CLIMATE CHANGE
ADAPTATION PROGRAM

Modification of Radiation and Energy Balances Using Plastic Films as Soil Mulches and In Low Tunnels

Funding for this project has been provided by the Governments of Canada and British Columbia through Growing Forward 2, a federal-provincial-territorial initiative. The program is delivered by the Investment Agriculture Foundation of BC.

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Modification of Radiation and Energy Balances Using Plastic Films as Soil Mulches and In Low Tunnels

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Terminal Report
February 2018

a place of mind
UBC

Acknowledgments

Funding for this project has been provided in part by the Governments of Canada and British Columbia through the Investment Agriculture Foundation of BC under *Growing Forward 2*, a federal-provincial-territorial initiative. The program is delivered by the BC Agriculture & Food Climate Action Initiative.

Thanks to Robert Borsato and Catherine Allen of Mackin Creek Organic Farm, and Lydia Ryall of Cropthorne Organic Farm for collaborating on this research. Thanks are due to our PhD student Hughie Jones for taking the lead on this research, and to undergraduate summer research assistants (USRA's) - Thea Rodgers, Ernest Wu, Nikki Lax and Brian Wang - for their help in setting up experiments and instrumentation and help with data collection. Financial assistance from Dean Rickey Yada, Faculty of Land and Food Systems, UBC, Center for Sustainable Food Production at UBC, and NSERC (for partly supporting two USRA's), and in-kind support from Osborne Seed Company and ATI Films is gratefully acknowledged. We are thankful to project manager Samantha Charlton (Farm Adaptation Innovator Program, BC Agriculture & Food Climate Action Initiative) for her liaison work and quality guidance throughout the project.

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Contents

Executive summary

Use of plastic films as mulches and in enclosures has become a standard practice in horticulture to aid in weed control, conserve soil water, and raise soil and air temperature. However, their potential as a means to adapt to climate change with increased occurrence of extreme weather conditions has not been explored. This has become more relevant with the availability of modern speciality films, such as low-albedo black films, high albedo white films, photosynthetically-active radiation blocking infrared transmitting films, black-on-white, and lower longwave transmitting films (e.g., Thermax). We studied the effects of nine state-of-the-art commercially available plastic films as mulches and in low tunnels for their ability to modify microclimates and affect plant growth at three certified organic farms: UBC Farm (Vancouver, BC), Mackin Creek Farm (Near Soda Creek, BC) and Cropthorne Farm (Westham Island, BC). First of all, these nine plastic films were characterized for their radiative properties in the laboratory and outside under the sun using a shortwave spectroradiometer. Their use as mulches in an experiment conducted at UBC Farm showed that black plastic films reflected very little sunlight (i.e. low albedo) and increased soil temperature. In contrast, white plastic films reflected more sunlight (i.e. high albedo), and typically decreased soil temperature. While transparent plastic films reflected a similar amount of sunlight as the soil surface they covered, they caused the largest increase in measured soil temperature. Highest achievable soil temperature occurred with black and transparent plastic films for high and low degrees of contact, respectively. Overall, these plastic film mulches provided a wide range of soil cooling and warming potential (-20% to 55%).

The effect of using Thermax and two high shortwave transmissivity regular and perforated polyethylene films in low tunnels on soil temperature and energy balance was studied at UBC Farm. On a sunny day, all three plastic films transmitted 90% of the incoming shortwave radiation to the black plastic mulch floor for heating inside air. However, due to lower net loss of longwave energy for Thermax compared to polyethylene films, it was about 30% more efficient in heating the inside of the low tunnels. In another experiment, also at UBC Farm, growth of Padrón pepper was studied in low tunnels covered with regular polyethylene and Thermax in comparison to no cover. Low tunnel grown peppers produced more peppers per harvest period, but by mid to late August, the harvest rate declined for the low tunnel grown peppers, most likely due to a depletion of CO_2 during the daytime. These results suggest the need to examine the value of periodic tunnel ventilation or CO_2 fertilization. Nevertheless, regular polyethylene and Thermax tunnels yielded ~12% more peppers than no-cover during the entire harvest period. At Cropthorne Farm and Mackin Creek Farm, regular polyethylene low tunnels increased zucchini and broccoli yields by 20% and 200%, respectively.

This research is beneficial to make decisions for choosing appropriate films depending upon seasons and eco-climate regions in BC. The outcome of this research was disseminated to scientists, students, extension workers and farmers through (1) eleven presentations at different

fora, (2) two fact sheets, (3) one handout, and (4) a video project on “Crop-protection research and innovation for adaptation to climate change in BC”.

List of presentations

1. Effect of plastic mulches on surface albedo and soil temperature. Joy of Feeding event at UBC Farm, September 2015. (35, 10)
2. Plastic film mulches and low tunnels to help BC farmers adapt to climate change. Agriculture and Climate Change Adaptation Research Workshop in Kelowna, December 2015.
3. Radiative properties of plastic films and their use as soil mulches and low tunnels to modify crop microclimate. Canadian Society of Soil Science Annual Meeting, Kamloops, May 14-19, 2016.
4. Radiative properties of plastic films and their use as soil mulches and low tunnels to modify crop microclimate. UBC Farm Staff Meeting, June 15, 2016.
5. Radiation and heat transfer from plastic films used as soil mulches and in low tunnels. Land & Food Systems at UBC, October 28, 2016.
6. Effects of plastic mulches and low tunnels on air and soil temperature. Food Sustainability symposium at UBC, January 26, 2017.
7. Radiation and heat transfer from plastic films used as soil mulches and low tunnels. Practical Tips and Tools for Small-Scale, Diversified Farmers, UBC Botanical Garden, January 29, 2017.
8. Radiative properties of plastic films and their use as soil mulches and in low tunnels to modify crop microclimate. CGU and CSAFM Joint Annual Scientific Meeting, Vancouver, BC, 28-31 May 2017.
9. Plastic films and their use as soil mulches and in low tunnels to modify crop microclimate and productivity. BC Agricultural Climate Adaptation Research Workshop, December 7-8 2017, Abbotsford, BC.
10. Using plastic film mulches and low tunnels for crop protection and season extension. Horticulture Growers Short Course, Abbotsford BC, January 25-27 2018.
11. Using plastic film mulches and low tunnels for crop protection and season extension in the Cariboo Region of BC. Cariboo Agricultural Research Alliance: Launch & Applied Research Workshop Pioneer Complex, Williams Lake BC, February 14, 2018.

List of Fact Sheets

Chapter 1
Introduction

While use of plastic mulches has become standard practice in horticulture to aid in weed control, conserve soil water, and raise soil temperature, their potential as a means to adapt to climate change has not been explored. Similarly, studying plastic films in low tunnels, which have long been a tool used in horticulture to extend the growing season and increase produce quality by sheltering the crop from the weather, has become even more relevant under climate change with increased occurrence of extreme weather conditions. Crop producers worldwide are facing challenges and opportunities associated with climate change and variability (e.g., Lee et al. 2011; Olesen et al. 2011; Traore et al. 2013; Mereu et al. 2015). In Canada, with generally low mean annual temperatures, climate change-induced warming may provide opportunities for new types of crops, increased growing-season length, and increased crop productivity. However, water deficits may offset potential crop productivity gains in some regions (Smith et al. 2011). In British Columbia (BC), increased annual temperature may enable fruit to be grown in regions where previously it was not possible (Rayne and Forest 2016). In BC, temperatures have increased on average by 1.4 ^{o}C from 1900 to 2013 (BC Ministry of Environment 2016), and it is predicted that in southwestern BC, temperatures will increase by 0.8 to 2.6 ^{o}C and 1.4 to 3.6 ^{o}C in the wintertime and summertime, respectively, by the 2050's (Zwiers et al., 2011). Annual precipitation has increased across BC, yet it is expected that more wintertime precipitation will fall as rain, limiting snowpack and glacier accumulation, which are essential for summer streamflow and irrigated lands in BC (Kang et al. 2016; Schiefer et al. 2007; Werner et al. 2013).

Different plastic mulches and low tunnels can be used to modify the cropping environment of vegetable crops thereby enhancing crop yields and quality in addition to the benefits of protection from wind, rain, insects, disease, and vertebrate pests. Thus these mulches have a great potential to help farm adaptation to predicted climate change. For example, the use of transparent (clear) and black films result in large and moderate increases in soil temperature, respectively, while white-on-black film lowers soil temperature. Black films also have the advantage of eliminating weeds. Highly reflective metallized films also reduce soil temperature but in addition reduce insect populations. Infrared transmitting films blocks PAR, thereby preventing weed growth but transmits in the near infrared part of the solar spectrum thereby resulting in warming greater than low-albedo black films. Using lower longwave transmitting films (e.g., Thermax, AT Films Inc.) in low tunnels should provide superior frost protection by reducing longwave (far infrared) radiant heat loss. It also has exceptional condensation control properties and generates a high proportion of diffuse PAR beneficial for crop growth. This film has considerable potential in northern interior BC in producing early berries and vegetables.

