blocks. Three 9 meter wide by 14.6 meter long rolling high tunnels (Premium Round Style, FarmTek, South Windsor, CT) were constructed during September and October of 2014. The tunnels feature rollup side walls for ventilation, and a single layer of greenhouse grade 6-mil (0.15 mm) polyethylene film plastic glazing. End wall gable ventilation was added before the 2017 season in the form of 0.58 m<sup>2</sup> aluminum shutters operated by Univent automatic openers (Nolt's Greenhouse Supply, Ephrata, PA). The high tunnels were installed in a staggered fashion to minimize shading of an adjacent high tunnel.

The planting area in each rolling high tunnel consisted of six beds, 75 cm wide by 12 meters long with 45 cm walkways between beds. Half of the beds in each high tunnel were randomly assigned to be covered with AGRIBON-19 ploy spun bond row cover (Berry Plastics, San Luis Potosí, Mexico), supported ~ 50 cm above the soil surface by wire frames. The manufacturer states that AGRIBON-19 is rated to provide 4°F of frost protection while transmitting 85% of sunlight. A similar row cover set-up was constructed outside the high tunnel in order to compare the effect of row cover only on light and temperature.

## 2.2 Micrometeorological instrumentation

Hourly average air temperature, soil temperature, and photosynthetic photon flux density (PPFD) were calculated from measurements made every 60 seconds using a Campbell Scientific CR-1000 data logger (Logan, UT) connected to the sensors described in Table 3.2. Air temperature and PAR sensors were mounted approximately 45 cm above the soil surface. Soil temperature was measured at a depth of 10 cm. Hourly averages of PPFD, air and soil temperatures were recorded for the following locations: Outside (O), outside under row cover (OR), inside the high tunnel (I) and inside the high tunnel under row cover (IR).

Table 3.2. Sensors used to measure micrometeorological parameters.

Device	Sensing	Units
Thermistor Temperature Sensor (Apogee ST-110) Housed within an Aspirated Radiation Shield (Apogee TS-110)	Air Temperature	°C
12 cm Soil Water Content Reflectometer (Campbell Scientific CS 655)	Soil Temperature	°C
Sun Calibration Quantum Sensor (Apogee SQ-110)	PPFD	$\mu\text{mols}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$

### 2.3 Data analysis

April and October were chosen for the study as they are two critical months for growers making row cover deployment decisions, with an average minimum night air temperature near the freezing mark (table 3.1) which might justify the addition of row cover in the high tunnel. The study was conducted from April 2016 through May 2018, for a total of three Aprils and two Octobers. Analysis was performed using R and R studio statistical software.

By averaging the temperature and PPFD readings for each hour of each day of selected weeks, composite day plots were constructed to represent a ‘typical’ day for each week. Composite day plots smooth out the variation in temperature and PPFD due to passing clouds and storm fronts and provides a clearer representation of the impact each of the layers of season extension is having on temperature and PPFD at the crop level and when those changes are occurring. Growing degree hours (GDH) and soil degree hours (SDH) were calculated from the hourly average air and soil temperatures using the method described by Gu (Gu, 2016) . GDH delivers a more accurate representation of heat accumulation during prolonged periods when the temperature is below the base temperature than the more commonly reported growing degree day (Gu, 2016). For this study, a 4°C base air temperature and 0°C base soil temperature were chosen, which represent common base temperatures for many cool season vegetable crops (Maynard and Hochmuth, 1997).

## Results and Discussion

### 3.1 April 1<sup>st</sup>-7<sup>th</sup> air and soil temperatures

The average air temperature during the first week of April in 2016 and 2017 was 2.7°C and 0.9°C warmer than the long term average of 4.7°C for that week (www.ncdc.noaa.gov). Conversely the first week of April in 2018 was -6.4°C below average. Table 3.3 lists weekly average air and soil temperatures for outside, outside under row cover, inside the high tunnel, and inside the high tunnel under row cover for the first weeks of April 2016-2018.

Table 3.3. Average air and soil temperatures for April 1<sup>st</sup>-7<sup>th</sup>, 2016-2018 for outside, outside under row cover (RC), inside the high tunnel and inside the high tunnel under row cover. MSU Horticulture Farm, Bozeman, MT

<b>Location</b>	<b>April 1-7, 2016 (°C)</b>	<b>April 1-7, 2017 (°C)</b>	<b>April 1-7, 2018 (°C)</b>
Outside Air	7.4	5.6	-2.6
Outside Air w/ RC	9	6.3	0.6
Inside Air	8.1	7.3	3.3
Inside Air w/RC	10.3	9.5	7
Outside Soil	7.7	7.3	1.3
Outside Soil w/RC	8.9	8.2	3.4
Inside Soil	10.1	10.7	8.2
Inside Soil w/ RC	11	10.7	9.5

Outside under row cover average air temperatures for the first week of April were 0.7°C to 3.2°C warmer than outside air temperatures, with the greatest increase in 2018 when outside air temperature was the lowest of the three sampling periods. High tunnel air temperature ranged 0.7° to 5.9°C above outside, the same to slightly warmer than outside with row cover, with 2018 again recording the largest positive temperature difference. Adding row cover inside the high tunnel increased weekly average air temperatures from 2.9°C in 2016 to 9.6°C above outside in 2018. The lower the outside

air temperature, the greater the positive, differential air temperature under the various layers of season extension, with the increase being more than an additive effect when combining row cover use in the high tunnel. Since April 2018 had the greatest differences between outside temperatures and the various layers of season extension, this sampling period will be the focus of the rest of the results and discussion section dealing with spring conditions.

The graph of the composite air temperature for April 1<sup>st</sup>-7<sup>th</sup>, 2018 (figure 3.1) illustrates the increase in air temperature in the high tunnel under row cover. The second layer is critical at night as the high tunnel with row cover was the only treatment to be consistently warmer than the single layer treatments. There is little difference in night time temperatures of outside with row cover and high tunnel treatments.

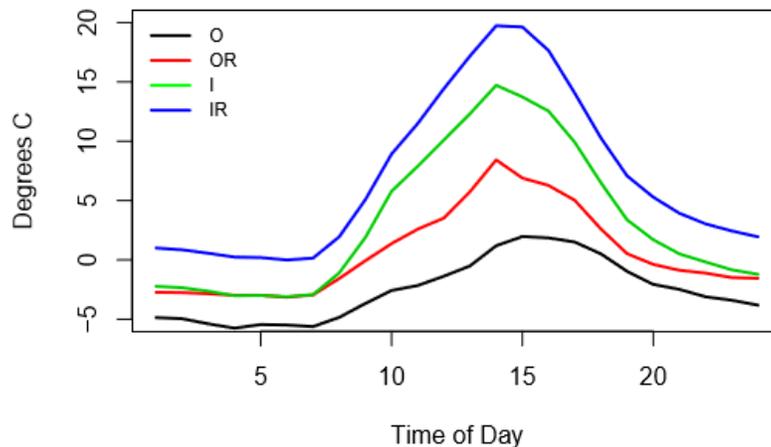


Figure 3.1. Composite air temperatures for outside (O), outside under row cover (OR), inside the high tunnel (I) and inside the high tunnel under row cover (IR) for April 1<sup>st</sup>-7<sup>th</sup>, 2018. MSU Horticulture Farm. Bozeman, MT

Soil temperatures were slightly warmer under all forms of season extension but there was little difference between the high tunnel and the high tunnel with row cover in 2016 and 2107, years with mild air temperatures in April. Conversely in the much colder

April 2018, the high tunnel with row cover treatment increased soil temperature over the high tunnel alone by 1.3°C and 8.2°C above outside soil temperature (figure 3.2).

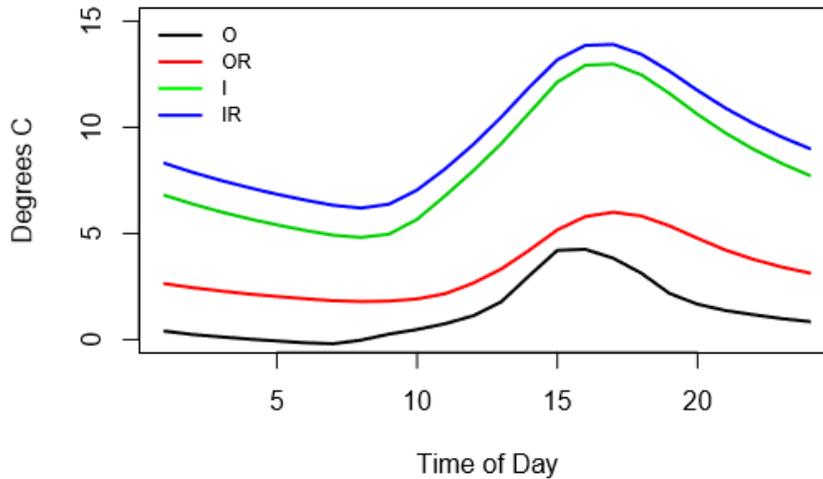


Figure 3.2. Composite soil temperatures for outside (O), outside under row cover (OR), inside the high tunnel (I) and inside the high tunnel under row cover (IR) for April 1<sup>st</sup>-7<sup>th</sup>, 2108. MSU Horticulture Farm. Bozeman, MT.

### 3.2 October 1<sup>st</sup>-7<sup>th</sup> air and soil temperatures

The first week of October 2106 and 2107 were -3.4°C and -5.9°C respectively below the weekly average of 10°C, respectively ([www.ncdc.noaa.gov](http://www.ncdc.noaa.gov)). Table 3.4 lists weekly average air and soil temperatures for outside, outside under row cover, inside the high tunnel, and inside the high tunnel under row cover for the first weeks of October 2016 and 2107.

Row cover averaged 0.5°C and 1.2°C warmer than outside air temperature during the first week of October 2016 and 2017 respectively. High tunnel averages were slightly warmer at 0.8°C and 2.1°C above outside. The trend of high tunnel plus row cover having a greater positive influence on air temperature as outside temperature decrease continued during October 1<sup>st</sup>-7<sup>th</sup> in 2017.

Table 3.4 Average air and soil temperatures for October 1<sup>st</sup>-7<sup>th</sup>, 2016-2017 for outside, outside under row cover (RC), inside the high tunnel and inside the high tunnel under row cover. MSU Horticulture Farm, Bozeman, MT

Location	October 1-7, 2016 (°C)	October 1-7, 2017 (°C)
Outside Air	6.6	4.1
Outside Air w/ RC	7.1	5.3
Inside Air	7.4	6.2
Inside Air w/RC	8.9	8.7
Outside Soil	8.8	6.8
Outside Soil w/RC	11.3	9.8
Inside Soil	10.2	9.5
Inside Soil w/ RC	11.8	11.4

Since October 2107 had the greatest differences between outside temperatures and season extension temperatures, it will be the focus of the results and discussion section dealing with fall conditions.

Figure 3.3 is a graph of the composite air temperature for the week of October 1<sup>st</sup>-7<sup>th</sup>, 2017 and illustrates the night time heat retention afforded by a second layer. There is little night time air temperature difference between outside, outside plus row cover and inside the high tunnel.

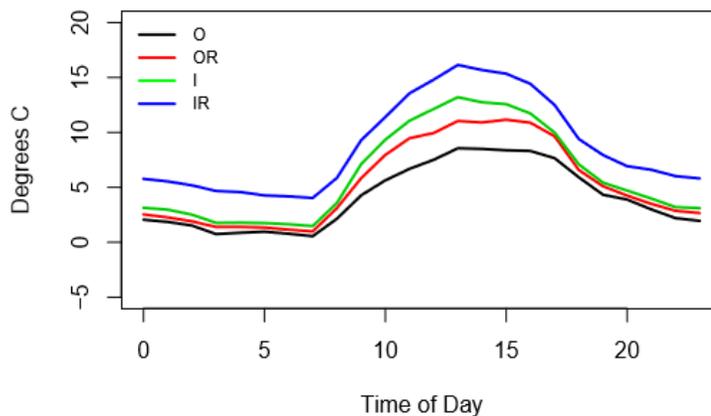


Figure 3.3. Composite of air temperatures for outside (O), outside under row cover (OR), inside the high tunnel (I) and inside the high tunnel under row cover (IR) for October 1<sup>st</sup>-7<sup>th</sup>, 2017. MSU Horticulture Farm. Bozeman, MT

There was little difference in soil temperature between outside plus row cover and high tunnel (figure 3.4) both were  $\sim 3^{\circ}\text{C}$  warmer than the outside soil. The addition of row cover in the high tunnel raised average soil temperature  $4.6^{\circ}\text{C}$  above outside and  $1.9^{\circ}\text{C}$  above the high tunnel alone. While not as great an increase as in April, figure 3.4 illustrates the additional soil heat retention contributed by the second layer.

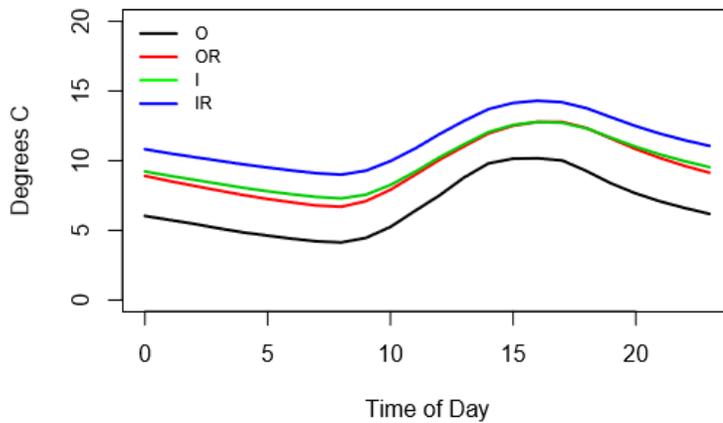


Figure 3.4. Composite of soil temperatures for outside (O), outside under row cover (OR), inside the high tunnel (I) and inside the high tunnel under row cover (IR) for October 1<sup>st</sup>-7<sup>th</sup>, 2017. MSU Horticulture Farm. Bozeman, MT

### 3.3 The effect of high tunnel plus row cover on air and soil temperature

The positive influence on air temperature in the high tunnel plus row cover is greater as the outside temperature decreases. Figure 3.5 is a scatterplot of the differential air temperature minus outside air temperature (y-axis) vs. outside air temperature (x-axis) for April 2018. Red dots indicate day time readings and blue triangles indicate night time readings. Values above the horizontal line indicate when the average hourly air temperature was warmer in the high tunnel under row cover than outside. For example, on April 3<sup>rd</sup> the 3-4am outside air temperature averaged  $-18.6^{\circ}\text{C}$ , while air temperature in the high tunnel under the row cover was  $13.9^{\circ}\text{C}$  warmer than outside and  $5.5^{\circ}\text{C}$  warmer

than the high tunnel alone. The few readings below the horizontal line illustrate the lag time in heating in the high tunnel plus row cover location when a warm front passed through, especially during evening hours.