Plastic mulches are known to conserve soil moisture (θ_s) by reducing soil evaporation (E_s) (Dlamini et al. 2016; Yin et al. 2016), alter the surface energy balance (Hanson 1963; Tanner 1974), and alter soil (T_s) and air temperature (T_a) (Baille et al., 2001; Tarara 2000; Singh et al., 2012). Unlike thick mineral or organic mulches, plastic film mulches are thin while also reducing soil evaporation (E_s), allowing for unique shortwave (S) and longwave (L) properties (e.g., high shortwave radiation τ (τ_s) and low longwave τ (τ_L). High reflectivity (ρ_s) plastic films not only reduce net solar radiation (S_n) at the plastic surface they also reduce the S_n of the soil they cover, which results in reduced soil heat flux (G) and T_s at the soil surface at midday (Ham et al., 1993). The effect of various mulches on crop growth and yield has been studied extensively. Brandenberger and Wiedenfeld 1997 found use of any plastic mulch increased average T_s, total yield and fruit size, with an average yield increase of 42% and 27% for muskmelon in the first and second year of growth, respectively. Taber et al. (1993) found that clear polyethylene and wavelength selective (IRT 76) polyethylene films used as mulch increased early muskmelon yield by 300% and muskmelon survivability from 64% to 86% and 98% when plastic mulch and row covers (i.e., like low tunnel) were used, respectively. Ibarra et al. 2001 found that early muskmelon plant biomass, total leaf area and total marketable yield (10 to 32 days after seeding) were 0.59 g, 27.7 cm^2 and 13 t ha^{-1} for bare soil and 1.77 g, 195 cm^2 and 48 t ha^{-1} for black plastic mulch, respectively. Interestingly, Egel et al. (2008) found that although cumulative watermelon yields were 19,655 and 35,373 kg ha^{-1} for bare soil and black plastic mulch, respectively, tap root length was significantly lower for watermelons grown using black plastic, which was attributed to drought-like conditions experienced by the watermelon grown in bare soil. In China, Wang et al. (2016) showed that black plastic mulch increased maize yield and aboveground biomass more in dry regions, 93% and 59%, respectively, and less in wet regions, 30% and 37%, respectively, compared to bare soil. In Eastern Canada, Kwabiah et al.

(2004) found black plastic mulch increased corn cob weight, compared to corn grown in bare soil, by 18-26%, 19-24% and 9-13% for corn planted on May 1, May 15 and May 29, respectively. In BC Canada, Baumann et al. (1997) found that total strawberry yield increased from 2.8 t ha^{-1} in bare soil (i.e., control) to 3.2 t ha^{-1} and 3.5 t ha^{-1} when strawberries were grown in green and black plastic mulched plots, respectively. Ćosić et al. (2017) found that yield of irrigated sweet pepper increased from 6.5 Mg ha^{-1} in non-mulched plots to 11.3 Mg ha^{-1} in black plastic mulched plots. In contrast to many studies that found increased yield associated with plastic mulches, Wang et al. (2009) and Li et al. (1999) found reductions in yield of potato and spring wheat when black and transparent mulches were used for too long. Li et al. (1999) found if transparent plastic mulch was applied for more than 40 days after sowing (DAS), photosynthesis was supressed, which decreased yield.

Regarding low tunnels, those covered with medium to high sunlight transparency (i.e., high transmissivity) plastic films can significantly alter T_a and have potential to increase crop yields. The τ_s of the plastic film used to cover a low tunnel is of critical importance to the energy balance inside the tunnel as S_d is the largest term in the radiative balance during the daytime. Particularly in temperate climates, and during the shoulder seasons in tropical and arid climates, producers aim to maximize T_a and as a result seek the highest τ_s film. Elevation of T_a inside an enclosure can be beneficial for crop production but it is important to consider how elevated T_a affects vapour pressure deficit (VPD), E_s and evapotranspiration (E_c) in the enclosure and how productivity is affected. Although increased T_a may be favourable for plant growth and fruit production, particularly in cold and temperate regions, it may exceed the critical maximum temperature for a particular crop. Crop producers in arid or tropical climates often experience excessively high T_a and VPD, and high values of direct S_d during the summer, which can cause unwanted plant heat stress. Typically, evaporative cooling strategies are used in extremely hot climates, whereas ventilation and shading are used in less severe climates, but a combination of many cooling strategies can be advantageous depending on the desired outcomes of the producer (Kittas et al., 2003). Hunter et al. (2012) showed that early marketable tomato yield was increased from 1.2 kg $plant^{-1}$ in an unheated control high tunnel to 1.87 kg $plant^{-1}$ in a soil-and-air-heated high tunnel, an approximate difference of 0.7 kg $plant^{-1}$ between treatments, which equalled the difference in total marketable yield at the end of the growing season, which was 0.6 kg $plant^{-1}$ between treatments. Retamal-Salgado et al. (2014) found that blueberries grown under a high tunnel increased cumulative yield by 44% and harvest began 14 days earlier than blueberries grown outside the high tunnel.

In the last few years, increased abundance of plastic film products has corresponded to diversification of plastic film properties, resulting in the emergence of 'designer' plastic films, which contain certain additives. Additives give plastic films unique chemical, physical and radiative properties, enabling consumers to choose the plastic film most suitable for their specific growing applications. The additives used in plastic film manufacturing include ultraviolet (UV) stabilizers, longwave radiation absorbers and reflectors, photo-selective additives, fluorescent additives, photo-luminescent additives, anti-drip and anti-fog surfactants, pro-degradant additives (i.e., increased degradation in-situ) and ultra-thermic additives (Epsi et al., 2006, Markarian, 2006; Markarian, 2009; Scarascia-Mugnozza et al., 2011). Despite the aforementioned technological advances in plastic film manufacturing and the resulting benefits to consumers, plastic films also have the potential to cause adverse negative impacts to the local, regional and global environment. The most common thermoplastic polymers used to produce plastic films in agriculture include polyethylene (PE) (i.e., linear low density polyethylene (LLDPE), low density polyethylene (LDPE), high density polyethylene (HDPE)), polycarbonate (PC), ethylenvinyl acetate (EVA), and, to a lesser extent, polyvinylchloride (PVC) (Scarascia-Mugnozza et al., 2011). In fact, use of plastic films in horticultural production is increasing due not only to their general affordability, versatility, low weight and mechanical strength, but also to their suitable radiative properties (reflectivity (ρ), transmissivity (τ) and absorptivity (α)), and potential to alter soil and atmospheric microclimate.

The objectives of this research were 1) Evaluate state-of-the-art commercially available plastic films for their ability to enable crop producers to adapt to regional climate variability and change (e.g., soil moisture preservation, soil and atmospheric temperature alteration, and increased crop production), 2) Communicate predicted climate change impacts on growing conditions to increase grower awareness and knowledge regarding the role and efficacy of soil mulches and low tunnels. The field research of this project was performed at three certified organic farms: Research Farm of the University of British Columbia, Vancouver, BC (UBC Farm), Mackin Creek Farm (Near Soda Creek, BC) and Cropthorne Farm (Westham Island, BC). Work performed at UBC Farm and in the Biometeorology and Soil Physics Group (BIOMET) laboratory focused on instrument-intensive experiments related to radiation, energy and gas exchange in various soil mulch and low-tunnel treatments, which required continuous on-site measurements during the growing season. Work performed at Mackin Creek Farm and Cropthorne Farm focused on quantifying the effects of treatments on crop productivity.

Chapter 2

Spectral characterisation of plastic films

The aim of this chapter is to characterize the shortwave and longwave radiative properties of nine different plastic-film-mulches and their effects on T_s and G. The solar spectral irradiance (350-2500 nm) shown in Figure 1, for a typically sunny day in Vancouver, BC, is essential for calculating the shortwave radiative characteristics of these plastic films. Spectral radiative properties, ρ_λ and τ_λ, were measured for 9 plastic films (Table 1) using a shortwave spectroradiometer (350 nm – 2500 nm) (Fieldspec 3, ASD Inc., Longmount CO, USA) and α_λ was calculated as a residual of the sum of ρ_λ and τ_λ ($\alpha_\lambda = 1 - (\rho_\lambda + \tau_\lambda)$). ρ_s, τ_s and α_s were calculated as follows:

$$\rho_s = \frac{\int_{350}^{2500} \rho_\lambda E_\lambda d\lambda}{\int_{350}^{2500} E_\lambda d\lambda} \quad (1)$$

$$\tau_s = \frac{\int_{350}^{2500} \tau_\lambda E_\lambda d\lambda}{\int_{350}^{2500} E_\lambda d\lambda} \quad (2)$$

$$\alpha_s = \frac{\int_{350}^{2500} \alpha_\lambda E_\lambda d\lambda}{\int_{350}^{2500} E_\lambda d\lambda} \quad (3)$$

where E_λ is the shortwave spectral irradiance (Diffey et al., (2015) supplementary material).

Table 1. List of names and abbreviations for the 9 plastic mulch treatment used in this study.

Plastic mulch name	Plastic mulch abbreviation
Black embossed #2	BE2
Black embossed PABPNARB	BEP
Black on white	BW
White on black	WB
Infrared transmitting	IRT100

Green	GN
Red	RD
Thermax	TMX
Super 4	S4

The resulting values of τ_s, calculated using Eq. (2), are in Figure 2 and vary considerably. TMX and S4 are both moderately to highly transparent (60-80%) to visible radiation (VIR) and near-infrared radiation (NIR, 700-1400 nm). Transmissivity is highest in the shortwave infrared (SWIR, 1400-2500 nm) region of the spectrum, approximately 80%, but declines abruptly in two region of the SWIR region to values of 70% and 40-50%, at wavelengths 1650 to 1850 nm and 2200 to 2500 nm, respectively (Figure 2). GN has a much lower τ_s (0.34) than TMX and S4 which can be attributed to its low transmissivity to VIR and NIR with values if 0.01 to 0.2 and 0.01 to 0.7, respectively. RD has a distinct spectral shortwave transmissivity, with consistent values of 0.05 in the VIR region after which the spectral transmissivity gradually increases, with a nearly constant slope, from 0.05 at the start of the NIR region to 0.3 at the end of the SWIR region. All of the remaining plastic films (WB, BW, BE2 and BEP) have extremely low τ_s, particularly BEP. Aside from BEP, which has a transmissivity of nearly 0 for all shortwave wavelengths, the remaining plastic films (WB, BW and BE2) have similar shortwave spectral transmissivities, with values near 0 at 350 nm which gradually increase to a maximum of 0.1 at 2500 nm (Figure 2).

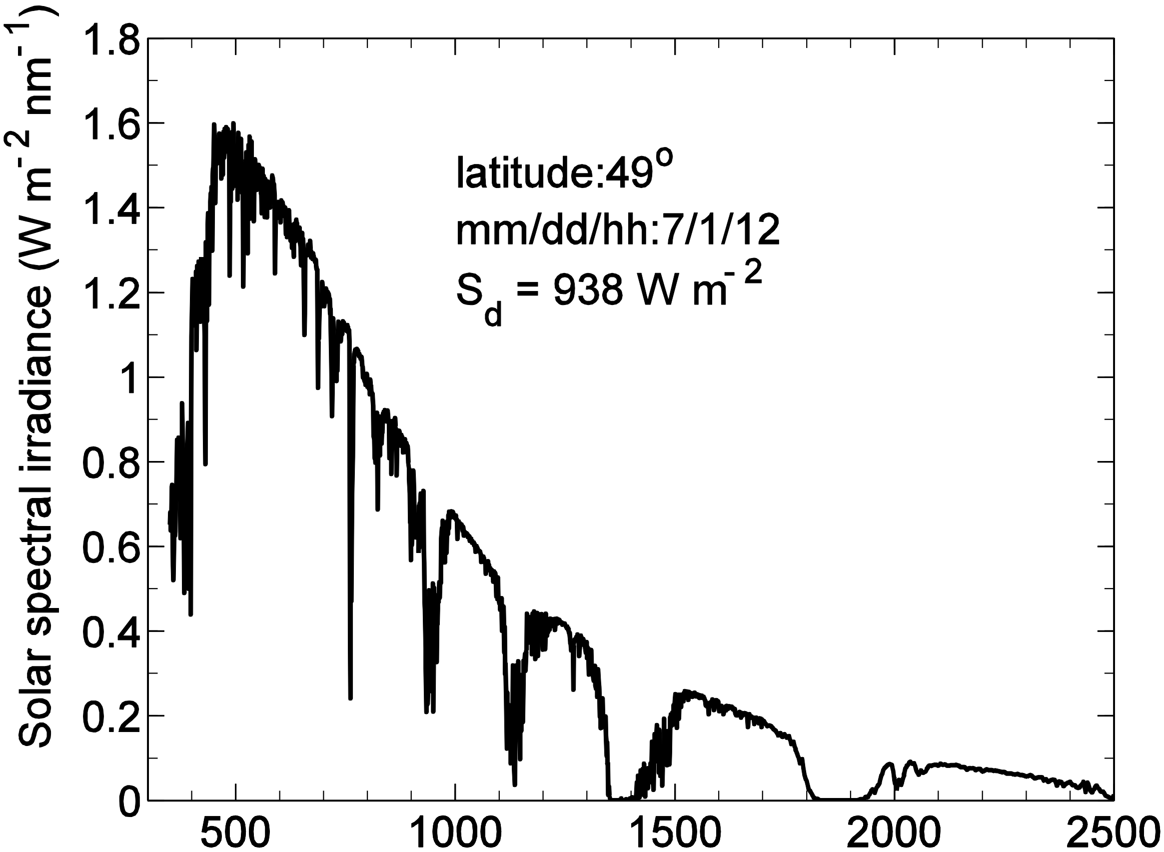

Figure 1. Solar spectral irradiance (350 – 2500 nm, 1 nm resolution) taken from Diffey (2015). Latitudinal angle (similar to Vancouver BC), time of year and day, and downwelling solar radiation (S_d) (W m^{-2}) are also shown.