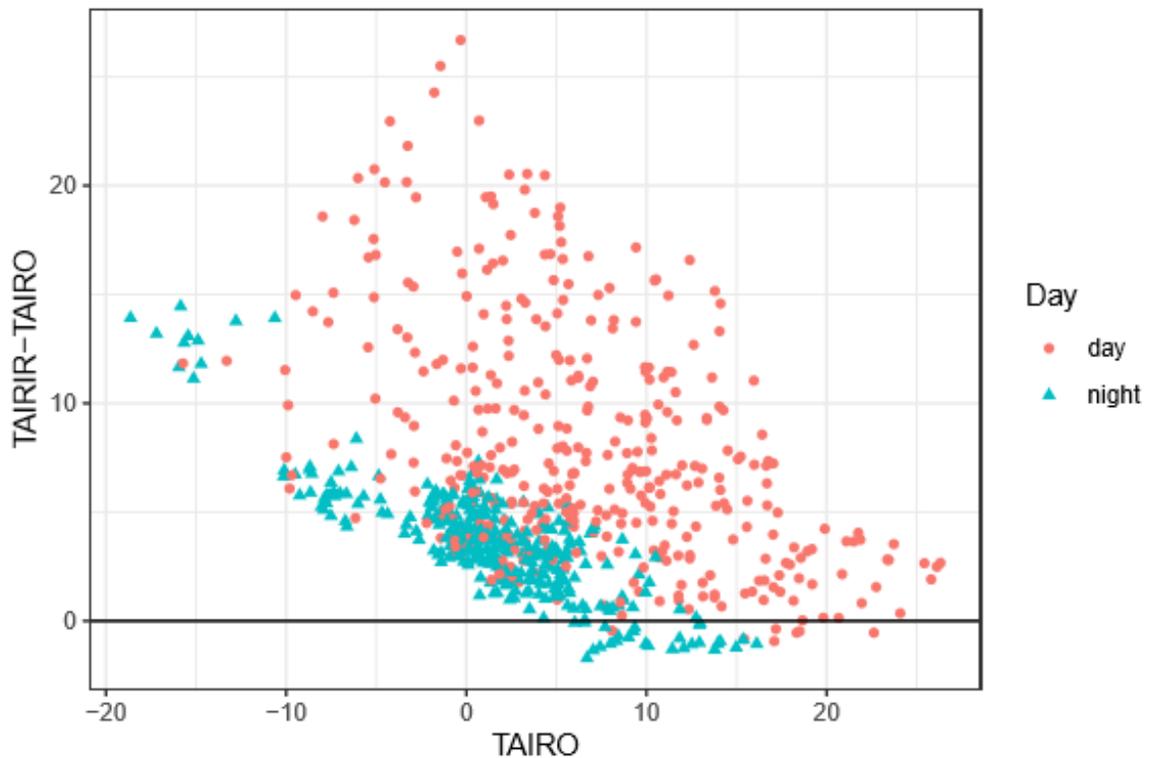


Figure 3.5. Differential air temperature between inside the high tunnel under row cover (TAIRIR) and outside (TAIRO) vs. outside air temperature. Red dots are day time (PPFD > 20  $\mu\text{mol s}^{-1} \text{m}^{-2}$ ) hour average air temperatures and blue triangles are night time hourly average air temperatures for April 2018. Horizontal line indicates no air temperature difference between locations. MSU Horticulture Farm, Bozeman, MT.

Soil temperature in the high tunnel responded in a similar fashion, when outside soil temperature was 0°C, soil temperature in the high tunnel under row cover was 4°C to 13°C warmer at night (figure 3.6). The wide range in high tunnel plus row cover soil temperature differences when outside soil temperature is near 0°C reflects the phase change as water transitions from solid to liquid in the outside location, as energy that

would raise soil temperature under dry conditions is used to freeze and thaw water in the soil (Bonan, 2015).

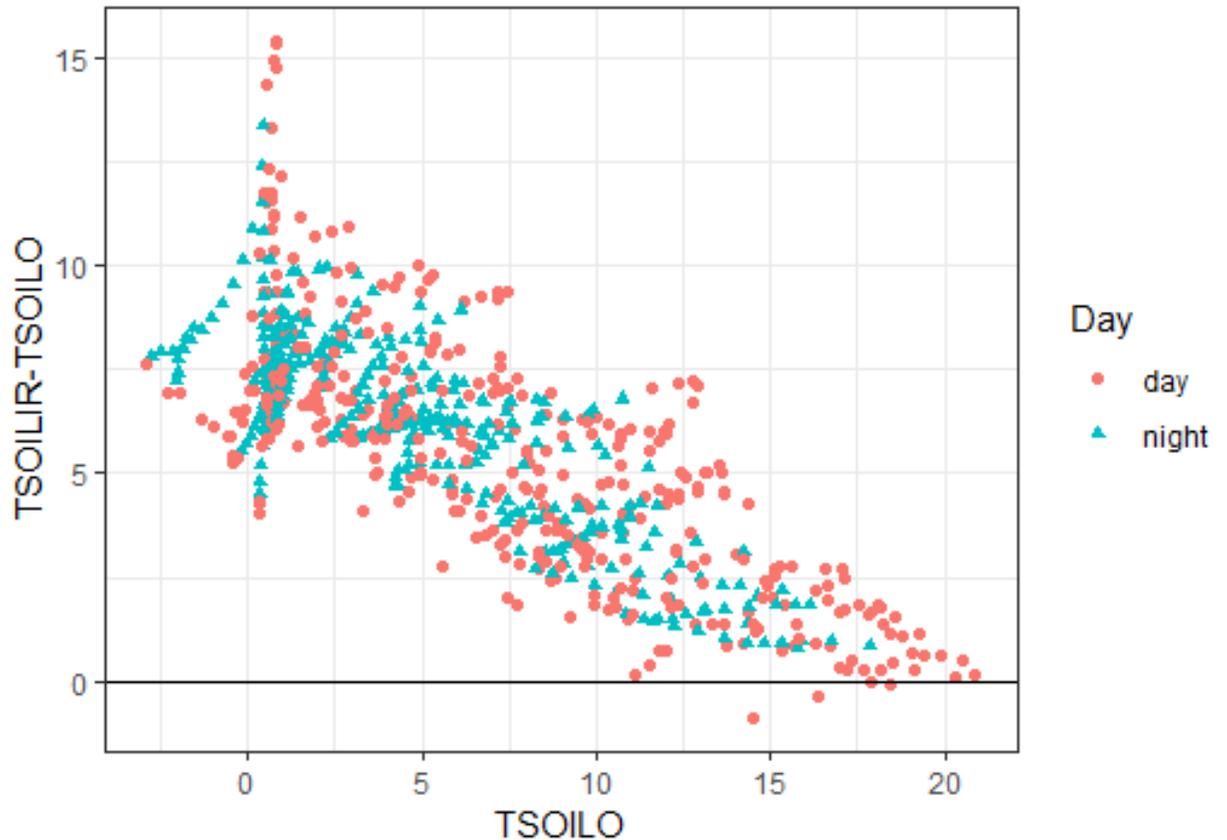


Figure 3.6 Differential soil temperature between inside the high tunnel under row cover (TSOILIR) and outside (TSOILO) vs. outside soil temperature. Red dots are day time hour average soil temperatures and blue triangles are night time hourly average soil temperatures for April 2018. Horizontal line indicates no soil temperature difference between locations. MSU Horticulture Farm, Bozeman, MT.

### 3.4 April growing degree hours and soil degree hours

Growing degree hours (GDH) and soil degree hours (SDH) provide a measure of the contribution of row cover and high tunnel on the accumulation of heat above the base temperature where growth ceases. For many cool season crops, such as leafy greens, 4°C is a suitable base temperature for above ground growth and 0°C for below ground

(Borrelli et al., 2013). Figure 3.7 illustrates GDH for April 2016, 2017, and 2018 for outside, outside under row cover, inside the high tunnel and inside the high tunnel under row cover at a 4°C base temperature. Despite vastly different GDH for outside and single layer treatments over the three years, the addition of a second layer in the high tunnel resulted in similar GDH accumulation regardless of year. Outside plus row cover and high tunnel GDH averaged 30% and 33% higher respectively than outside GDH. The high tunnel plus row cover averaged 78% greater GDH accumulation than outside and 34% more than the high tunnel alone.

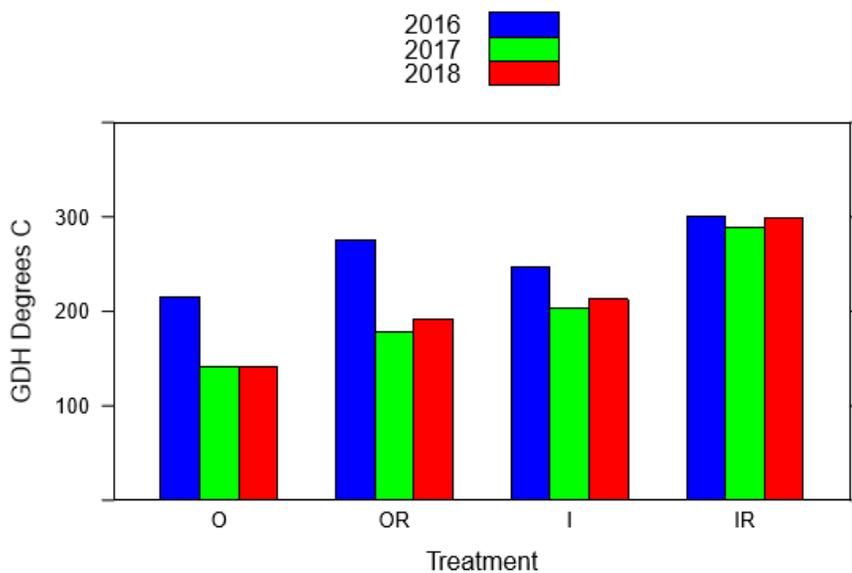


Figure 3.7. Growing Degree Hours (Base 4°C) for outside (O), outside under row cover (OR), inside the high tunnel (I) and inside the high tunnel under row cover (IR) for April 2016, 2107 and 2108. MSU Horticulture Farm, Bozeman, MT.

Both high tunnel and high tunnel plus row cover treatments resulted in similar SDH accumulation over the three years, with the high tunnel plus row cover having slightly higher SDH (figure 3.8).

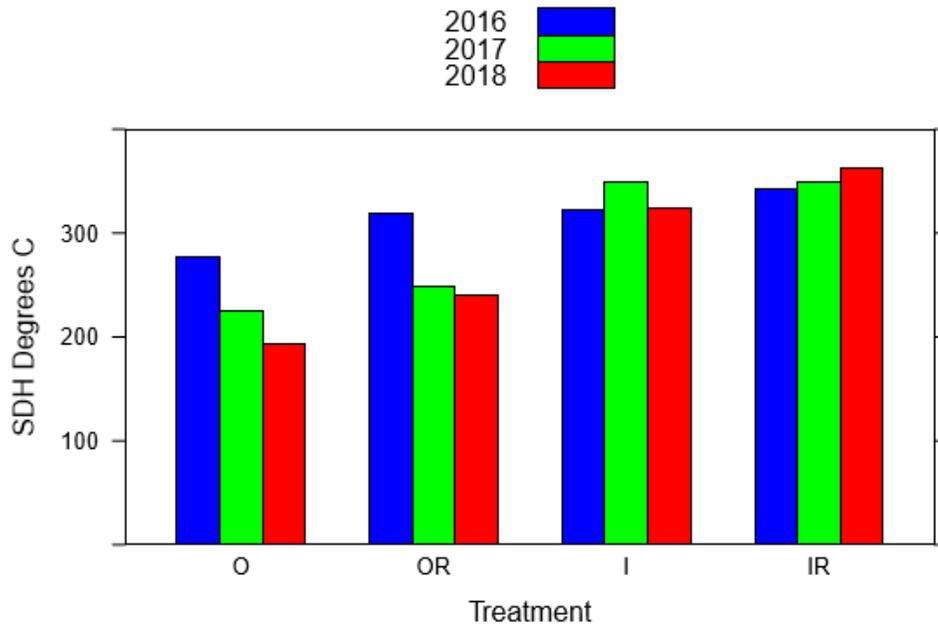


Figure 3.8. Soil Degree Hours (Base 0°C) for outside (O), outside under row cover (OR), inside the high tunnel (I) and inside the high tunnel under row cover (IR) for April 2016, 2107 and 2108. MSU Horticulture Farm. Bozeman, MT.

### 3.4 October Growing Degree Hours and Soil Degree Hours

October 2016 had considerably greater GDH accumulation than October 2107, but the difference between the years shrank under the high tunnel plus row cover treatment (figure 3.9). The positive influence on GDH accumulation under single and double layers was less in October than April, averaging a 6% increase under row cover, 11% increase in the high tunnel and a 30% increase the high tunnel under row cover. The difference between GDH gains under season extension layers in April vs. October can be attributed to less solar heating due to a lower DLI in October than April.

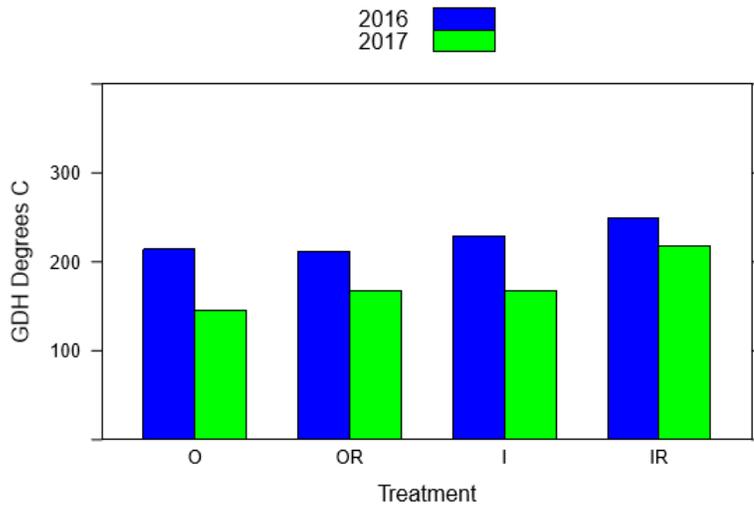


Figure 3.9. Growing Degree Hours (Base 4°C) for outside (O), outside under row cover (OR), inside the high tunnel (I) and inside the high tunnel under row cover (IR). October 2016 and 2017. MSU Horticulture Farm, Bozeman, MT.

Except for outside under row cover (with a 29% increase), October SDH accumulation was also lower than April (figure 3.10), with an average increase of 30% for the high tunnel alone and a 45% in the high tunnel plus row cover. The 2017 SDH total was slightly higher than the 2016, despite having a much lower outside SDH accumulation.

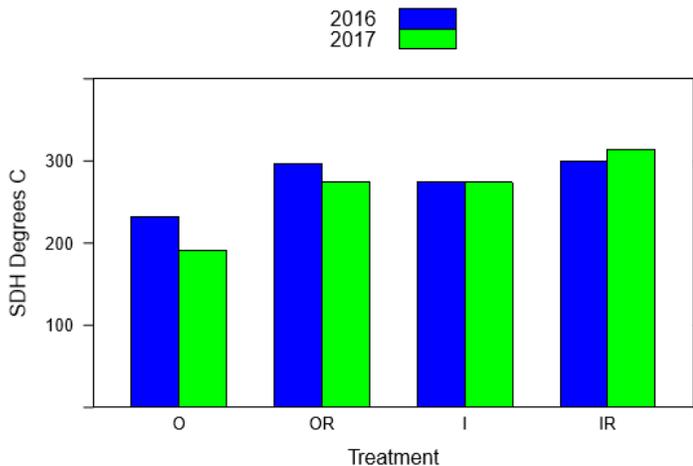


Figure 3.10. Soil Degree Hours (Base 0°C) for outside (O), outside under row cover (OR), inside the high tunnel (I) and inside the high tunnel under row cover (IR). October 2016 and 2017. MSU Horticulture Farm, Bozeman, MT.

### 3.5 Row cover and high tunnel reduction in PPFD and DLI

Unlike with heat accumulation, there is no commonly reported long term measurement for photosynthetic photon flux density (PPFD) besides the daily light integral (DLI), therefore results and discussion will concentrate on influences on PPFD and DLI for the first weeks of April 2108 and October 2107. These sampling periods are both approximately 10 days past the equinox and illustrate the rapidly changing levels in PAR that northern latitude growers face. Figure 3.11 is a composite day derived from hourly average PPFD levels for April 1<sup>st</sup>-7<sup>th</sup>, 2018, and depicts the impact that snow has on PPFD levels on the outside under row cover location. Accumulating snow fell on April 2<sup>nd</sup>, 2018 and stuck on the outside plus row cover location while sliding off the slick surface of the high tunnel. DLI levels were lower under the outside plus row cover location than in the high tunnel for the remainder of the week. Figure 3.12 displays the DLI for the first week of April 2108 and shows that DLI levels were above the threshold at all locations besides outside plus row cover for cool season crop growth.

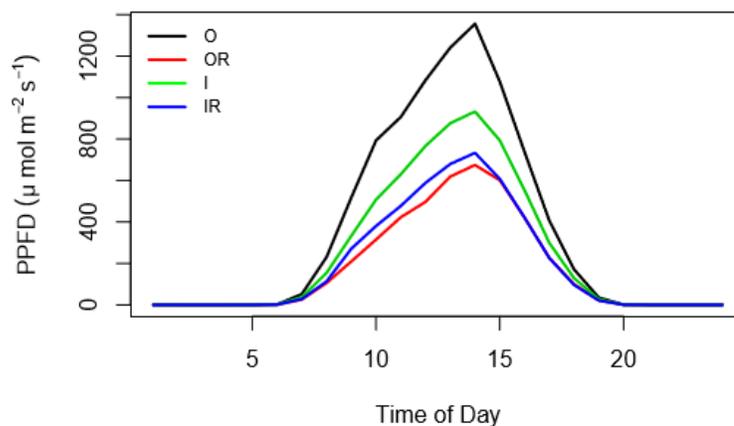


Figure 3.11. Composite PPFD for outside (O), outside under row cover (OR), inside the high tunnel (I) and inside the high tunnel under row cover (IR) for the week of April 1<sup>st</sup>-7<sup>th</sup>, 2018. MSU Horticulture Farm, Bozeman, MT.

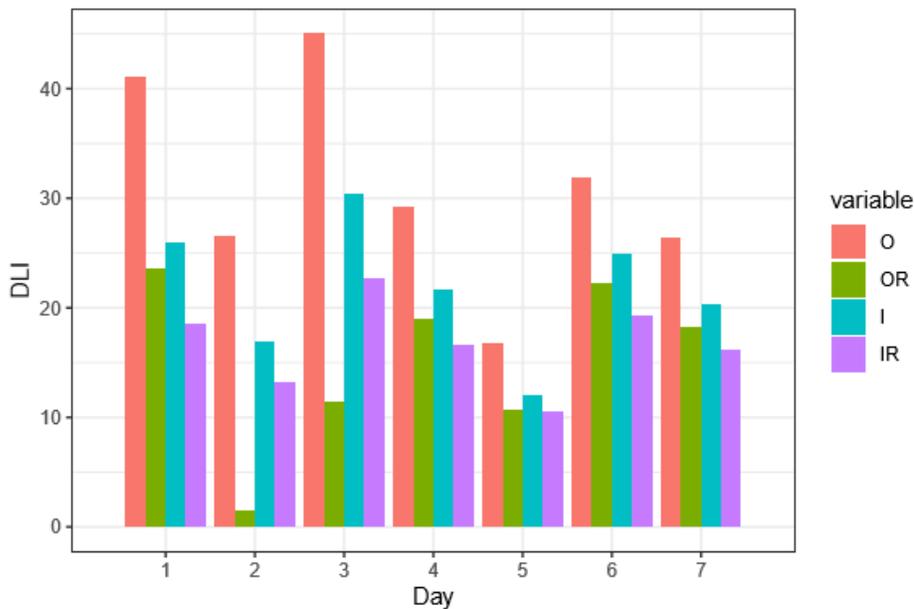


Figure 3.12. DLI for outside (O), outside plus row cover (OR), inside the high tunnel (I), and inside the high tunnel plus row cover (IR) for April 1<sup>st</sup>-7<sup>th</sup>, 2018. MSU Horticulture Farm, Bozeman, MT.

Figure 3.13 illustrates the composite day of PPFD for the first week of October 2107 and depicts the reduction in light energy after the autumnal equinox. Average outside PPFD level is ~73% of the first week of April, and the percentage of PAR passing through high tunnel plus row cover drops from 54% in April to 44% in October. The dip in PPFD in the early afternoon was due to shading from a small outbuilding housing the data logger.

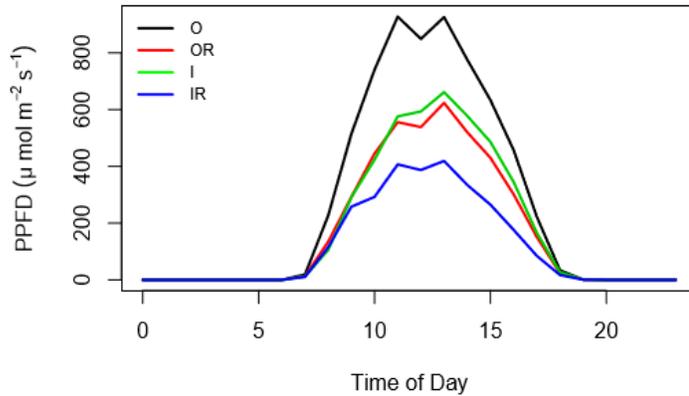


Figure 3.13. Composite PPFD for outside (O), outside under row cover (OR), inside the high tunnel (I) and inside the high tunnel under row cover (IR) for October 1<sup>st</sup>-7<sup>th</sup>, 2017. MSU Horticulture Farm, Bozeman, MT.

PAR levels were also impacted by accumulating snow during the first week of October, reducing DLI (figure 3.13). An October 2<sup>nd</sup>, 2017 snow storm deposited snow on the outside plus row cover location, reducing DLI below the high tunnel location for the rest of the week.

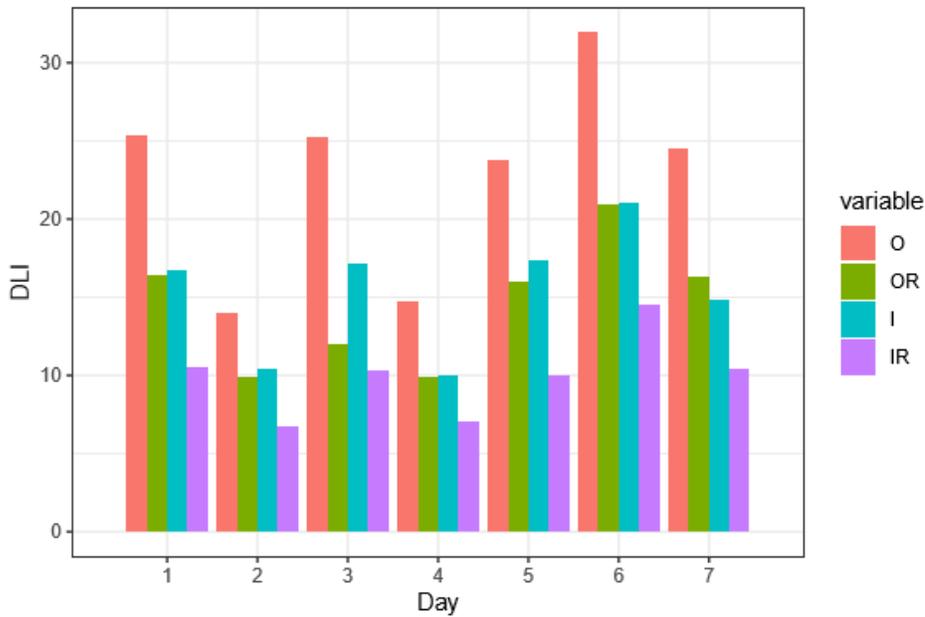


Figure 3.14. DLI for outside, outside plus row cover, inside the high tunnel, and inside the high tunnel plus row cover the week of October 1<sup>st</sup>-7<sup>th</sup>, 2017. MSU Horticulture Farm, Bozeman, MT.

#### 4.1 Conclusion

Trade publications and the popular gardening press often extol fall as “the second spring” (Coleman, 2008; Luckhurst, 2015) and while the average air and soil temperatures may be similar, the disparity in DLI between the two months not only results in lower photosynthesis rates in October, but lower heat accumulation under layers of season extension. April high tunnel and high tunnel plus row cover GDH and SDH had greater gains than similar locations in October.

The positive contribution of both air and soil heat retention afforded by the addition of row cover in the high tunnel was greater as the outside temperature dropped. However, this additional heat retention came at the expense of lower light levels. PPFD levels in the high tunnel under the row cover averaged 54% of outside early April levels and 44% of outside early October levels. In this study the row covers were not removed from the planting beds on sunny days and that would be an area for future research. If gains in DLI were found, then a process to speed the installation and removal of row covers should be developed to make this procedure less labor intensive.

The outside plus row cover location often had similar heat retention and PAR levels as the high tunnel. This benefit is achieved at a fraction of the cost of a high tunnel. Prolonged snow cover on the row cover can be both positive and negative, as the snow insulates the area under the row cover from low outside air temperatures but also greatly reduces PAR levels until it melts.

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CHAPTER FOUR

SEASON, SOWING DATE, AND ROW COVER INFLUENCE  
THE PRODUCTION OF COOL SEASON VEGETABLES  
IN THE MOVEABLE HIGH TUNNEL

Contribution of Authors and Co-Authors

Manuscript in Chapter 4

Author: David A. Baumbauer

Contributions: Conceived of study, performed the analysis, and wrote the manuscript

Co-Author: MacDonald H. Burgess

Contributions: Discussed results and edited the manuscript

Manuscript Information

David A. Baumbauer and Macdonald H. Burgess

Canadian Journal of Plant Science

Status of Manuscript: [Put an x in one of the options below, delete this]

Prepared for submission to a peer-reviewed journal

Officially submitted to a peer-reviewed journal

Accepted by a peer-reviewed journal

Published in a peer-reviewed journal

Canadian Science Publishing

## Season, Sowing Date and Row Cover Influences the Production of Cool Season

### Vegetables in the Moveable High Tunnel

#### Abstract

Spring and fall crops of three leafy greens and three root crops were grown in moveable high tunnels to determine the effect that seeding date and the addition of row cover would have on fresh weight and days to harvest (DTH). Using row cover within the high tunnel increased growing degree hours (GDH) and soil degree hours (SDH) over the high tunnel alone. High tunnel plus row cover reduced daily light integral over high tunnel alone by an average of 25% in the spring and 31% in the fall. Late March seeded spring leafy greens and salad turnips had lower DTH than early March seeded crops. The addition of row cover increased yield in one of the three springs over which the experiment was repeated, when the outside air temperature was considerably below average. Early seeded fall leafy greens out yielded late seeded due to the ability to make a second harvest. Fall beet and carrot performed poorly, with late seeded crops only producing market sized roots one of the three falls. Row cover deployment within the high tunnel increased fall yields of all species except lettuce in 2016 but had little effect in fall 2015 and 2017. Our research suggests that unless high tunnel temperatures are below the base temperature for the crop, the higher light level in the high tunnel without row cover is more important for crop yield than the extra heat retained under the row cover.

Key Words: Season extension, high tunnels, cool season crops

## Introduction

High tunnel growers in northern latitude locations wishing to extend their growing season face several challenges related to low temperatures, and low light energy in the early spring and late fall. Crop selection and scheduling become increasingly important as high tunnel growers must decide if there is enough time to produce an early spring crop prior to establishing the warm season crop, and when to terminate a warm season crop and establish a fall crop in the hope that there is enough cumulative light and heat to produce a marketable crop. Producing an early spring crop of hardy leafy greens is challenging because of cold soils, which slow germination and early crop development. However, the crop benefits from an increasing daily light integral (DLI) and warming average air temperature as spring progresses. In contrast, fall production of cool season crops benefits from warm soils and adequate DLI at establishment, but is hampered by decreasing DLI and air temperature as the calendar moves from September to November. As an example of the seasonal change in temperature and light energy at a northern latitude, table 4.1 lists average monthly DLI, air temperature, and minimum air temperatures for Bozeman, MT (45.6770°N, 111.0429°W, elevation 1491 meters, USDA plant hardiness zone 4b) for spring and fall months.

### *Moveable high tunnels*

Moveable high tunnels are a potential solution to this scheduling challenge, allowing growers to establish a fall crop outside the high tunnel where air and soil temperatures might be more favorable to germination and early crop growth. The high

tunnel is moved over the fall crop after the summer crop is terminated. Additional potential benefits of moveable high tunnels include the ability to utilize green manures to improve soil health without sacrificing a cash crop, and exposure of the soil to precipitation to leach salt accumulation often associated with intensive crop production (Coleman, 2009; Coleman, 2013; Janke et al., 2017). Coleman (2009) reports that earliest record of a moveable high tunnel was in England circa 1898, when a glass covered, iron framed greenhouse was mounted on railroad wheels and moved on rails to protect successive crops. Several greenhouse manufacturers offer moveable high tunnels that either utilize a wheel and track mechanism or a skid mounted to the high tunnel frame to facilitate dragging with a tractor. Given the extra material required to make the moveable high tunnel frame tolerate the additional stress associated with not being anchored in the ground and extra components such as wheels and track, a moveable high tunnel of the size used in this study costs ~60% more than a stationary high tunnel of the same size ([www.growerssupply.com](http://www.growerssupply.com)).

### *Crop selection*

Selection criteria for cool season high tunnel crops include characteristics such as the ability to tolerate cold temperatures, maintain a marketable appearance under low light conditions, and tolerate the wide diurnal temperature swings common in the high tunnel environment. Siberian kale (*Brassica pabularia*), spinach (*Spinacia oleracea*) and turnip (*Brassica rapa*) are classified as hardy species and beet (*Beta vulgaris*), carrot (*Daucus carota* var. *sativus*) and lettuce (*Lactuca sativa*) as half- hardy in their relative resistance to frost and light freezes (Maynard and Hochmuth, 1997). Cardinal

temperatures for seed germination and growth for selected vegetables are listed in table 4.2. While the six species share the same optimum temperature range, spinach and lettuce will germinate at lower temperatures, and beet, kale, and turnip have the same base temperature.

Spinach is the most dependable cool season leafy green, that once acclimated can survive temperatures as low as  $-17^{\circ}\text{C}$  (Schöner and Krause, 1990). Spinach also has the ability to withstand repeated freeze-thaw cycles and still be marketable (Coleman, 2009). Cool season grown spinach is reported to be sweeter due to the increased production of soluble sugars in response to exposure to low temperatures (Blomgren and Frisch, 2007; Gent, 2016; Orde et al., 2018). Brassica greens are also hardy and yield higher than lettuce and spinach when grown under cool season conditions (Borrelli et al., 2013). Lettuce is tenderer than spinach and kale, with a lower temperature limit of  $-2^{\circ}\text{C}$  (Mansour and Raab, 1988).

#### *Scheduling of crops for shoulder season production*

Michigan State University's Student Organic Farm has prepared a crop planting schedule based on their East Lansing location ( $42^{\circ}\text{N}$ , 270 m elevation, USDA plant hardiness zone 5b) that recommends direct seeding beet, carrot and turnip as early as February 1<sup>st</sup> and kale, lettuce, and spinach being transplanted on February 11. Fall seeding of beets and turnips should be completed by September 15<sup>th</sup> and carrot should be seeded by August 8<sup>th</sup> in order to harvest a crop before winter sets in. Fall lettuce final transplant date is September 18<sup>th</sup> while spinach may be transplanted as late as October 15<sup>th</sup> (Biernbaum and Montri, 2013). In an effort to accommodate regional

differences in DLI, Coleman (2009) recommends that growers schedule their crops so three quarters of the desired growth is done before the day length is less than 10 hours, which at 45°N latitude is November 2<sup>nd</sup>.

#### *Using secondary layers in high tunnels*

A layer of poly spun bond row cover suspended above the crop canopy offers additional night time heat retention by trapping long wave radiant energy emitted by plants and soil (Biernbaum, 2013). Drost et al. reported that the temperature under a row cover deployed in a Northern Utah high tunnel was 3°C to 5°C warmer at night than in the high tunnel without row cover during the period of October through March and that spinach yields were significantly improved with the addition of the row cover (Drost et al., 2012).

#### *Study objectives*

The objectives of this study are three fold: 1) investigate the effect of the addition of row cover in the high tunnel on the production of six cool season crops during the shoulder seasons of spring and fall and 2) determine if mid-month or end of month sowing dates in March and August influences the yield and or days to harvest of six cool season species and 3) Determine if fall yields differ from those in spring.