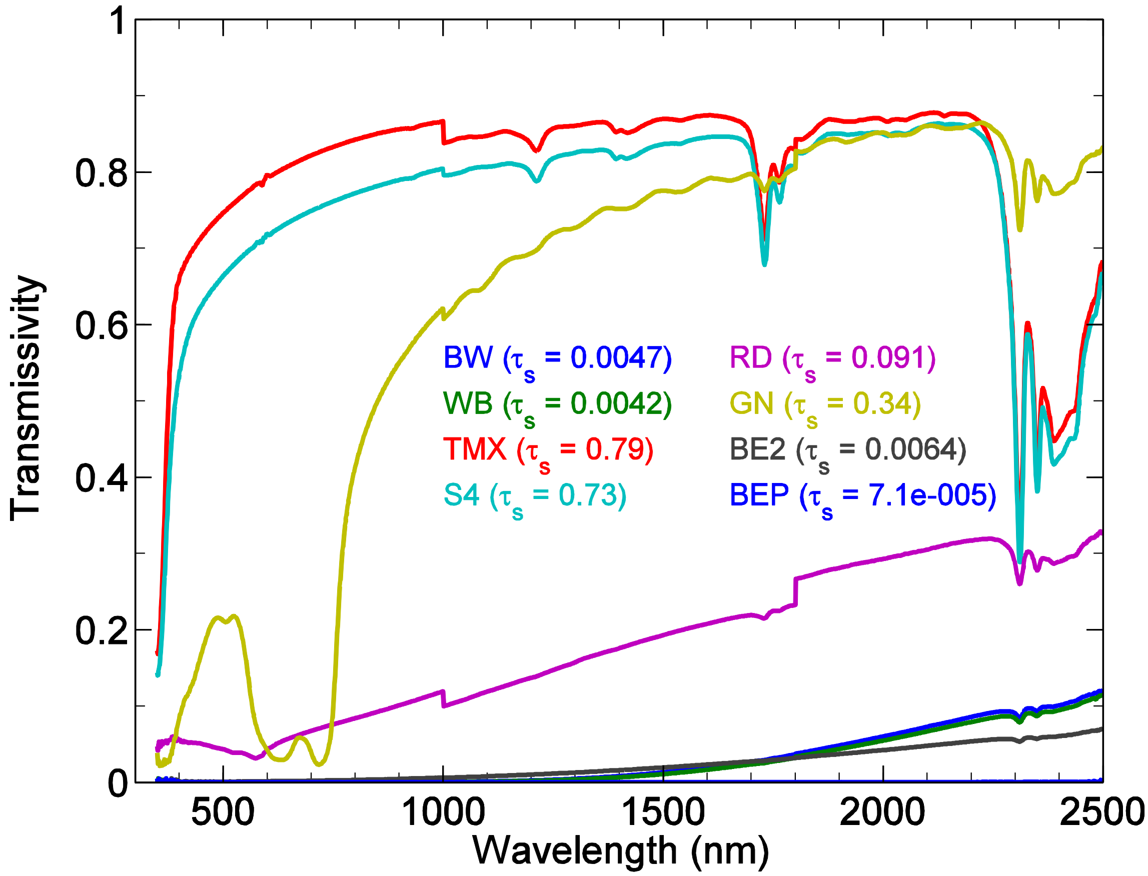

Figure 2. Shortwave (350 – 2500 nm) spectral transmissivity (τ_s) of 8 plastic mulch films: Black Embossed #2 (BE2); Black Embossed PABPNARB (BEP); and Black on White (BW), 2 clear: Thermax (TMX) and Super 4 (S4), Green (GN), Red (RD), and White on Black (WB) (the 9th film, Infrared Transmitting (IRT 100) was not included in this set of measurements). Values in parentheses were calculated using Eq. (2) and solar spectral irradiance data from Diffey (2015).

Chapter 3

Effects of plastic mulches on soil temperature and surface energy balance

The study was conducted at the UBC Farm (49°14'59.3"N, 123°14'15.4"W, 72 m.a.s.l). UBC Farm has a mild oceanic climate with humid, mild winters and dry summers with a 25-year (1991-2016) mean annual T_a and precipitation (P) of 10.6 ^{o}C and 1054 mm. UBC Farm experiences a sea and land breeze during the daytime and nighttime, respectively, due to its close proximity to the Strait of Georgia. In June of 2015, 10 treatments (9 plastic mulches, 1 control i.e., no plastic) were implemented on 1 m x 1 m plots on a tilled Podzolic soil at UBC Farm in a simple randomized complete block design (n = 3) with a 1.2 m buffer between each treatment (Figure 3). The site was prepared by installing an irrigation dripline at 0.05 m (near the center of the treatment area) and leveling the soil surface parallel to the predominant slope at the site (1^{o} grade, southerly aspect). A 0.15-m-wide and 0.15-m-deep perimeter trench was dug around each 1 m x 1 m treatment area to bury the edges of the plastic film, after which stones (> 2 cm) on the soil surface were removed by hand and the treatment area was levelled again with a 30-cm ruler. 1.2-m x 1.2-m sheets were cut from each plastic film roll and installed by: 1) securing one edge of the plastic film replacing soil removed during trenching, 2) minimizing the air gap between the soil surface and the plastic film by pulling the remaining 3 edges of the plastic tight while replacing soil removed during trenching. Although each plastic film was installed to minimize air gap between the soil surface and the plastic film a 0.01 – 0.02 m air gap remained after installation.

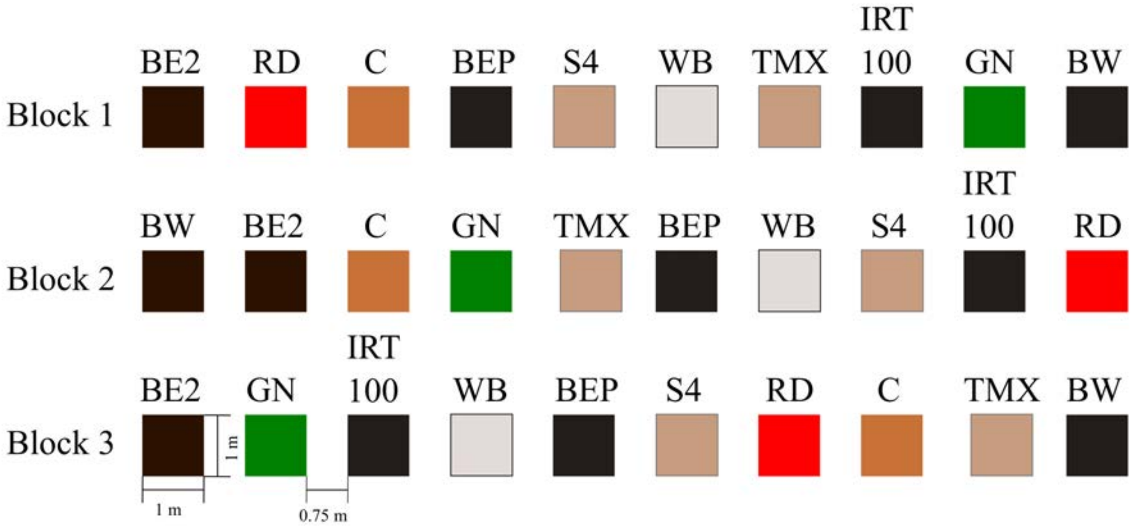

Figure 3. Overhead view of the experimental layout for comparing plastic films as mulches.

A weather transmitter (WXT520, Vaisala Oy, Helsinki, Finland) provided half-hourly mean T_a, P, wind velocity (u) and direction, barometric pressure (p) and relative humidity (RH) at a height of 2 m. For each treatment, previous to installing the plastic films, 1 soil heat flux plate was installed at the 3-cm depth, and 2 T_s and θ_s sensors (5TM, Decagon Devices Inc., Pullman, WA, USA) were installed at the 2-cm and 10-cm depths. All soil sensors were installed 12 cm uphill of the dripline. Net radiation (R_n), calculated as the sum of downwelling shortwave (S_d) and longwave (L_d) radiation minus the sum of the upwelling shortwave (S_u) and longwave (L_u) radiation, was measured using 2 four-way net radiometers (model CNR1, Kipp and Zonen, The Netherlands) consisting of upward and downward-facing pyranometers and pyrgeometers, mounted 15 cm above each treatment. All instrumentation was sampled once every 5 seconds, averaged and stored every 30 minutes on a datalogger (model CR5000, Campbell Scientific Inc. (CSI)), and collected weekly.

When placed on the soil surface, plastic films change the reflectivity of sunlight (albedo) and strongly control T_s. Black plastic films reflected very little sunlight (i.e. low albedo) and increased T_s (Table 2, Figures. 4 and 5). In contrast, white plastic films reflected more sunlight (i.e. high albedo), and decreased T_s. Thus modern plastic films used as soil mulches provide a wide range of soil cooling and warming potential (-20% to 55%).

Table 2. Effect of different plastic film mulches on soil temperature (T_s).

Plastic mulch	**Approximate % effect T_s (2 cm)**
BE2	+ 20%
BEP	+ 30%
BW	+ 30%
WB	- 20%
IRT100	+ 20%
GN	+ 30%
RD	+ 30%
TMX	+ 55%
S4	+ 30%

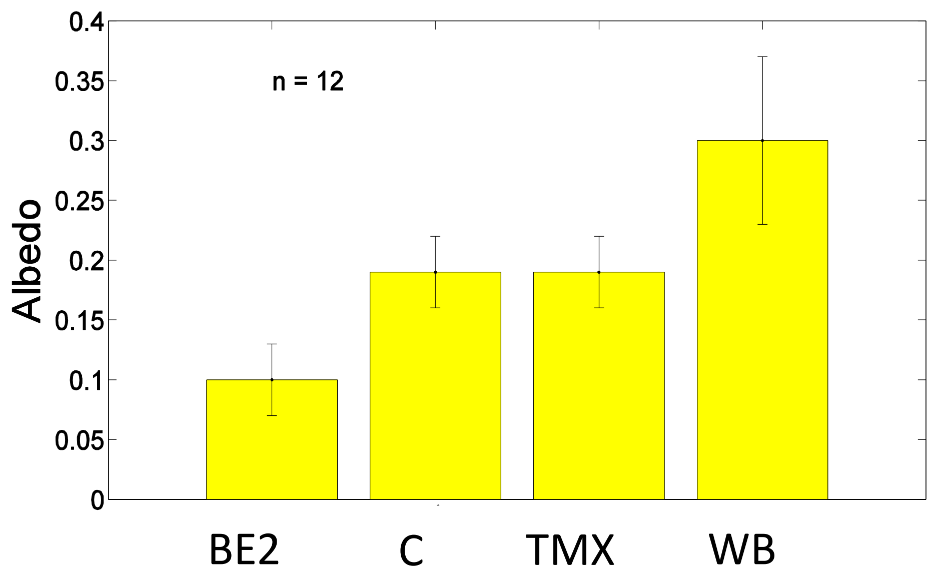

Figure 4. Measured albedos (i.e., reflectivity) of various plastic films at UBC Farm during a sunny day in August 2015 at mid-day.

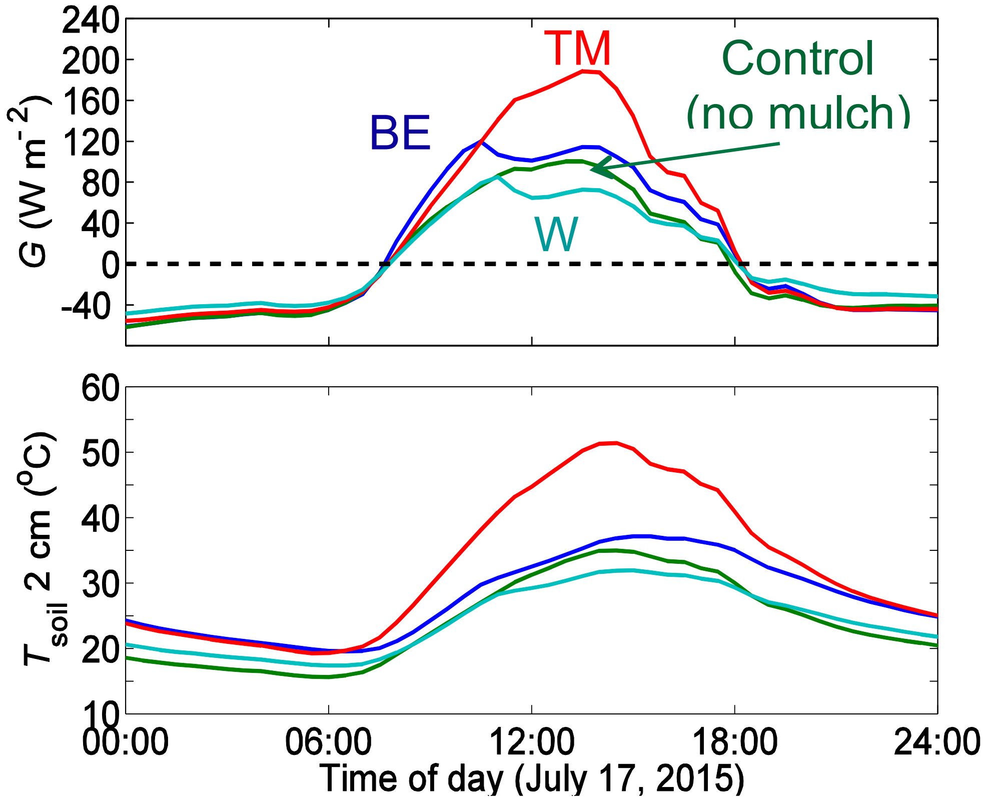

Figure 5.The daytime and nighttime effects of BE2, S4 and TMX plastic films on soil heat flux density (panel a) and soil temperature (*T_s*) (panel b) in relation to the control (i.e., no plastic).

Chapter 4

Using plastic films in low tunnels for modification of microclimate

This study was also conducted at the UBC Farm. In May 2016, 4 treatments (3 low tunnels floored with black embossed #2 (BE2) plastic film, 1 control (mulched with BE2 but no tunnel) were installed on 12 m x 1 m plots on tilled Podzolic soil. The low tunnel treatments comprised 3 polyethylene plastic films: polyethylene (0.15 mm thick) (POLY), perforated polyethylene (0.1 mm thick) ($POLY_{perf}$) and Thermax (0.15 mm thick) (TMX) (Figure 6). The site was prepared by installing an irrigation dripline at the 5-cm depth (near the center of the treatment area) and leveling the soil surface. A 0.15-m x 0.15-m-deep perimeter trench was dug around each 12-m x 1-m treatment area to bury the edges of the BE2 plastic film, after which stones (> 0.02 m) on the soil surface were removed by hand and the treatment area was levelled again with a ruler. The BE2 plastic film mulch was installed following the procedure described in Section 4.1.1. Although each plastic film was installed to minimize air gap between the soil surface and the plastic film a 0.01 – 0.02 m air gap resulted after installation. Steps 1-3 were repeated for each treatment. 3 low tunnels (10-m-long x 0.8-m-wide x 0.7 m height) were installed using gable roof shaped steel rod hoops (0.008 m rod diameter, 0.8 m low tunnel base width, 2.1 m low tunnel arch perimeter length) installed with 1.5-m spacing (7 hoops low-tunnel^{-1}). Low-tunnel covers were cut to aforementioned dimensions and secured at the ends using a 0.6-m-long steel rod stake and cable ties. Finally, the low tunnel cover was secured to each hoop using 1.2-m-long bungee cords tied to the tunnel base.

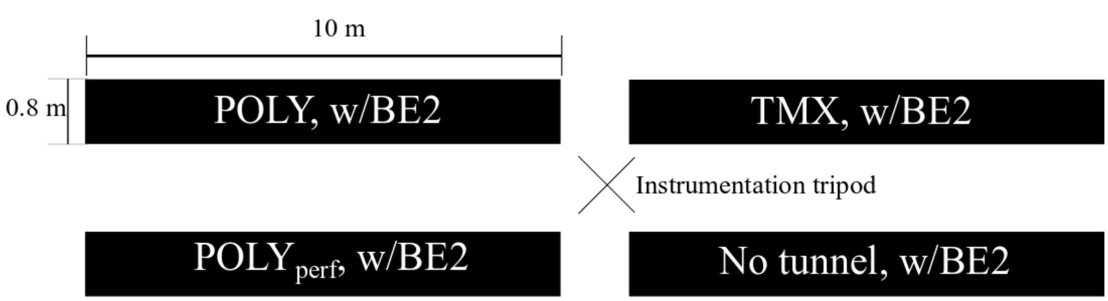

Figure 6. Overhead view of the experimental layout for comparing vegetation-free low tunnels.

A weather transmitter (WXT520, Vaisala Oy, Helsinki, Finland) provided half-hourly mean T_a, P, wind velocity (u) and direction, barometric pressure (p) and relative humidity (RH) at a height of 2 m. Net radiation (R_n), calculated as the sum downwelling shortwave (S_d) and longwave (L_d) radiation minus the sum of the upwelling shortwave (S_u) and longwave (L_u) radiation, was measured using a four-way net radiometer (model CNR1, Kipp and Zonen, The Netherlands) consisting of upward and downward-facing pyranometers and pyrgeometers mounted at two separate locations: 1) in the low tunnel 15 cm above the low tunnel mulch floor, 2) outside the low tunnel 15 cm above the top of the low tunnel cover. Due to cost and datalogger channel availability only 2 CNR-1 sensors were used in this study, which meant they needed to be moved between treatments periodically. Previous to the installation of BE2 plastic film mulch soil sensors were place at two locations, 3 m and 6 m from the end of the low tunnel, and comprised: 1 soil heat flux plate installed at the 3-cm depth and 3 θ_s and T_s sensors (5TM, Decagon Devices Inc., Pullman, WA, USA) were installed at the 2-cm, 5-cm and 10-cm depths. Mulch surface temperature (T_m) and low tunnel cover surface temperature (T_c) were measured using chromel-constantan thermocouple wire which was woven into the plastic films 6 times and attached to the top of the plastic surface using high thermal conductivity epoxy (OB 200, Omega Engineering Inc., Laval, Quebec, CA). Replicate measurement of T_m were measured using four downward-facing infrared radiometers (model SI-111, Apogee Instruments Inc. (AI), Logan, UT, USA) mounted 0.5 m above the mulch surface, and an fifth upward-facing infrared radiometer measured sky temperature (T_{sky}). Air temperature inside (T_{in}) and outside (T_{ou}) the low tunnels were measure at 0.5 m above the BE2 mulch at a single location inside and outside the tunnels, respectively. Relative humidity was not measured within the low tunnels. All instrumentation was sampled at 0.2 Hz, averaged and stored every 30 minutes on two CSI CR1000 dataloggers and two CSI AM25T multiplexers. Data was collected, using a Wi-Fi modem connection, and stored daily in the BIOMET database.

The shortwave and longwave radiative characteristics of TMX, POLY and $POLY_{perf}$ (along with 2.3 and 4.7 mm thick glass) were determined on a sunny day using the following procedure:

1. 1.2 m x 1.2 m sheets of each material listed above was cut, labelled and equilibrated with the ambient T_a.
2. A CNR-1 net radiometer was mounted 1.5 m above the ground.