#### *Materials and Methods*

##### *Site Description and Preparation*

The Season Extension Research Program (SERP) site is located at the Montana State University Horticulture Farm in Bozeman, Montana, and consists of six nine meter by 14.6 meter blocks (figure 4.1). The blocks were laid out in such a fashion to facilitate

the installation of moveable high tunnels with the ridgelines in an east – west orientation, which maximizes light within the high tunnel during fall and spring. Three nine meter wide by 14.6 meter long rolling high tunnels (Premium Round Style, FarmTek, South Windsor, CT) were constructed during the fall of 2014, and to minimize shading were sited on alternating blocks. The tunnels feature rollup side walls for ventilation, and a single layer of greenhouse grade 6-mil (0.15 mm) polyethylene film plastic glazing. End wall gable ventilation was added before the 2017 season in the form of 0.58 m<sup>2</sup> aluminum shutters operated by Univent automatic openers (Nolt's Greenhouse Supply, Ephrata, PA). The soil series at the SERP site is a Turner Loam – Typic Argiustoll and the site was amended with a five-centimeter-thick layer of commercially prepared wood products based compost (Glacier Gold Compost, Mountain West, L.L.C. Olney, MT) that was incorporated into the top 15 cm of soil with a rototiller in December of 2014. The planting area in each rolling high tunnel consists of six beds, 75 cm wide by 12 meters long with 45 cm walkways between beds and each bed was divided into four split plots. Soil testing was performed prior to each seeding and there were adequate levels of all nutrients except nitrogen. Fifteen g m<sup>-2</sup> of nitrogen in the form of blood meal (13-0-0) (Marion Ag Services, Aurora, OR) was broadcast on each plot prior to planting in March and August. Seed bed preparation methods followed those outlined by Coleman and Fortier et al. and utilized a series of operations involving a board fork, cordless drill powered rototiller, seed bed rake and seed bed roller (all tools from Johnny's Selected Seeds, Albion, ME) (Coleman, 2009; Fortier and Bilodeau, 2014).

### *Cool Season Crops*

Three leafy greens and three root crops were selected for this study. ‘Red Ace’ (F<sub>1</sub>) beet is a common red, Detroit type variety and a farmers market standard. ‘Napoli’ (F<sub>1</sub>) carrot is a cool season fresh market carrot that performs well in the high tunnel. ‘Hakurei’ (F<sub>1</sub>) turnip is a quick growing salad turnip which is popular with CSA and farmers market customers (Dylan Strike, personal communications). ‘Red Russian’ kale is a popular baby kale variety that has the potential for multiple harvests. All-Star Gourmet Lettuce Mix is a mixture of green oakleaf, red oakleaf, green romaine, red romaine, lollo rossa, and red leaf lettuces that is also suited for repeated harvests. This mix of lettuce varieties was selected to produce leaves with darker reds and greens even under low light conditions. Two varieties of spinach were selected, ‘Space’ (F<sub>1</sub>) a slow bolting variety, was grown for the spring trials and ‘Emperor’ (F<sub>1</sub>), a quick growing cold hardy variety for the fall studies. All seeds are from Johnny’s Selected Seeds in Albion, ME.

### *Study Design*

The research design was a randomized complete block with split plot. The main plot factor was season extension (row cover or uncovered) and the split plot factor was the factorial combination of timing of sowing (early or late) and species. Half of the six beds in each tunnel were randomly assigned to be covered with AGRIBON-19 poly spun bond row cover (Berry Plastics, San Luis Potosí, Mexico), supported ~ 50 cm above the soil surface by wire frames. The manufacturer states that AGRIBON-19 is rated to provide 4°F of frost protection while transmitting 85% of sunlight. Each bed was divided

into four three meter split plots resulting in a total of 24 split plots per high tunnel. Species and planting date (early and late) were randomly assigned so that each were represented in a row cover and uncovered situation. The three tunnels served as three replications and were considered blocks for purposes of statistical analysis.

For spring season sowings, a concession to complete randomization was made, as spring beet and carrot were grown in the outer beds due to their long production time and the resulting expectation that they would not be ready to harvest before our target warm season transition date of May 15. Leafy greens and salad turnips were grown in the interior four beds and were harvested by the middle of May in order to make room for transplanted warm season crops such as tomato, cucumber, pepper, and eggplant. Summer crop performance was not part of this study. The outer beds containing beet and carrot were allowed to grow for an additional month in order to reach market size. In split plots that were designated for leafy greens, twelve rows of seeds were sown with seeds spaced every 2 cm for a target density of ~ 800 seeds per square meter. In split plots designated for root crops, five rows of seeds were sown with seeds spaced every 2.5 cm. Root crops were thinned to 5 cm between plants after seedlings were ~ 4 cm tall, for a target density of ~130 plants per square meter. Overhead sprinkler irrigation (Netafim Spinnet Micro-Sprinkler without Anti-Drain Valve, Fresno, CA) was used throughout the production cycle to keep the seed bed moist during germination and as needed once plants were established.

### *Crop Scheduling*

The timing of the early sowing of spring crops was dictated by soil moisture in the outer planting beds of the high tunnel. Snow melt seeped under the sidewall, wetting the soil, so bed preparation would commence as soon as conditions permitted. Early sowing dates ranged from March 4<sup>th</sup> to March 13<sup>th</sup>, with late sowing two weeks later. Early fall crops were sown from August 14<sup>th</sup> to 17<sup>th</sup> and late sowing dates ranged from August 26 through September 3<sup>rd</sup>. Fall crops were sown in the open plots that were later covered with the moveable high tunnel during the last week of September. Beds selected for row cover treatment were covered after the initial irrigation and row covers were only removed for subsequent irrigation and harvest activities. Fall crop and seeding date locations were completely randomized within the row cover main plots. Figure 4.1 shows the SERP plots in early September 2015 after fall crops have been sown, but prior to moving the high tunnels. The fall crop season was terminated when DLI dropped below  $8 \text{ mol m}^{-2} \text{ d}^{-1}$  and air temperature dropped to the point of damaging foliage, typically by the third week of November.

### *Micrometeorological Instrumentation and Methodology*

Hourly average air temperature, soil temperature, and photosynthetic photon flux density (PPFD) were calculated from measurement every 60 seconds using a Campbell Scientific CR-1000 data logger (Logan, UT) connected to the sensors described in table 4.3. Air temperature and PAR sensors were mounted approximately 45 cm above the soil surface. Soil temperature was measured at a depth of 10 cm. Hourly averages of PPFD, air and soil temperatures were recorded for the following locations: Outside (O), outside

under row cover (OR), inside the high tunnel (I) and inside the high tunnel under row cover (IR). While outside and outside with row cover data were collected, no crops were grown outside of the high tunnels. Micrometeorological data collection began in March 2016. Growing degree hours (GDH) and soil degree hours (SDH) were calculated following the method outlined by Gu (2016) using a 4°C base temperature for GDH and 0°C for SDH, typical for cool season leafy greens (Borrelli et al., 2013). Spring and fall seasons for GDH and SDH calculations were defined as the period of March 15<sup>th</sup> through April 30<sup>th</sup> and October 1<sup>st</sup> through November 15<sup>th</sup>. Typically, by early May in Bozeman, row cover deployment in the high tunnel is not required and after mid-November, DLI and air temperatures are low enough that growth ceases. Fall 2017 micrometeorological data collection was truncated on November 10<sup>th</sup> as low air temperatures and snow cover on the solar panel caused the data logger battery to fail.

#### *Data Collection and Analysis*

Leafy greens were harvested when leaf height was between 10 cm and 15 cm, the typical market size for baby greens (Borrelli et al., 2013). For fall 2015 through fall 2106 harvests of I and IR plots were performed at the same time, when both had reached market size, occasionally resulting in one plot being slightly over mature. For spring 2017 through spring 2018, I and IR plots were harvested independently when market size was obtained. A one meter long section was randomly chosen from the split plot and the greens were hand cut ~ 3cm above soil to allow for the possibility of a second harvest. Fresh weights and days to harvest (DTH) were recorded. A second harvest of leafy greens was made if conditions were favorable for regrowth. Root crops were considered

market sized when the following root diameters were reached: beets at ~40 mm, carrots at ~20 mm and salad turnips at ~25 mm (Johnny's Selected Seeds, 2018). Fresh weight, DTH and the number of market sized roots of beet, carrot and turnip were recorded. A simple growth rate was calculated by dividing total yield by DTH. This was done to determine if the change in harvest protocol midway through the study influenced the analysis. R and R-studio statistical software were used to perform a linear mixed effect analysis on total yield ( $\text{g m}^{-2}$ ) and growth rate ( $\text{g m}^{-2} \text{d}^{-1}$ ). Significance was determined at the  $p < 0.05$  level.

## Results

### *Season and row cover influences on GDH and SDH in the high tunnel*

Spring 2016 (figure 4.2) had the greatest number of outside (O) GDH with 2017 and 2018 being progressively colder, and while GDH increased under the single layer treatments (OR and I), the addition of a second layer (IR) resulted in very similar levels of GDH despite large differences in O GDH among the three springs. Spring I and IR SDH levels (figure 4.3) were not correlated with GDH of any treatments. Spring 2018 had the lowest GDH for O, OR, I, and IR for the three springs but the highest IR SDH levels.

Fall 2017 (figure 4.4) was considerably colder than 2016, and each layer of season extension had a far greater influence on GDH accumulation than during the mild fall of 2016. SDH accumulation (figure 4.5) mirrored GDH for the two falls.

*Season and row cover influences on DLI in the high tunnel*

While there is not a widely reported method for describing the accumulation of photosynthetically active radiation (PAR) for a period longer than a day, calculating an average DLI for week long periods provides insight on the impact season, meteorological factors, snow, and the various layers of season extension materials have on light transmission. One week for spring and fall was selected to illustrate influences of row cover and season on DLI. Figure 4.6 illustrates weekly average DLI levels for O, OR, I, and IR locations for March 15-21, 2016, 2017 and 2018. March 15-21, 2018 had the highest DLI levels in the O, I, and IR treatments of the three years, and the lowest DLI level for OR due to snow accumulation on the OR treatment. PAR in the high tunnel for the three springs, ranged from 70-84% of outside PAR and 54-60% of outside in the IR treatment.

November 1<sup>st</sup>-7<sup>th</sup>, 2017 DLI readings (figure 4.7) were lower than 2016 for all treatments due to snow cover and very low temperatures ( $-22^{\circ}\text{C}$  on November 7<sup>th</sup>) precluding the snow from melting off the OR and high tunnel. DLI was below  $8 \text{ mol m}^{-2} \text{ d}^{-1}$  for IR in both years, a level at which lettuce and spinach growth greatly slows. PAR in the high tunnel was 67-72% of outside and from 46-50% for the IR treatment. A more detailed analysis on the influences of high tunnel and row cover on air and soil temperatures and DLI levels at the SERP plots is reported in Baumbauer, 2019.

*Row cover and seeding date influences on high tunnel crop production*

Preliminary statistical analysis performed indicated that there was a significant year by treatment interaction, therefore years are reported separately. High tunnel plus

row cover significantly increased yields for all species except lettuce during fall 2016, however, in fall 2015 and 2107, the addition of row cover had no significant impact on crop yields and growth rates. Table 4.4 summarizes crop yields for fall 2015, 2016 and 2017. Timing of seeding date had positive impacts on yields during fall 2015, with early seeded beet, carrot, lettuce, and spinach producing greater yields than late seeded. Early seeded kale and turnip suffered crop failures due to mis-sown seed and flea beetles. Fall 2016 early seeded crops had higher yields than late seeded. In fall 2017, beet, carrot and lettuce produced greater yields from the early seeding date. Leafy greens that produced higher yields from early seeding dates were the result of consistent second harvests. Early seeded fall leafy greens and turnips had lower DTH (table 4.6) than late seeded. Early lettuce and kale averaged 12-15 fewer DTH than late seeded. Early seeded turnips were ready 8-9 days sooner than late seeded. Beet and carrot did not produce market sized roots in fall 2015 and 2017 and produced very low yields in 2016. Late seeded fall beet and carrot grew and survived but the roots did not size up by mid-November.

Row cover in the high tunnel only had a positive impact on spring crop yields (table 4.5) in 2018, in which carrot, kale, lettuce and turnip benefited from the second layer of protection. DTH for spring crops (figure 4.7) were 5-7 days longer for early seeded crops than late seeded, and row cover did not influence DTH.

Early seeding of turnip produced higher yields in 2016. Seeding date had a positive impact on yields of lettuce and turnip in 2018, but reduced yields of carrot.

### *Seasonal Effects*

There were no difference in yields between fall and spring grown lettuce, spinach, and turnip. However, fall grown kale out yielded spring kale. Spring grown beet and carrot yielded more than fall grown beet and carrot, with the increase due to a greater number of market sized roots.

### Discussion

#### *High tunnel plus row cover influences on light and temperature*

Row cover within the high tunnel moderated the effect of low outside air temperature on IR GDH and SDH accumulation, especially during the three spring seasons. Large differences in O GDH and SDH were largely mitigated when row cover was used within the high tunnel. Solar energy not only warms daytime high tunnel air temperatures, thereby increasing GDH, it is also responsible for warming the soil and thus increasing SDH. Row cover reduces radiative heat loss from the soil at night, warming the air around the crops. Soil temperature impacts seed germination and early plant development as the growing point for leafy greens are near the soil surface. Spring 2018 had the lowest average outside air temperature and lowest outside GDH of the three springs reported but had the highest IR SDH due to having the highest DLI. Mid-March 2018 IR DLI levels averaged 17.3 mol m<sup>-2</sup> d<sup>-1</sup>, 47% higher than 2017, and 9.5% higher than 2016. Research on utilizing high tunnels plus row cover to produce bedding plants in Indiana, reported that daytime removal of the row cover resulted in March DLI levels that were 89-94% of the high tunnel alone (Gerovac et al., 2015).

*Row cover and seeding date influences on crop yield*

Row cover did not have a significant effect on yields for two of three springs and falls. When high tunnel temperatures are above the crop base temperature, increasing PAR is more important than temperature in dictating yields. Michigan State University researchers recommend that growers utilize one layer of season extension when the air temperature drops to 1.7°C and the second layer added when air temperature drops to -9.4°C (Biernbaum, 2013). Row cover deployment and removal is a labor intensive process and development of a method to facilitate this process is an area for future research.

Much of the reported research on cool season leafy greens production utilized a transplant system, where plug seedlings were produced in a climate controlled facility before planting in the high tunnel (Borrelli et al., 2013; Drost et al., 2017; Orde et al., 2018). Transplant systems overcome the limitations of cold soil seed germination but are more labor intensive than direct seeding and it is difficult to establish the high plant density associated with baby leafy green production. The average yield of all our fall produced direct seeded spinach was 3.11 kg m<sup>-2</sup>. Late fall spinach production from transplants in a New Hampshire high tunnel was 3.66 kg m<sup>-2</sup> (Orde et al., 2018) and winter spinach production from transplants equaled 2.3 kg m<sup>-2</sup> from a Vancouver, WA high tunnel (Borrelli et al., 2013).

High tunnel production of beet, carrot and salad turnip are not widely reported in the literature. Coleman (2009) reports success with direct marketing of these high tunnel produced crops to restaurants and farm stand customers. Bozeman area market gardeners

report customer interest in a greater diversity of produce in spring CSA shares besides leafy greens (Dylan Strike, personal communication). Spring production of high tunnel fresh market beet and carrot make for appealing farmers market stands and CSA shares, but fall production would require an earlier seeding date than mid-August to produce market sized roots. A possible explanation for the low yields of fall produced beet and carrot, especially from the late seeding date comes from Hole and Dearman (1993), as they reported that while red beet and carrot maintains leaf area and shoot fresh weight at a range of PPFD, storage organ weights are greatly reduced under low PPFD (Hole and Dearman, 1993). The economic feasibility of high tunnel fall beet and carrot is questionable considering that storage varieties of these species can be field grown and stored for later sale.