3. Measurements of S_d and L_d were recorded in the absence of any obstructions above the CNR-1.
4. Separately, each material listed above was then held 0.02 m above the upward-facing pyranometers and pyrgeometers (to maximized the proportion of the view factor occupied by the materials), and measurements of S_d and L_d were again recorded, respectively.
5. The values of S_d, L_d and R_n after the material was brought into the upward-facing pyranometers and pyrgeometers view factor was subtracted from the values of S_d, L_d and R_n before the material was brought into the upward-facing pyranometers and pyrgeometers view factor. In this analysis, it was assumed that the downward-facing pyranometers and pyrgeometers unaffected.

The largest reduction in S_d occurred when S4 or 4.7-mm thick glass ($GL_{4.7}$) was placed above the upward-facing pyranometer, resulting in a ~125 W m^{-2} reduction in S_d. Nevertheless, all materials caused a reduction S_d of approximately 110 ± 16 W m^{-2} (mean ± standard deviation). Regarding L, there was large variability in the effect of each material on L_d, with POLY and $GL_{2.3}$ causing ~25 and 130 W m^{-2} increases in L_d, respectively (Figure 7). When comparing plastic material alone, it is clear that TMX has the greatest potential to increase L_d by as much as 2 MJ m^{-2} day^{-1} when compared to POLY covered low tunnels (Figure 8). When TMX and POLY are used on a low tunnel (i.e., fully enclosed), L_n is less negative for TMX than for POLY (Figure 8). Overall, due to TMX's low τ_L (i.e., glass-like longwave radiative properties), it clearly has potential to increase R_n.

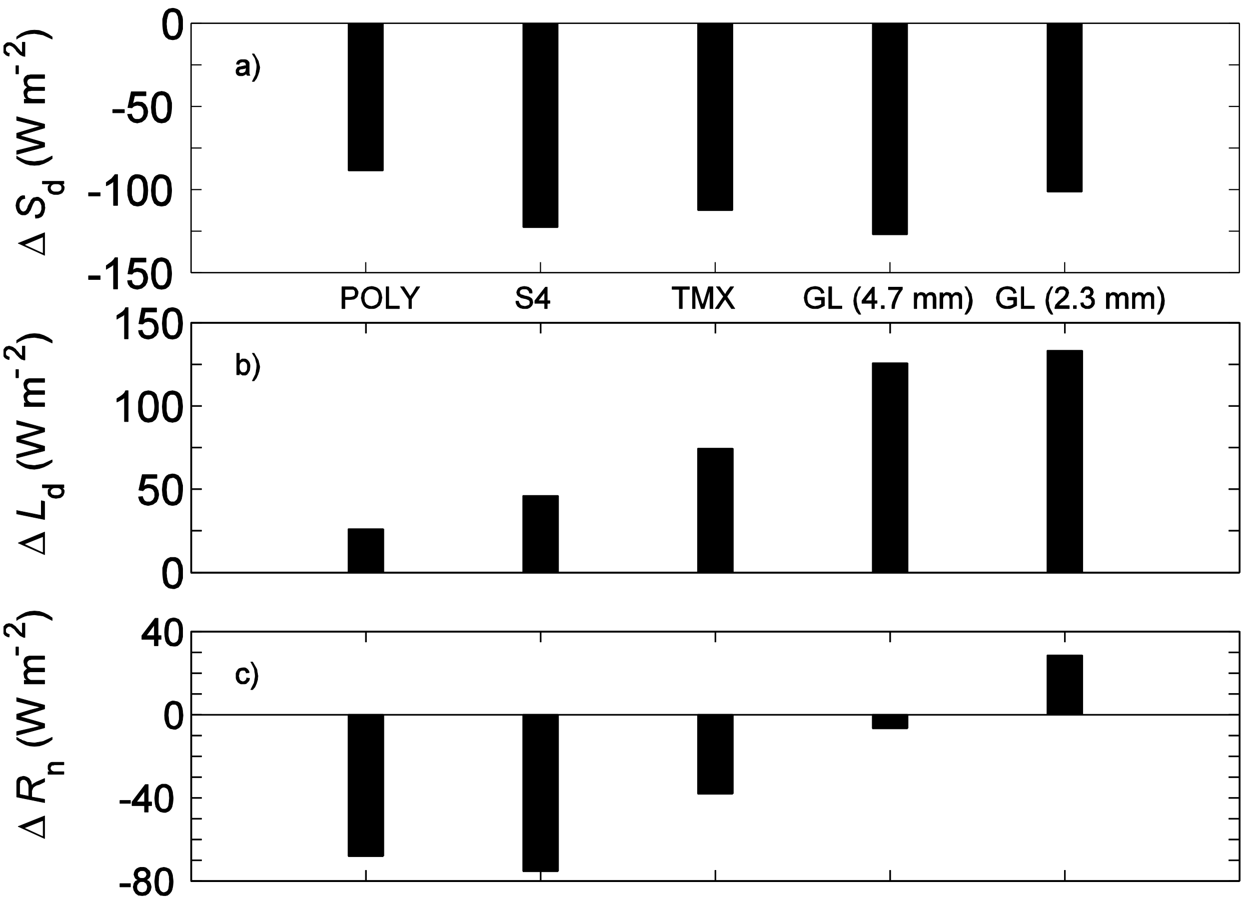

Figure 7. Panels a), b) and c) show change in downwelling shortwave (S_n), downwelling longwave (L_d) and net radiation (R_n), respectively, when 1.2 x 1.2 m^2 (L x W) POLY, S4, TMX, $GL_{4.7mm}$ and $GL_{2.3mm}$ sheets were placed 0.15 m above a CNR-1 exposed to a clear sky.

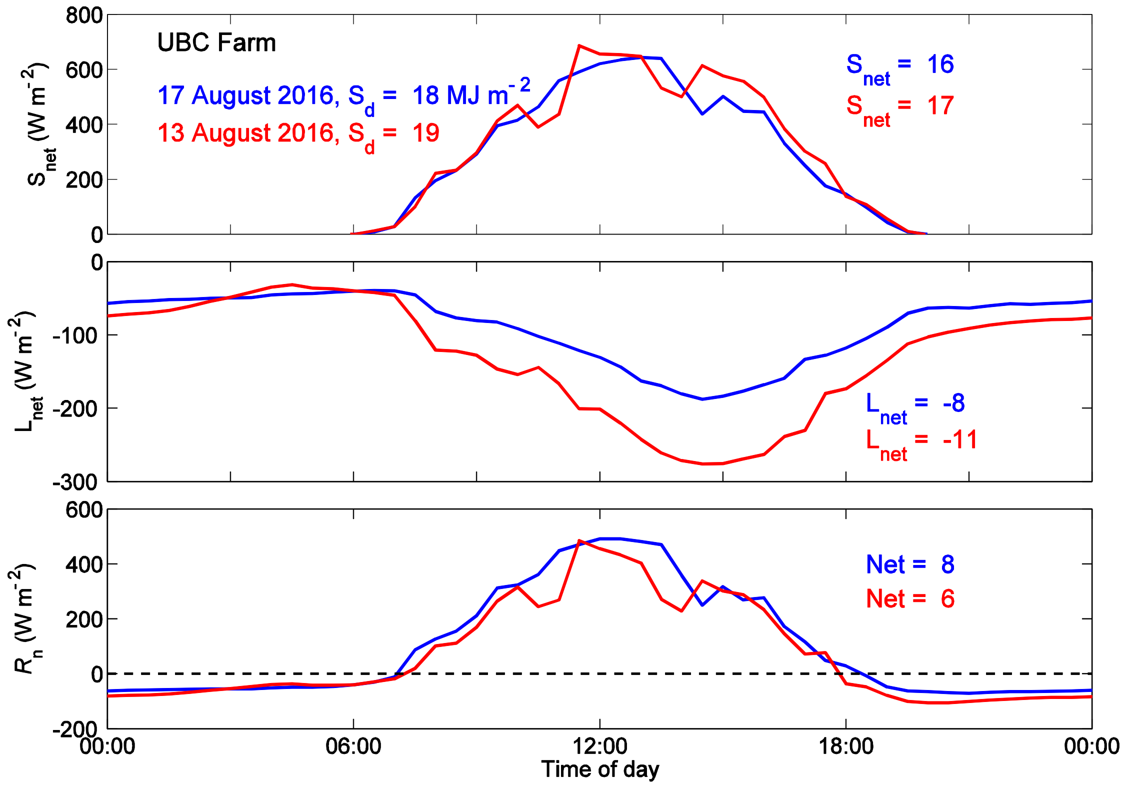

Figure 8. Net shortwave (S_n), longwave (L_n) and net radiation (R_n) for TMX (blue) and POLY (red) covered low tunnels on two sunny days.