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Table 4.1. Average monthly daily light integral (DLI) and minimum and average air temperatures for spring and fall months in Bozeman, MT

	March	April	May	September	October	November
DLI ( $\text{mol m}^{-2} \text{d}^{-1}$ ) <sup>a</sup>	24.6	36.3	43.1	32.8	20.9	11.3
Min. temperature ( $^{\circ}\text{C}$ ) <sup>b</sup>	-4.9	-1.1	3.3	5.0	-0.1	-5.8
Ave. temperature ( $^{\circ}\text{C}$ ) <sup>b</sup>	1.9	6.3	7.6	13.7	7.6	0.3

<sup>a</sup>. U.S. Daily Light Integral Map (Faust and Logan, 2018).

<sup>b</sup>. [www.ncdc.noaa.gov](http://www.ncdc.noaa.gov)

Table 4.2. Cardinal temperature for seed germination and growth of selected cool season vegetables.

Species	Minimum Germination (°C)	Minimum Growing (°C)	Optimum Range (°C)
Beet	4.4	4.4	15.6 - 18.3
Carrot	4.4	7.2	15.6 - 18.3
Kale	4.4	4.4	15.6 - 18.3
Lettuce	1.7	7.2	15.6 - 18.3
Spinach	1.7	1.7	15.6 - 18.3
Turnip	4.4	4.4	15.6 - 18.3

Adapted from Knott's Handbook for Vegetable Growers.

<sup>1</sup>Johnny's Selected Seeds for selected varieties

Table 4.3. Sensors used in this experiment to measure micrometeorological parameters.

Device	Sensing	Units
Thermistor Temperature Sensor (Apogee ST-110) Housed within an Aspirated Radiation Shield (Apogee TS-110)	Air Temperature	°C
12 cm Soil Water Content Reflectometer (Campbell Scientific CS 655)	Soil Temperature	°C
Sun Calibration Quantum Sensor (Apogee SQ-110)	PPFD	$\mu\text{mols}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$

Table 4.4. Average fresh weight (kg m<sup>-2</sup>) for early and late sowing dates, high tunnel (I) and high tunnel plus row cover (IR) plots for fall 2015, 2016 and 2017. MSU Horticulture Farm, Bozeman, MT.

Species	Fall 2015				Fall 2016				Fall 2017			
	Early		Late		Early		Late		Early		Late	
	<u>I</u>	<u>IR</u>	<u>I</u>	<u>IR</u>	<u>I</u>	<u>IR</u>	<u>I</u>	<u>IR</u>	<u>I</u>	<u>IR</u>	<u>I</u>	<u>IR</u>
Beet	3.9 <sup>a1</sup>	4.67 <sup>a</sup>	0 <sup>b</sup>	0 <sup>b</sup>	4.94 <sup>aC2</sup>	6.48 <sup>aD</sup>	2.66 <sup>bC</sup>	4.06 <sup>bD</sup>	1.23 <sup>a</sup>	2.7 <sup>a</sup>	0 <sup>b</sup>	0 <sup>b</sup>
Carrot	1.42 <sup>a</sup>	2.41 <sup>a</sup>	0 <sup>b</sup>	0 <sup>b</sup>	2.88 <sup>aC</sup>	4.33 <sup>aD</sup>	0.12 <sup>bC</sup>	0.68 <sup>bD</sup>	0.08 <sup>a</sup>	1.11 <sup>a</sup>	0 <sup>b</sup>	0 <sup>b</sup>
Kale	N/A	N/A	2.56	1.94	2.31 <sup>aC</sup>	3.04 <sup>aD</sup>	1.58 <sup>bC</sup>	2.2 <sup>bD</sup>	1.3	1.49	1.17	1.47
Lettuce	1.98 <sup>a</sup>	2.77 <sup>a</sup>	1.11 <sup>b</sup>	0.96 <sup>b</sup>	3.7 <sup>a</sup>	3.62 <sup>a</sup>	1.26 <sup>b</sup>	1.7 <sup>b</sup>	3.63 <sup>a</sup>	2.48 <sup>a</sup>	1.86 <sup>b</sup>	2 <sup>b</sup>
Spinach	3.43 <sup>a</sup>	2.56 <sup>a</sup>	1.02 <sup>b</sup>	0.42 <sup>b</sup>	3.44 <sup>aC</sup>	4.49 <sup>aD</sup>	1.92 <sup>bC</sup>	2.63 <sup>bD</sup>	1.98	2.77	2.17	1.69
Turnip	N/A	4.21	1.58	3.02	6.57 <sup>aC</sup>	8.27 <sup>aD</sup>	4.21 <sup>bC</sup>	5.44 <sup>bD</sup>	4.18	2.82	2.94	5.08

<sup>1</sup>lower case letters indicate significant differences at the p < 0.05 level between early and late seeding dates.

<sup>2</sup>Upper case letters indicate significant differences at the p < 0.05 level between row cover and uncovered control plots.

N/A indicates crop failure

Table 4.5. Average fresh weight (kg m<sup>-2</sup>) for early and late sowing dates, high tunnel (I) and high tunnel plus row cover (IR) plots for spring 2016, 2017 and 2018. MSU Horticulture Farm, Bozeman, MT.

Species	Spring 2016				Spring 2017				Spring 2018			
	Early		Late		Early		Late		Early		Late	
	<u>I</u>	<u>IR</u>	<u>I</u>	<u>IR</u>	<u>I</u>	<u>IR</u>	<u>I</u>	<u>IR</u>	<u>I</u>	<u>IR</u>	<u>I</u>	<u>IR</u>
Beet	6.28	5.86	5.11	N/A	6.92	7.45	6.89	8.82	9.3	10.11	10	12.8
Carrot	2.82	3.25	3.47	3.2	5.5	5.92	5.15	7.76	4.27 <sup>aC1,2</sup>	5.91 <sup>D</sup>	7.82 <sup>bC</sup>	9.56 <sup>bD</sup>
Kale	0.72	0.88	1.39	1.02	1.55 <sup>a</sup>	1.81 <sup>a</sup>	2.44 <sup>b</sup>	2.03 <sup>b</sup>	1.88 <sup>C</sup>	1.92 <sup>D</sup>	1.12 <sup>C</sup>	2.27 <sup>D</sup>
Lettuce	1.18	2.29	0.7	1.11	4.22	3.44	3.62	3.43	2.95 <sup>aC</sup>	3.94 <sup>aD</sup>	1.04 <sup>bC</sup>	1.5 <sup>bD</sup>
Spinach	1.3	0.7	1.09	0.46	3.87	3.48	3.78	2.89	4.45	3.26	2.31	4.32
Turnip	4.23 <sup>a</sup>	4.4 <sup>a</sup>	1.97 <sup>b</sup>	1.24 <sup>b</sup>	4.89	5.93	5.36	7.38	5.7 <sup>aC</sup>	7.11 <sup>aD</sup>	4.08 <sup>bC</sup>	6.7 <sup>bD</sup>

<sup>1</sup>lower case letters indicate significant differences at the  $p < 0.05$  level between early and late seeding dates within a year.

<sup>2</sup>Upper case letters indicate significant differences at the  $p < 0.05$  level between row cover and uncovered control plots within a year.

N/A indicates crop failure.

Table 4.6. Average days to harvest (DTH) for early and late sowing dates, high tunnel (I) and high tunnel (IR) plots for fall 2015, 2016, and 2017. DTH for leafy greens represents the first harvest. Numbers within ( ) following species names are DTH from the seed supplier under optimum conditions. MSU Horticulture Farm, Bozeman, MT.

	Fall 2015				Fall 2016				Fall 2017 <sup>1</sup>			
	Early		Late		Early		Late		Early		Late	
<u>Species</u>	<u>I</u>	<u>IR</u>	<u>I</u>	<u>IR</u>	<u>I</u>	<u>IR</u>	<u>I</u>	<u>IR</u>	<u>I</u>	<u>IR</u>	<u>I</u>	<u>IR</u>
Beet (50)	92	92	N/A	N/A	94	94	81	81	88	83	N/A	N/A
Carrot (58)	95	95	N/A	N/A	94	94	84	84	88	88	N/A	N/A
Kale (25)	N/A	N/A	59	59	28	28	38	38	26	26	46	39
Lettuce (28)	34	34	63	63	35	35	38	38	43	32	55	46
Spinach (26)	54	54	63	63	42	42	38	38	50	39	61	46
Turnip (38)	N/A	56	61	61	45	45	54	54	50	39	61	53

<sup>1</sup> Harvest protocol changed to accommodate differing growth rates  
N/A indicates crop failure.

Table 4.7. Average days to harvest (DTH) for early and late sowing dates and high tunnel (I) and high tunnel plus row cover (IR) plots for spring 2016, 2017 and 2018. DTH for leafy greens represents the first harvest. Numbers within ( ) following species names are DTH from the seed supplier under optimum conditions. MSU Horticulture Farm, Bozeman, MT.

Species	Spring 2016				Spring 2017 <sup>1</sup>				Spring 2018			
	Early		Late		Early		Late		Early		Late	
	<u>I</u>	<u>IR</u>	<u>I</u>	<u>IR</u>	<u>I</u>	<u>IR</u>	<u>I</u>	<u>IR</u>	<u>I</u>	<u>IR</u>	<u>I</u>	<u>IR</u>
Beet (50)	111	111	96	N/A	93	90	86	87	90	87	85	85
Carrot (58)	97	97	89	89	93	90	87	86	90	87	85	85
Kale (25)	56	56	50	50	42	40	41	35	46	37	41	36
Lettuce (28)	56	56	50	50	47	41	41	36	46	40	44	41
Spinach (25)	65	65	52	52	47	41	44	35	47	37	42	36
Turnip (38)	66	66	53	53	57	52	52	52	54	50	49	46

<sup>1</sup> Harvest protocol changed to accommodate differing growth rates  
N/A indicates crop failure.



Figure 4.1. View of the Season Extension Research Program (SERP) plots. Fall crops are sown in the open plots and warm season crops are finished in the high tunnels. Row covers are installed over wire frames and conduit hoops ~50 cm above the soil and are held in place by rocks and t-posts on the ends. MSU Horticulture Farm, Bozeman, MT.

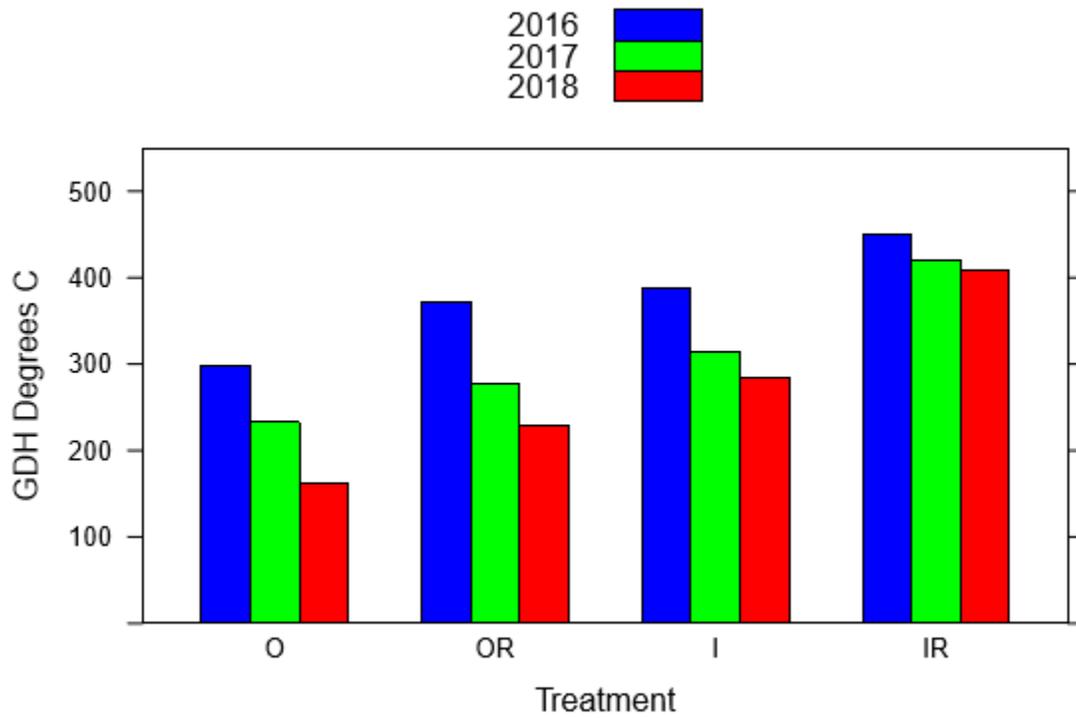


Figure 4.2. Growing degree hours (GDH) for March 15 – April 30, 2016, 2017, and 2018 for outside (O), outside under row cover (OR), inside the high tunnel (I) and inside the high tunnel under row cover (IR). MSU Horticulture Farm, Bozeman, MT.

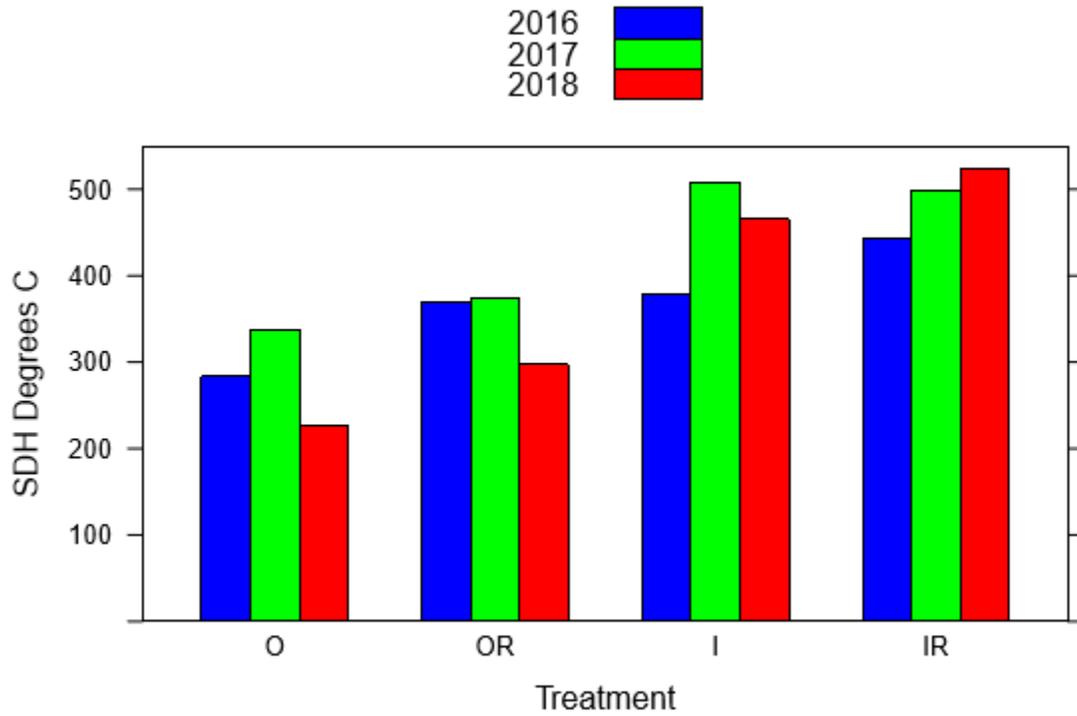


Figure 4.3. Soil degree hours (SDH) for March 15 – April 30, 2016, 2017, and 2018 for outside (O), outside under row cover (OR), inside the high tunnel (I) and inside the high tunnel under row cover (IR). MSU Horticulture Farm, Bozeman, MT.

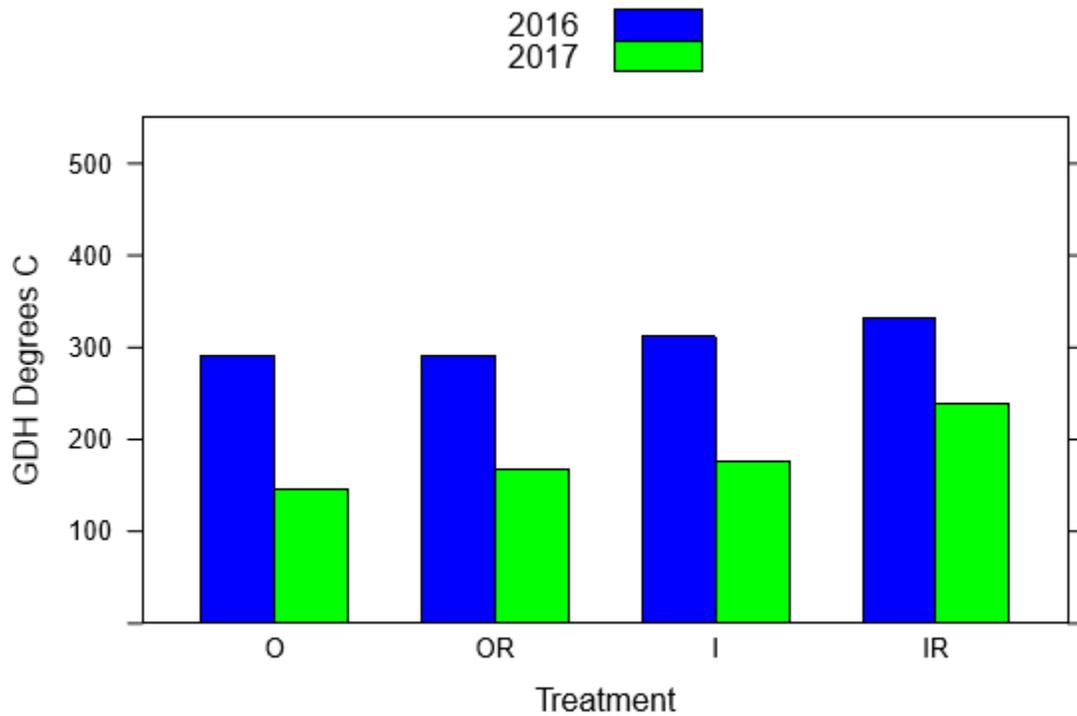


Figure 4.4. Growing degree hours (GDH) for October 1 – November 15, 2016 and October 1 – November 9, 2017 for outside (O), outside under row cover (OR), inside the high tunnel (I) and inside the high tunnel under row cover (IR). Cold air temperatures caused data logger battery failure on November 10<sup>th</sup>, 2017, truncating data collection. MSU Horticulture Farm, Bozeman, MT.

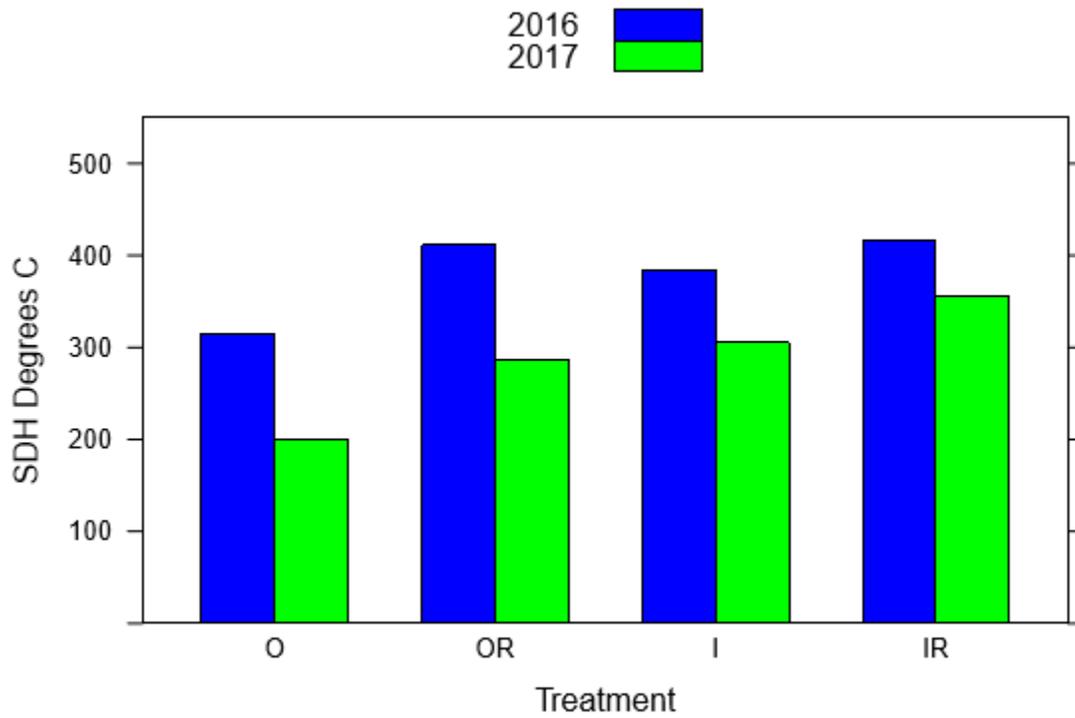


Figure 4.5. Soil degree hours (SDH) for October 1 – November 15, 2016 and October 1 – November 9, 2017 for outside (O), outside under row cover (OR), inside the high tunnel (I) and inside the high tunnel under row cover (IR). Cold air temperatures caused data logger battery failure on November 10<sup>th</sup>, 2017, truncating data collection. MSU Horticulture Farm, Bozeman, MT.

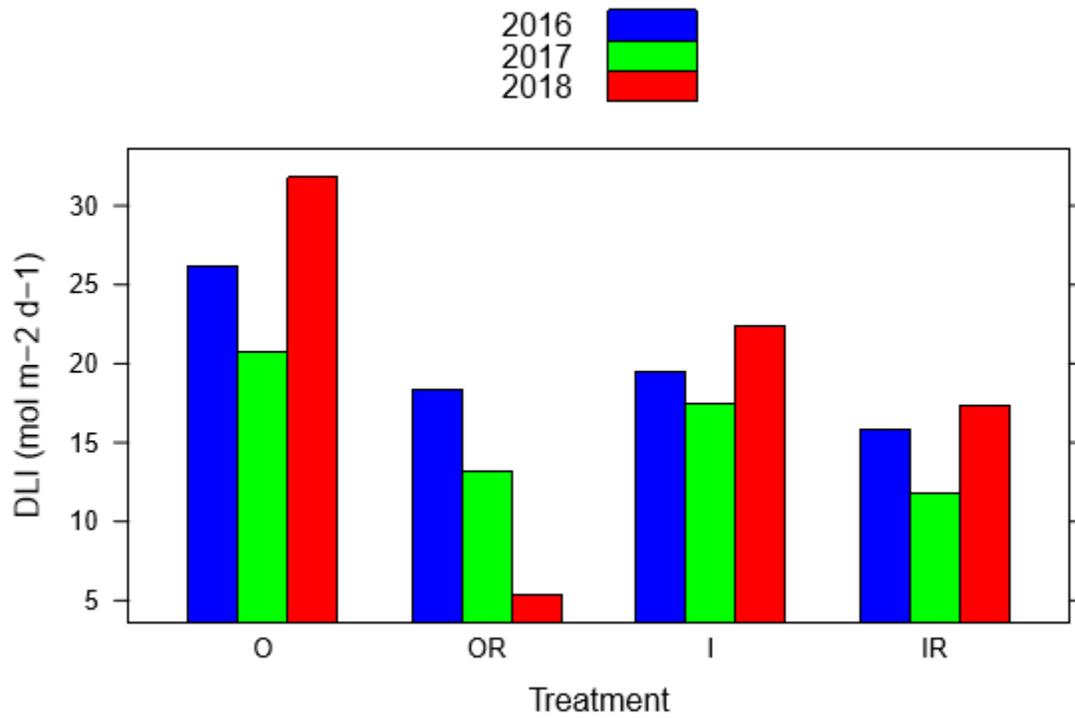


Figure 4.6. Average DLI for March 15<sup>th</sup>-21<sup>st</sup>, 2016, 2017 and 2018 for outside (O), outside under row cover (OR), inside the high tunnel (I) and inside the high tunnel under row cover (IR). MSU Horticulture Farm, Bozeman, MT.

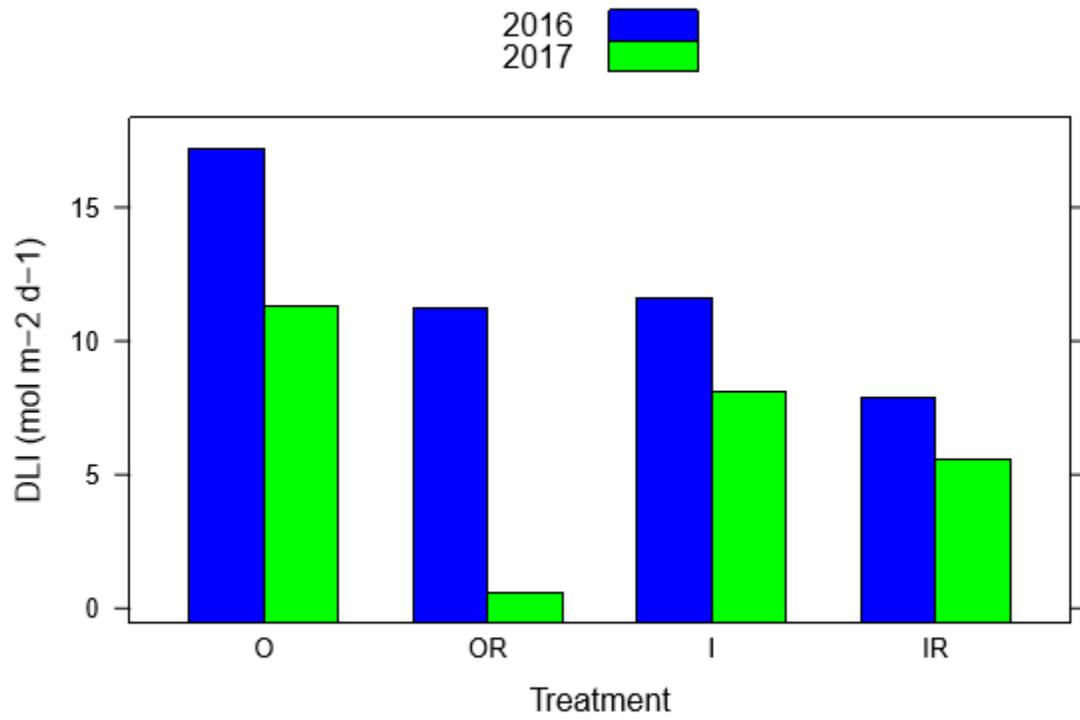


Figure 4.7. Average DLI for November 1<sup>st</sup>-7<sup>th</sup>, 2016 and 2017 for outside (O), outside under row cover (OR), inside the high tunnel (I) and inside the high tunnel under row cover (IR). MSU Horticulture Farm, Bozeman, MT.

CHAPTER FIVE

THE INFLUENCE OF LOW DAILY LIGHT INTEGRAL ON THE GROWTH OF  
BABY KALE, LETTUCE AND SPINACH

Contribution of Authors and Co-Authors

Manuscript in Chapter Five

Author: David A. Baumbauer

Contributions: Conceived of the study, performed the analyses, interpreted results and wrote the manuscript.

Co-Author: Colleen B. Schmidt

Contributions: Assisted with study, discussed results and implications, assisted with manuscript preparation.

Co-Author: Macdonald H. Burgess

Contributions: Discussed results and implications and edited earlier manuscripts.

Manuscript Information

David A. Baumbauer, Colleen B. Schmidt, and Macdonald H. Burgess

HortScience

Status of Manuscript:

- Prepared for submission to a peer-reviewed journal
- Officially submitted to a peer-reviewed journal
- Accepted by a peer-reviewed journal
- Published in a peer-reviewed journal

American Society of Horticultural Science

The Influence of Low Daily Light Integral on the Growth of Baby Kale, Lettuce, and Spinach

David A. Baumbauer<sup>1</sup>, Colleen B. Schmidt<sup>2</sup> and Macdonald H. Burgess<sup>3</sup>

<sup>1,3</sup>Department of Plant Sciences and Plant Pathology, Montana State University  
Bozeman, Montana, 59717

<sup>2</sup>Department of Ecology, Evolution, and Environmental Biology, Columbia University,  
New York, NY, 10027

<sup>1</sup> Corresponding author. Email address: baumbauer@montana.edu

Keywords: Leafy greens, low light response, cool season production

#### Abstract

Kale, leaf lettuce, and spinach were grown for 28 days in growth chambers under daily light integrals (DLI) of 8, 10, 12, and 14 mol m<sup>-2</sup> d<sup>-1</sup>. Fresh weight, dry weight, leaf area, and chlorophyll were measured. Lettuce fresh weight was positively influenced by increasing DLI. Dry weight for all species increased in a linear fashion under increasing DLI. Leaf area response was species dependent with lettuce leaf area increasing under increasing DLI while kale leaf area decreased under higher DLI. Chlorophyll levels in kale leaves decreased from DLI of 8 to 12 mol m<sup>-2</sup> d<sup>-1</sup>, then increased at 14 mol m<sup>-2</sup> d<sup>-1</sup> DLI. Chlorophyll content in kale leaves had a non-linear response to DLI, best fit by a quadratic model.

#### Introduction

Northern tier high tunnel growers of leafy greens who wish to extend their growing season past early November are faced with two significant challenges: low air temperatures, primarily at night, and low daily light integral (DLI) due to short day length and low sun angle, light attenuation by season extension plastic. For instance, Bozeman, Montana (45.677°N, 111.0429°W) has a monthly average DLI for November of 11.3 mol m<sup>-2</sup> d<sup>-1</sup>, December of 7.6 mol m<sup>-2</sup> d<sup>-1</sup>, January of 8.2 mol m<sup>-2</sup> d<sup>-1</sup> and February of 14.7 mol m<sup>-2</sup> d<sup>-1</sup> (Faust and Logan, 2018). Coupled with the 60%-70% reduction in light energy at the crop level due to the high tunnel structure and glazing in December and January (Biernbaum, 2013), low DLI can limit growth even if the high tunnel air temperature is adequate. High tunnel growers have managed below freezing air temperatures by adding

heat to the air and/or soil, and by utilizing secondary row covers. (Bumgarner et al., 2012; Drost et al., 2017; Hunter et al., 2012). The concept of a minimally heated high tunnel has been called the ‘cool greenhouse’ by Eliot Coleman, who reported that maintaining the greenhouse air temperature at 1.5°C resulted in twice as many harvests and allowed for a wider selection of crops during the winter months as compared to unheated high tunnels (Coleman, 2009). Determining the amount of heat to add to a high tunnel to keep the air temperature above freezing is a relatively simple calculation (Nelson, 2012). On the other hand, the optimum amount of additional light required to maximize profit is species- and location-specific, and therefore more difficult to determine.

*Plant responses to varying light intensity.* Leafy greens react to low light intensity both physically, by exhibiting changes in fresh and dry biomass and leaf area, and chemically, through variation in chlorophyll content and compounds both beneficial and harmful to human health. Past literature reports increases in fresh and dry biomass across cultivars with increasing DLI. Lefsrud et al. (2006) reported linear increases in kale fresh and dry biomass with DLI increases from 10.8 to 43.2 mol m<sup>-2</sup> d<sup>-1</sup> (Lefsrud et al., 2006a). Likewise, Gent (2016) found an increase in spinach dry mass as DLI increased from 3 to 27 mol m<sup>-2</sup> d<sup>-1</sup>, and Gaudreau et al. (1994) reported lettuce yield increases between 140% and 270% with supplemental DLI of 12-13 mol m<sup>-2</sup> d<sup>-1</sup> as compared to plants grown without supplemental lighting (Gaudreau et al., 1994; Gent, 2016). Past research supports both increases and decreases in leaf area with increasing DLI depending on cultivar. Whereas Fu et al. (2017) reported that lettuce leaf area decreased when DLI increased

from 4 to 14 mol m<sup>-2</sup> d<sup>-1</sup>, Proietti (2004) found that spinach leaf area increased under higher DLI levels, and Yao (2017) found that leaf area was 2.4 times higher in kale grown under 13 mol m<sup>-2</sup> d<sup>-1</sup> than in kale grown under 8.6 mol m<sup>-2</sup> d<sup>-1</sup> (Fu et al., 2017; Proietti et al., 2004; Yao et al., 2017).