The results showed that midday temperature of the plastic mulch floor (T_m) was only slightly higher for the tunnel treatments compared to the control (i.e., NLT) (Figure 9a). On the other hand, at night T_m was 3 and 5 °C higher inside POLY and TMX covered tunnels, respectively, than in the NLT treatment. For T_a, the NLT treatment exhibited daytime and nighttime behavior typical of Vancouver, with the highest T_a near 4 pm PST. Interestingly, all treatments covered with low tunnels exhibited diurnal behavior very different than NLT, showing diurnal variability similar to S_d. At 2 pm, T_a inside the $POLY_{perf}$ and POLY tunnels was ~10 and 12 °C higher than NLT. TMX resulted in additional heating with T_a rising to 16 °C higher than NLT (Figure 9b).

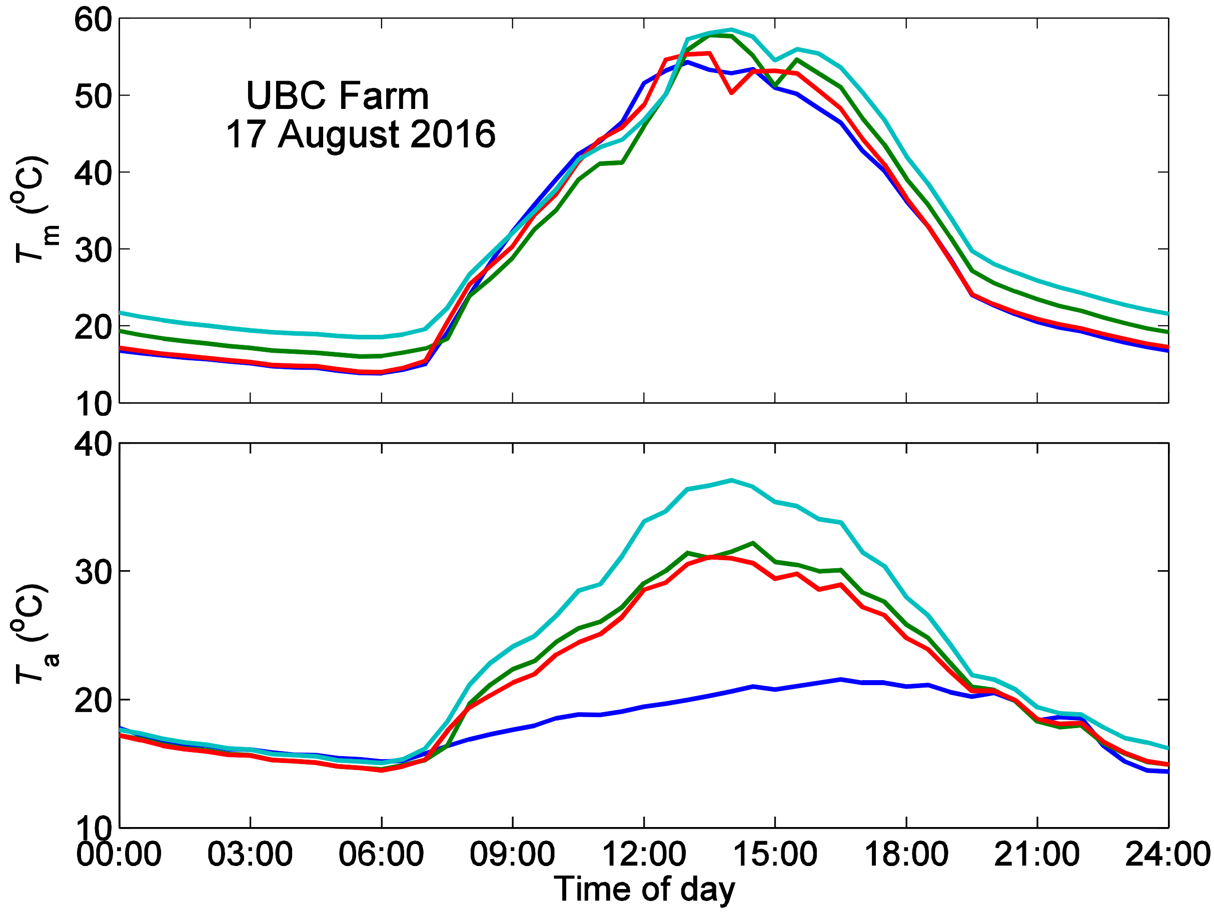

Figure 9. Mulch surface temperature (T_m) and air temperature (T_a) inside low tunnels under POLY (green), $POLY_{perf}$ (red) and TMX (cyan) films in comparison with a BE2 mulch control (NLT) (blue).

Chapter 5

Using plastic films in low tunnels for enhancing plant growth

The main plant growth experiment was conducted at UBC Farm. In June 2017, four treatments (Table 3) (three 12 m x 1 m low tunnels and one control (i.e., no tunnel), all with BE2 soil mulch, were installed on tilled Podzolic soil. The low-tunnel treatments comprised two polyethylene plastic films: polyethylene (0.15 mm thick) (POLY) and Thermax (0.15 mm thick) (TMX) (Figure 10). Site preparation included plowing and disk cultivation to a depth of 10 cm. Afterwards an irrigation dripline was installed at the 5-cm depth (near the centre of the treatment area) and feather meal was applied above the dripline (15.7 g m^{-2}). A 0.15 m x 0.15 m deep perimeter trench was dug around each 12 m x 1 m treatment area to bury the edges of the BE2 plastic film, after which stones (> 0.02 m) on the soil surface were removed by hand and the treatment area was levelled again with a ruler. The BE2 plastic film mulch was installed as described earlier. Three low tunnels (12 m length x 0.8 m base wide x 0.7 m height) were installed using gable roof shaped steel rod hoops (0.008 m rod diameter, 0.8 m low tunnel base width, 1.5 m low tunnel perimeter length) installed with 1.5 m spacing (7 hoops low-$tunnel^{-1}$). Low-tunnel covers were cut to aforementioned dimensions and secured at the ends using a 0.6 m steel rod stake and cable ties. Finally, the low tunnel cover was secured at each hoop using 1.2 m long bungee cords tied to the tunnel base. On July 12, 2017 the height of the hoops was increased by 50 cm to accommodate Padrón pepper (*Capsicum annuum*) growth.

Padrón peppers were seeded in 0.1 m x 0.1 m plastic pots in organic soil mix (Sunshine mix #1 LC1, SunGro® Agawam, MA, USA) and kept in the UBC Horticulture greenhouse from early April until early June when they were moved to a high tunnel at UBC Farm for 5 days in order to be hardened off and transplanted June 12, 2017. Eighty Padrón pepper seedlings were transplanted into 2 rows (40 Padrón peppers row^{-1}) in each of the treatments containing Padrón peppers (i.e., $Poly_{PP}$, TMX_{PP} and NLT_{pp}). Each row was planted 0.15 cm from the dripline and both rows were planted with 0.30 m spacing within rows. The two rows within each treatment were staggered 0.15 cm lengthwise to ensure even distribution of leaf area (LA).

Table 3. List of treatment abbreviations, mulch names, tunnel cover names and plant name for the 4 treatments in this study.