Chlorophyll content is closely correlated with leaf nitrogen levels, leaf area, plant size, transpiration rate and antioxidant compounds such as anthocyanins and carotenoids (Basyouni and Dunn, 2013; Kopsell et al., 2004; Steidle Neto et al., 2017). Literature on chlorophyll content variation with increasing DLI indicates that chlorophyll response to increasing DLI is species-specific. Lefsrud et al. (2006) found that the total chlorophyll content of kale increased as DLI increased from 11 to 21.6 mol m<sup>-2</sup> d<sup>-1</sup> (Lefsrud et al., 2006a). Conversely, Fu et al. (2012) found that chlorophyll-A and chlorophyll-B contents in lettuce decreased with DLI increasing from 4 to 14 mol m<sup>-2</sup> d<sup>-1</sup>. Yao (2017) found no difference in chlorophyll content between kale grown in 8.6 mol m<sup>-2</sup> d<sup>-1</sup> and kale grown in 13 mol m<sup>-2</sup> d<sup>-1</sup>. In addition to influencing growth characteristics, low light intensities may reduce compounds beneficial to human health such as antioxidants and increase potentially harmful compounds such as nitrate and oxalate (Proietti et al., 2004; Zhu et al., 2017).

By growing common cool season leafy greens under varying low to moderate DLIs, this study aims (1) to determine the minimum DLI required to produce market quality baby kale, leaf lettuce, and spinach, and (2) to ascertain whether individual cultivars respond linearly or otherwise to increasing DLI. Our study differs from similar light intensity effects studies in that (1) the growth chamber conditions were kept

constant throughout the experimental cycle. Seedlings were not grown in one environment and transferred into experimental conditions, and (2) plant density was consistent with commercial high tunnel cultivation of baby leafy greens. High density plant spacing creates light competition not found in a study that utilizes a single plant per pot design.

#### Materials and Methods

*Growth conditions.* This study utilized two Conviron PGR-15 (Winnipeg, CAN) growth chambers. A  $20^{\circ}\text{C} \pm 1^{\circ}\text{C}$  air temperature set point and 12-hour photoperiod were constant for both chambers for the duration of the study. The DLI treatment range for this study was drawn from the recommendations of Glenn et al. (1984) and Runkle (2011), which suggest that a DLI between 8 and  $12 \text{ mol m}^{-2} \text{ d}^{-1}$  is sufficient for production; Glenn et al. (1984) reports that a minimum DLI of  $8 \text{ mol m}^{-2} \text{ d}^{-1}$  was required to produce market quality bib lettuce and spinach in an Arizona greenhouse, whereas Runkle (2011) recommends a minimum of  $12\text{-}14 \text{ mol m}^{-2} \text{ d}^{-1}$  for lettuce production (Glenn et al., 1984; Runkle, 2011). To achieve the various DLIs of 8, 10, 12, or  $14 \text{ mol m}^{-2} \text{ d}^{-1}$  (henceforth referred to as DLI 8, DLI 10, DLI 12, and DLI 14), both growth chambers were programed to deliver a Photosynthetic Photon Flux Density (PPFD) of 185, 231, 278, and  $324 \mu\text{mol m}^{-2} \text{ s}^{-1}$  for each 28 day growth cycle respectively. The light source was a combination of fluorescent tubes (F39W/T5/841 ECO) and 43 watt soft white incandescent bulbs (both lamps from GE, Boston, MA). The chambers feature Photosynthetically Active Radiation (PAR) sensors (Apogee Model SQ-225, Logan, UT). PPFD levels were checked daily, and adjustments to the light canopy height were made

to maintain PPFD levels  $\pm 25 \mu\text{mol m}^{-2} \text{s}^{-1}$  of the desired level. Each DLI level was repeated for a total of four replications.

*Plant culture.* ‘Space’ (F1) spinach (*Spinacia oleracea*), ‘Red Russian’ kale (*Brassica napus pabularia*), and ‘All Star’ lettuce mix (*Lactuca sativa*) (all from Johnny’s Selected Seeds, Winslow, ME) were sown (five rows with ~15 seeds per row) in galvanized metal flats (32 cm L x 22 cm W x 9 cm D) filled with Sunshine Mix # 1 soilless growing media (Sungro Horticulture, Agawam, MA). Three flats of each species were placed in each of the two growth chambers. Seedlings germinated in 3-6 days after sowing (DAS) and were thinned to 50 seedlings per flat 7-10 DAS (~700 seedlings  $\cdot \text{m}^{-2}$ ), a density representative of one used by high tunnel producers of baby leafy greens. Flats were watered as needed and fertilized weekly with a 100 ppm nitrogen solution of 20-20-20 fertilizer (Scotts Peter’s Professional, Marysville, OH). Flats were irrigated the afternoon prior to data collection so that the leaves were turgid, but leaf surfaces were dry. Data collection took place the following morning. Leaf area and chlorophyll measurements were taken, and above ground biomass was harvested at 28 DAS. The study was conducted between April and December 2018.

*Analyses.* Leaf area, chlorophyll content, fresh weight, and dry weight were measured. The first or second true leaf from plants located in the interior of each flat of each species were selected for measurement of chlorophyll content and leaf area, resulting in a total of six leaves, and thus six measurements, for each species in each growth chamber. The average of the six measurements was used for analysis. Since the ‘All Star’ lettuce mix consists of four varieties, a single variety (green romaine) was

selected for leaf area and chlorophyll content measurements. Leaf area was determined by taking a digital image of each leaf and analyzing the image with Leafscan software (<http://www.leafscanapp.com>) loaded on an Apple iPhone 6 smart phone (8-megapixel, 1.5 micro pixel iSight camera, aperture f/2.2). Chlorophyll content (CHL) was estimated using an atLEAF+ chlorophyll meter (FT Green LLC, Wilmington, DE), which compares the transmission of light in red and near infrared wavelengths to determine chlorophyll content in green leaves. The atLEAF+ meter produces a unit-less value that is the relative amount of chlorophyll in the tissue on a range of 1 to 100, and is reported to function in a similar manner as the more expensive SPAD meter (Basyouni and Dunn, 2013; Novichonok et al., 2016; Zhu et al., 2012). Above ground biomass was clipped and weighed to determine fresh weight, then placed in a drying oven at 40° C for seven days to determine dry weight. Fresh and dry weights for the three trays per species per chamber were averaged to determine the yield observations for each chamber. ANOVA, Least Significant Difference (LSD), linear and quadratic models were performed on the data using R software version 3.5.1 and RStudio version 1.1456. Significance was determined at the  $p < 0.05$  level.

## Results

*Influences on fresh weight.* A significant linear increase in fresh weight (FW) with increasing DLI occurred in lettuce, ranging from 1.27g for DLI 8 to 4.33g for DLI 14 ( $FW = -2.8 + 0.5(DLI)$ ,  $r^2 = 0.82$ ). Kale and spinach FW were not influenced by increasing DLI. Table 5.1 summarizes fresh weight, dry weight, leaf area, and chlorophyll content for each cultivar at the four DLI levels.

*Influences on dry weight.* In contrast to fresh weight, dry weight (DW) of kale, lettuce, and spinach all showed significant linear increases in response to increasing DLI. This implies differences in water content at harvest among the different light intensities, despite consistent irrigation before harvest. Figure 5.1 illustrates the positive, linear effect increasing DLI has on dry weight for each species. Kale consistently has the highest DW, ranging 0.188g at DLI 8 to 0.277g at DLI 14 ( $DW = 0.09 + 0.014(DLI)$ ,  $r^2=0.67$ ), while lettuce has the greatest increase in DW when ranging from 0.068g at DLI 8 to 0.206 g at DLI 14 ( $DW = -0.12 + 0.023(DLI)$ ,  $r^2=0.85$ ). Spinach had the lowest rate of increase in DW ranging from 0.133g at DLI 8 to 0.189g at DLI 14 ( $DW = 0.07 + 0.008(DLI)$ ,  $r^2=0.64$ ).

*Influences on leaf area.* In spinach and lettuce, leaf areas (LA) were significantly higher in DLI 14, and significantly lower in DLI 8 than other treatments. Conversely, kale leaf areas were significantly higher in DLI 8, and lower in DLI 14 than other treatments.

*Influences on chlorophyll.* The relationship between chlorophyll (CHL) and DLI for kale was best described by a quadratic model ( $CHL = 49.3 - 5.32(DLI) + 8.9(DLI)^2$ ) returned a  $r^2 = 0.34$ . CHL levels decreased from DLI 8 to DLI 12 then increased at DLI 14. Lettuce and spinach CHL levels displayed similar trends, but were not significant at the  $p < 0.05$  level.

## Discussion

The goal of this study was to advise northern tier high tunnel growers as to how much additional light to buy in order to maintain growth in leafy greens throughout low-

light winter months, and as to which species may be more responsive to additional lighting.

Several studies indicate positive linear response of FW to increasing light levels (Gent, 2014; Gent, 2016; Lefsrud et al., 2006a; Lefsrud et al., 2006b). These studies utilized a hydroponic growing system which would minimize variation in tissue water content at harvest. Our study attempted to simulate conditions similar to commercial production methods: high plant densities in growing media. Water content of leafy greens in this study were very high ranging from 91% - 95%, so a slight variation in plant water status at harvest could greatly influence FW results.

We can conclude that kale, lettuce, and spinach all positively respond to increases in DLI within the relatively narrow range of treatments, but that lettuce benefits the most from increased light: a DLI of 14 results in 203% in DW over a DLI of 8 compared to a 47% increase for kale and 42% increase for spinach (figure 5.2). We observed DW increases with each additional increase in DLI but increases between DLI 10 and DLI 12 treatments were never significant, indicating that the addition of  $2 \text{ mol m}^{-2} \text{ d}^{-1}$  to increase DLI from 10 to 12 is not effective. However, dry biomass increases for lettuce between DLI 12 and DLI 14 were significant, indicating that a  $2 \text{ mol m}^{-2} \text{ d}^{-1}$  addition could be effective for lettuce at a DLI of  $12 \text{ mol m}^{-2} \text{ d}^{-1}$ .

Curiously, kale has lower leaf area at higher DLI ( $18.73 \text{ cm}^2$  at DLI 12), and higher leaf area at lower DLI ( $25.46 \text{ cm}^2$  at DLI 8). Leaves may develop larger but thinner, a species-specific mechanism to intercept more light in low-light conditions.

We observed a consistent trend whereby CHL levels decreased from DLI 8 to DLI 12, and then increased from DLI 12 to DLI 14, indicating a similar reaction to increasing light levels across cultivars. There is evidence that low light conditions affect the density and size of chloroplasts. Fu et al. (2012) found fewer chloroplasts in lettuce grown under low light conditions than in lettuce grown under high light conditions, but that low light chloroplasts covered more surface area (Fu et al., 2012). Furthermore, research suggests that the chloroplasts themselves are denser in plants grown in low light conditions than in those grown in higher light conditions; Lichtenthaler et al. (1982) found broader grana and higher grana stacks with more thylakoids per granum in radish seedlings grown in low light conditions than those grown in higher light conditions. This combination of denser, wider chloroplasts leads to higher pigment density (Lichtenthaler et al., 1982). Our study indicates that chlorophyll levels in plants grown under low to moderate DLI levels requires further investigation.

While not quantitatively measured, red pigment expression in the red oak leaf lettuce variety included in the All Star mix was greatly influenced by DLI. Photos (Figure 5.3) illustrate little to no red coloration at DLI 8 to moderate red pigment expression at DLI 14. This observation would be consistent to reports in the literature correlating low light levels to reduced anthocyanin production (Kleinhenz et al., 2003).

*Practical application for northern high tunnel growers.* Faust and Logan's interactive DLI map indicates that the monthly average DLI in Bozeman, MT for November is  $11.3 \text{ mol m}^{-2} \text{ d}^{-1}$ . A typical high tunnel covered with a single layer of greenhouse plastic film located in Bozeman, MT blocks ~ 35% of the incoming

photosynthetically active radiation (PAR) in early November (Baumbauer, unpublished data). This reduction results in a DLI within the high tunnel of  $\sim 7 \text{ mol m}^{-2} \text{ d}^{-1}$ . Using this information high tunnel growers can calculate locally-specific additional light requirements for each cultivar and allocate additional lighting toward cultivars that respond more for a given DLI increase, allowing them to effectively extend the season and get the most out of their additional lighting investment while keeping production costs to a minimum.

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Table 5.1. Fresh weight, dry weight, leaf area, and chlorophyll levels for kale, lettuce and spinach grown under various DLIs utilizing Fluorescent-Incandescent lamps. Lower case letters refer to significant differences ( $P < 0.05$  level) between DLI levels determined by LSD test. Quadratic models were fit for CHL levels. Letters refer to significant difference at  $P < 0.05$  level.

Species	DLI ( $\text{mol m}^{-2} \text{d}^{-1}$ )	Fresh Weight (g)	Dry Weight (g)	Leaf Area ( $\text{cm}^2$ )	CHL
Kale	14	3.03 <sup>a</sup>	0.277 <sup>a</sup>	20.07 <sup>ab</sup>	49.91 <sup>a</sup>
	12	2.72 <sup>a</sup>	0.247 <sup>ab</sup>	18.73 <sup>b</sup>	45.60 <sup>b</sup>
	10	3.33 <sup>a</sup>	0.236 <sup>b</sup>	24.31 <sup>ab</sup>	48.90 <sup>c</sup>
	8	3.07 <sup>a</sup>	0.188 <sup>c</sup>	25.46 <sup>a</sup>	52.78 <sup>d</sup>
Lettuce	14	4.33 <sup>a</sup>	0.206 <sup>a</sup>	44.72 <sup>a</sup>	37.51
	12	2.90 <sup>b</sup>	0.146 <sup>b</sup>	36.61 <sup>ab</sup>	34.18
	10	2.39 <sup>b</sup>	0.108 <sup>b</sup>	33.02 <sup>ab</sup>	34.95
	8	1.27 <sup>c</sup>	0.068 <sup>c</sup>	27.75 <sup>b</sup>	38.68
Spinach	14	2.25 <sup>a</sup>	0.189 <sup>a</sup>	14.26 <sup>a</sup>	45.16
	12	2.07 <sup>a</sup>	0.166 <sup>ab</sup>	13.28 <sup>ab</sup>	41.95
	10	2.20 <sup>a</sup>	0.152 <sup>bc</sup>	14.07 <sup>a</sup>	44.66
	8	2.03 <sup>a</sup>	0.133 <sup>c</sup>	11.86 <sup>b</sup>	46.48

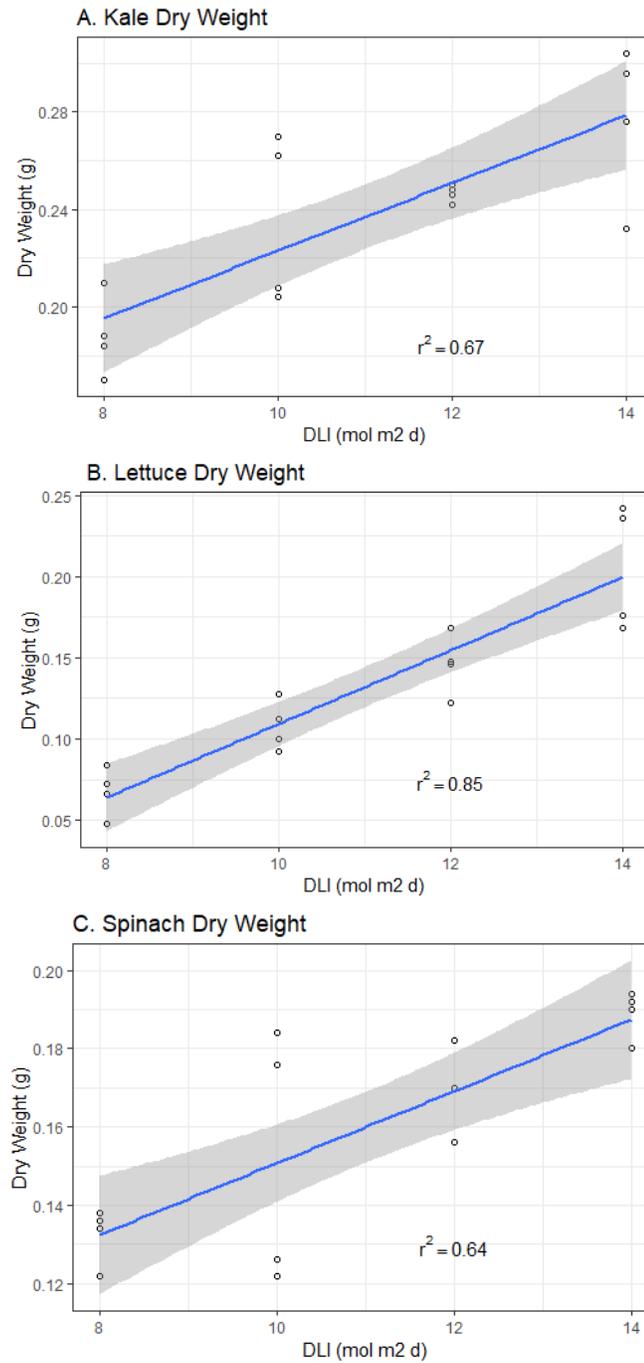


Figure 5.1. Average dry weight per plant of kale (A), lettuce (B), and spinach (C) at DLI of 8, 10, 12, and 14 mol m<sup>-2</sup> d<sup>-1</sup>. Shading around lines depicts the 95% confidence interval.

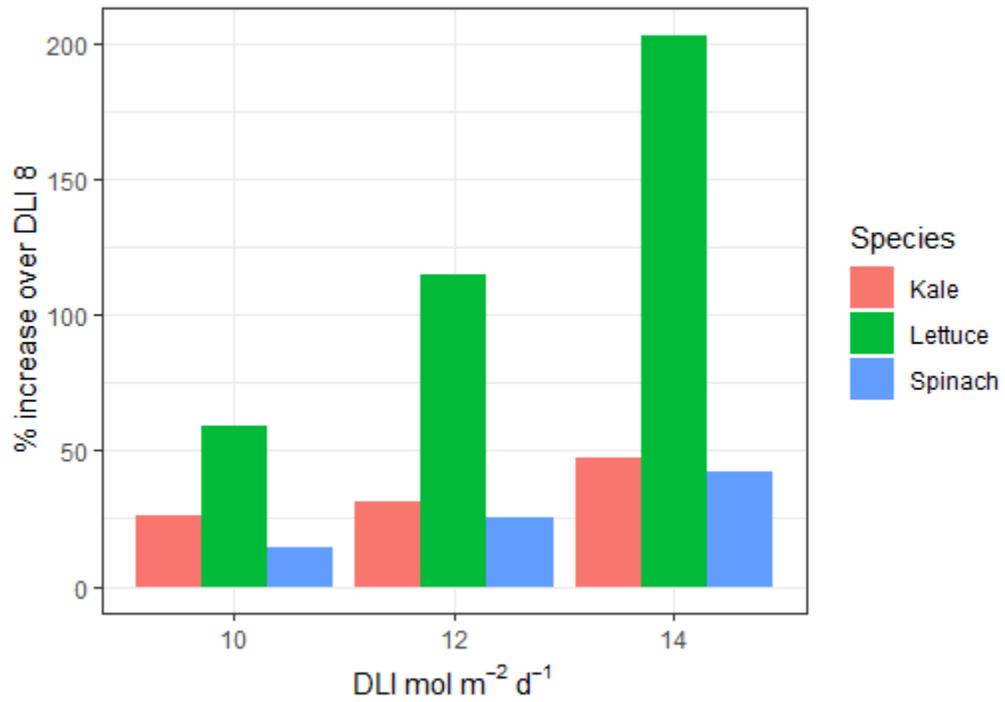


Figure 5.2. Percentage increase in dry weight of kale (pink), lettuce (green) and spinach (blue) grown at DLI = 10, 12, and 14 mol m<sup>-2</sup> d<sup>-1</sup> over the same species grown at a DLI of 8 mol m<sup>-2</sup> d<sup>-1</sup>.



Figure 5.3. Leaf color influenced by DLI. All Star lettuce mix grown for 28 days in a growth chamber at  $DLI = 14 \text{ mol m}^{-2} \text{ d}^{-1}$  (top) and  $DLI = 8 \text{ mol m}^{-2} \text{ d}^{-1}$  (bottom).

## CHAPTER SIX

## CONCLUSIONS

*Addressing Grower Needs*

High tunnels can be a valuable addition to the Montana market gardener's production system by increasing daytime air temperatures, and protecting crops from desiccating winds, hail storms, and frost damage. Many of the Montana high tunnel grower's survey (Chapter 2) respondents were new to market gardening with 48% of the respondents reporting having five or fewer years in business and new to high tunnel growing with 52% of respondents having four or less years of experience. Cool season high tunnel vegetable production was practiced by 61% of respondents and a follow-up on what limits the remaining from participating would be interesting future research. Farms located near urban areas might have the advantage of easier access to extended season markets such as winters farmer markets or CSAs. Ward et al., 2011 found that profitable high tunnel production in Utah depended on access to direct markets where returns were higher than wholesale (Ward et al., 2011). Waldman et al., 2012 followed 12 novice high tunnel farmers in Michigan for three years and the most successful growers reported their highest months of profit from the high tunnels occurred during the shoulder seasons of April/May and September/October (Waldman et al., 2012). The growing interest in local food should provide more opportunities for Montana high tunnel growers to take advantage of extended season markets.

Successful high tunnel production requires a mix of skill sets found in field production and greenhouse growing. Survey respondents appeared to have a good understanding of soil fertility management with high levels of participation with cover crops, crop rotations and soil testing. Protected cultivation techniques, whether they be low tunnels to fully automated greenhouses, not only accelerate plant growth they also tend to accelerate problems such as plant nutrition and pests, which can cause difficulties for growers with mainly field production experience. Future research at SERP could investigate high tunnel soil fertility and weed management strategies as there is evidence in the literature that these issues become more prevalent in the high tunnel over time (Reeve and Drost, 2012; Scotti et al., 2015).

#### *Balancing Light and Heat*

In the high tunnel, solar radiation not only provides the energy required for photosynthesis, it is also the source of heat. Solar radiation trapped by the structure warms the air and soil during the day. The work presented in chapter three emphasizes the role that a secondary layer of row cover used within the high tunnel can play to moderate very low outside air and soil temperatures. Our findings indicate that contribution of the row cover increases as night time air temperature decreases. Growers interested in maintaining the highest possible night time air and soil temperatures within their high tunnels need to utilize row cover within the tunnel. Future research could include adding daytime row cover removal as a treatment to determine the possible increase in PAR.

The heat retention afforded by the high tunnel plus row cover treatment did come at the cost of lower light levels, with high tunnel plus row cover having 68-81% of the PPFD transmission of the high tunnel alone. The results of the cool season crop production portion of the dissertation presented in chapter four indicate that increases in crop yields were only recorded when the average outside air temperature during the production cycle was below historical average air temperatures. Seeding date for fall crops had a great impact on crop yield, as all species had higher yields and fewer DTH from mid-August seeding dates than late August. Early fall seeded leafy greens consistently had enough time for regrowth to occur, allowing for a second harvest. Beet and carrot had to be sown by mid-August to ensure even a modest yield. As the DLI decreased as the fall season progressed, beet and carrot failed to increase root diameter to market size. Montana growers interested in fall produced fresh market beet and carrot should consider mid-August as the latest feasible sowing date. Spring seeding date was not as critical, as early March sown crops typically had greater DTH than mid-March sown crops. Row cover positively influenced yields only during the cold spring of 2018. Future research could investigate the influence on daytime row cover removal on crop yields and DTH. Multiple harvests based on discreet time intervals instead of market size would allow for the development of plant growth curves that could potentially be combined with GDH, SDH and DLI to develop a model to predict optimum row cover deployment conditions.

*Determining Minimum DLI for Leafy Greens*

Our survey results indicate that a few Montana growers utilize unit heaters within their high tunnels, with the thermostat set at the crop's base temperature. The concept of the 'cool' high tunnel or minimally heated high tunnel has been promoted in the popular press (Coleman, 2009; Fortier and Bilodeau, 2014). The work presented in chapter five reports on our efforts to determine the minimally illuminated greenhouse by utilizing growth chambers to deliver a consistent DLI over the 28 days cropping period for kale, lettuce, and spinach. All species responded positively to increasing DLI with lettuce having the greatest response to additional light, producing a 200% increase in dry weight when grown at DLI equal to  $14 \text{ mol m}^{-2} \text{ d}^{-1}$  versus  $8 \text{ mol m}^{-2} \text{ d}^{-1}$ .

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APPENDICES

APPENDIX A

MONTANA HIGH TUNNEL GROWERS SURVEY

### Montana High Tunnel Grower Survey

- 1) What county is your farm located? \_\_\_\_\_
- 2) How many years have you been market gardening?  
 \_\_\_\_\_ One year or less  
 \_\_\_\_\_ Two to four years  
 \_\_\_\_\_ Five to ten years  
 \_\_\_\_\_ More than 10 years
- 3) How many years have you gardened with a high tunnel?  
 \_\_\_\_\_ I don't have a high tunnel. You may stop the survey. Thank you for participating.  
 \_\_\_\_\_ One year or less  
 \_\_\_\_\_ Two to four years  
 \_\_\_\_\_ Five or more years
- 4) What is the total production area of your market garden?  
 \_\_\_\_\_ ½ acre or less  
 \_\_\_\_\_ ½ acre to 2 acres  
 \_\_\_\_\_ 2 to 5 acres  
 \_\_\_\_\_ 5 to 10 acres  
 \_\_\_\_\_ More than 10 acres
- 5) Which **one** of the following best describe your operation?  
 \_\_\_\_\_ Conventional practices  
 \_\_\_\_\_ Certified Organic  
 \_\_\_\_\_ Transitional Organic  
 \_\_\_\_\_ Organic practices without certification  
 \_\_\_\_\_ Other sustainable certification (i.e. Western Montana Growers Cooperative)  
 \_\_\_\_\_ No longer a market gardener
- 6) Which of the following categories of garden products do you grow and market?  
 \_\_\_\_\_ Vegetables  
 \_\_\_\_\_ Flowers  
 \_\_\_\_\_ Herbs  
 \_\_\_\_\_ Berries or other fruit  
 \_\_\_\_\_ Other \_\_\_\_\_

7) What are your three principal markets?

- Farmers markets  
 CSA  
 Restaurant  
 Farm stand  
 Grocery stores  
 Food processors  
 Others \_\_\_\_\_

8) How many high tunnels do you have on your farm? \_\_\_\_\_

9) Total Square Footage of High Tunnel(s)

Stationary tunnels \_\_\_\_\_ Moveable tunnels \_\_\_\_\_

10) If you have **moveable** high tunnels, how many times a year do you move the tunnels?

- 0  
 1  
 2  
 3 or more

11) What material is used to cover the roof of your high tunnels?

- One layer of polyethylene greenhouse film plastic  
 Two layers of polyethylene greenhouse film plastic with inflation  
 Another flexible film material  
 Rigid greenhouse covering

12) Which of the following are used to heat your high tunnel?

- Gas/Propane/Oil unit heater  
 Root zone heating (electric heat mat, hot water bench top heating)  
 Active solar heat collection with storage (water, rock...)  
 Passive solar heat collection (water barrels...)  
 No supplemental heating system

13) Which of the following are used to cool your high tunnel?

- End wall vents  
 Roll up side walls  
 Roof vents  
 Shade cloth  
 Exhaust fans  
 Evaporative cooling (fog cooling, pad cooling...)

14) Which of the following season extension products do you use in the high tunnel?

- Plastic mulch
- Spun polyester row cover (Agribon, Reemay....)
- PVA (Tufbell, Dio-Betalon film, .....
- Hot caps or Cloches
- Other \_\_\_\_\_

15) Please check which of the following statements most reflects your objective for high tunnel growing?

The high tunnel is used primarily for protecting warm season crops (tomatoes, cucumbers...) and allowing you to get drops early to market

High tunnels are critical in lengthening the growing season for producing cool season crops.

High tunnels are critical in lengthening the growing season and producing **both** cool season and warm season crops.

16) What are your top three economically important warm season high tunnel crops?

i) \_\_\_\_\_ ii) \_\_\_\_\_ iii) \_\_\_\_\_

17) What are your top three economically important cool season high tunnel crops?

i) \_\_\_\_\_ ii) \_\_\_\_\_ iii) \_\_\_\_\_

18) What three crops do you find particularly challenging to grow in the high tunnel?

i) \_\_\_\_\_ ii) \_\_\_\_\_ iii) \_\_\_\_\_

19) What are your three biggest challenges to producing crops in a high tunnel?

i) \_\_\_\_\_

ii) \_\_\_\_\_

iii) \_\_\_\_\_

20) Which of the following tools/services do you use when making soil fertility decisions? Please check all that apply.

- Regular soil testing using a commercial soil analytical lab (at least biennially)  
 Irrigation water quality test using a commercial lab  
 Plant tissue tests using a commercial lab  
 On farm soil tests using DIY test kits  
 On farm water tests using DIY test kits  
 Crop advisors  
 None of the above  
 Other \_\_\_\_\_

21) Which of the following soil amendments do you use on an annual or biennial basis? Please check all that apply.

- Farm made compost  
 Commercial compost  
 Farmyard manure  
 Commercial manure products  
 Others \_\_\_\_\_

22) Which of the following fertilizers do you utilize on an annual or biennial basis? Please check all that apply.

- Animal byproduct fertilizers (blood meal, bone meal, fish....)  
 Plant based fertilizers (alfalfa pellets, cottonseed meal, kelp....)  
 Rock/mined mineral powders (sulfur, gypsum, greensand....)  
 Multi-element fertilizers (10-10-10, 20-10-20...)  
 Urea or other Nitrogen fertilizers  
 Liquid fertilizers  
 None

23) What is the **primary** means of irrigating your high tunnel?

- Manual with a garden hose  
 Overhead sprinklers  
 Drip tape or soaker hose  
 Other \_\_\_\_\_

24) Which of the following techniques do you use to prepare the soil for planting/seeding? Please check all that apply.

- Pre-plant irrigation to leach salts from the root zone  
 Broad fork or spading fork to loosen soil  
 Rototilling  
 Spading machine  
 Rotary harrow  
 Rotary plow  
 Other \_\_\_\_\_

25) Do you practice crop rotation in the high tunnel?

- Yes
- No

26) When not producing a cash crop, do you grow a cover crop in the tunnel?

- Yes
- No
- Occasionally if the timing allows for a cover crop

27) **Rank** the following pest issues by economic importance, with 1 being the most important and 4 the least

Summer Growing

- Weeds
- Insects
- Diseases
- Vertebrate Pests (Gophers, Mice...)

Spring/Fall Growing

- Weeds
- Insects
- Diseases
- Vertebrate Pests

28) Which of the following pest management tools/practices do you use in the high tunnel? Please check all that apply.

- Weekly monitoring for pests using sticky cards, sweep nets, weed seedling scouting....
- Exclusion of pests by screening vents and doors
- Biological control agents such as beneficial insects and microbes
- OMRI approved pesticides
- Bio-rational pesticides (products with low mammalian toxicity, and soft on beneficial insects)
- Conventional pesticides

- 29) Please check your top **three** sources for high tunnel growing information?
- County or state extension service, including extension publications and websites
  - Commercial crop advisors
  - Horticulture/Farm supply vendors
  - Trade Publications and websites
  - NCAT-ATTRA
  - SARE
  - USDA
  - NRCS
  - Montana Department of Agriculture
  - Farmer Organizations
  - Other
- 

30) Please rank (1-5) the following areas for your greatest need for information to ensure your high tunnel is productive and profitable in the future? With 1 being the greatest need.

- Growing specific crops
- Pest, disease, insect and nutrient management
- Record keeping and accounting
- Marketing and sales
- Rules and regulations
- Other areas \_\_\_\_\_

Thank you for your cooperation in completing this survey.