Treatment abbreviation	Mulch name (abbreviation)	Tunnel cover name (abbreviation)	Plant name (genus and specific epithet)
Poly	Black embossed #2 (BE2)	Polyethylene (POLY)	none
$Poly_{PP}$	Black embossed #2 (BE2)	Polyethylene (POLY)	Padrón pepper (*Capsicum annuum*)
TMX_{pp}	Black embossed #2 (BE2)	Thermax (TMX)	Padrón pepper
NLT_{pp}	Black embossed #2 (BE2)	None	Padrón pepper

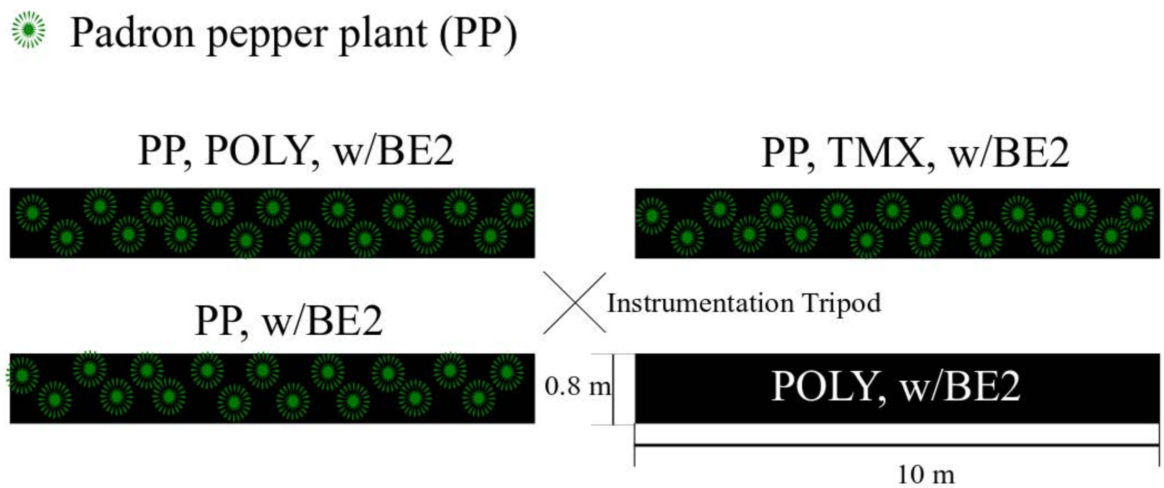

Figure 10. Overhead view of the experimental layout for comparing Padrón pepper productivity using low tunnels.

Each treatment was divided into four (3 m long) subplots containing ~20 plants $subplot^{-1}$. Pepper harvest measurements were performed on each subplot separately. Pepper harvest consisted of harvesting all peppers which were sufficiently large for sale (~3-4 inches long, ~10 g $pepper^{-1}$). Number of peppers for each subplot, total pepper mass $subplot^{-1}$ and number of blackened peppers in each subplot were recorded bi-weekly during the first two months (July and August) of harvest and weekly during the remainder of the harvest (September and early October) as total pepper mass in each subplot declined. Padrón pepper LA, height and stem diameter was measured weekly during the experiment. LA was calculated using a combination of manual field measurements and regression relationships of measured leaf diameter (L_{dia}) and length (L_{len}) and measured LA (LA_{meas}) (Padron et al., 2016). Initially, manual LA field measurements were performed on 16 randomly chosen padrón pepper plants within each treatment, reduced to 8 plants $treatment^{-1}$, and consisted of:

1. Separating leaves into small, medium and large size classes
2. Counting the number of leaves within each size class
3. Determining the mean L_{len} and L_{dia} of each size class

The regression relationships were developed by using direct measurements of L_{dia}, L_{len} and LA_{meas} taken using a leaf area meter (LI-3100, LI-COR Inc., Lincoln, NE, USA). A simple linear equation was used to determine an empirical model parameter S for determining LA within each leaf size class:

$$LA_{meas} = SL_{dia}L_{len} \quad (4)$$

$$S = \frac{LA_{meas}}{L_{dia}L_{len}} \quad (5)$$

Leaf area index was calculated as:

$$LAI = \frac{LA}{A_m} \quad (6)$$

where A_m is the calculated area of the mulch floor within each treatment.

Leaf-scale stomatal conductance (g_s) and CO_2 assimilation (A) were measured weekly using a portable photosynthesis system (model LI-6400, LI-COR Biosciences, Lincoln, Nebraska, USA).

Weekly measurements were performed at midday (12:00 – 2:00 PST) on four randomly chosen leaves (two sunlit and two shaded) from 16 randomly chosen plants treatment^{-1}.

A weather transmitter (WXT520, Vaisala Oy, Helsinki, Finland) provided half-hourly mean T_a, P, wind velocity (u) and direction, barometric pressure (p) and relative humidity (RH) at a height of 2 m. Net radiation (R_n), calculated as the sum downwelling shortwave (S_d) and longwave (L_d) radiation minus the sum of the upwelling shortwave (S_u) and longwave (L_u) radiation, was measured using a four-way net radiometer pyrgeometers (two model CNR1, Kipp and Zonen, The Netherlands and one SN-500, Apogee Instruments Inc. (AI), Logan, UT, USA) consisting of upward and downward-facing pyranometers and mounted at three separate locations: 1) 0.15 m above NLT_{pp}, 2) 0.15 m above $Poly_{PP}$, 3) 1.5 m above soil surface near the tripod tower. Two quantum sensors (LI-190, LI-COR Inc.) were mounted upward and downward-facing to measure downwelling (Q_d) and upwelling (Q_u) photosynthetically active radiation (PAR), respectively, 0.15 m above the top of the NLT_{pp} plant canopy. The remaining four PAR sensors were positioned upward-facing on the mulch surface of each treatment to measure low tunnel and canopy PAR transmissivity.

For each treatment, previous to installing the plastic films, four soil heat flux plates, two under sun and two under shade, were installed at the 0.03 m depth, and 2 T_s and θ_s sensors (5TM, Decagon Devices Inc., Pullman, WA, USA) installed at 0.03 m, 0.08 m and 0.15 m depth (one profile near and one profile 0.15 m from the irrigation dripline). CO_2 and water vapor concentrations were measured using an infrared gas analyzer (IRGA) (model LI-840, LI-COR Inc.), a pump and four solenoid pairs to sample tunnel air at 0.5 m above the mulch surface in all treatments in turn. The pump circulated air at a rate of 4 L min^{-1} and subsampled 0.8 L min^{-1} from the main air stream to be fed to IRGA. The IRGA sampled each inlet/outlet pair in sequence for 45 s at a frequency of 1 Hz and half-hourly means and standard deviations of CO_2 and water vapor concentrations were calculated from 1 Hz data.

In early July 2017, harvesting began and ended in late October. In early August 2017, it was clear that the low tunnel grown peppers produced more peppers per harvest period, but by mid to late August, the harvest rate declined for the low tunnel grown peppers, which was attributed to a depletion of CO_2 during the daytime (Figures 11 and 12), when the plants occupied a large proportion of the low tunnel volume and were growing vigorously. These results draw attention to the potential benefits (i.e., increased heating) and drawbacks (i.e., low CO_2 concentration, high humidity) associated with using low tunnels, and suggest the need to examine the value of periodic tunnel ventilation. Thus, $POLY_{pp}$ and TMX_{pp} yielded ~12% more peppers than NLT_{pp} during the entire harvest period at UBC Farm.

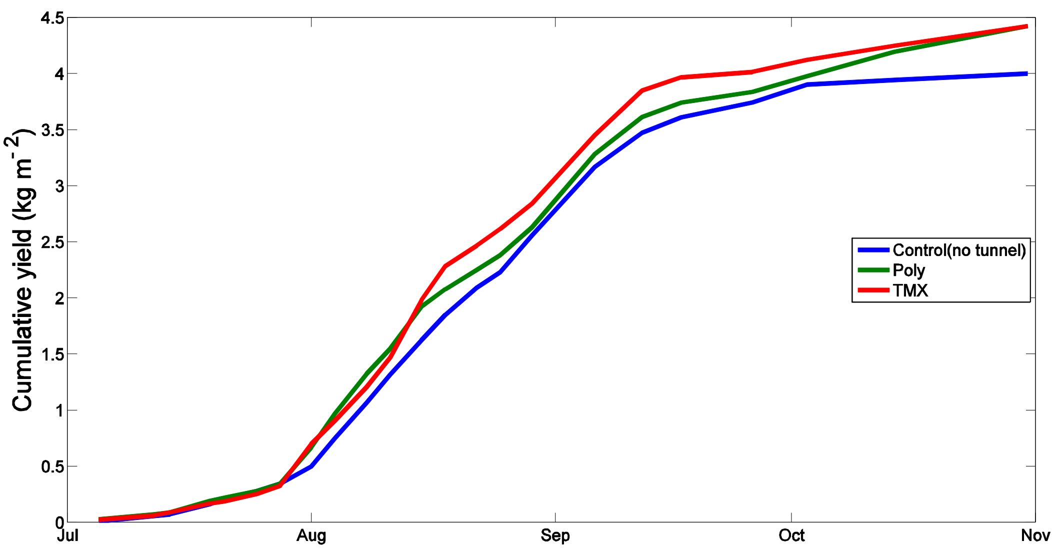

Figure 11. Cumulative Padrón pepper yield for peppers grown without a low tunnel (NLT) (blue), and in POLY (green) and TMX (red) low tunnels

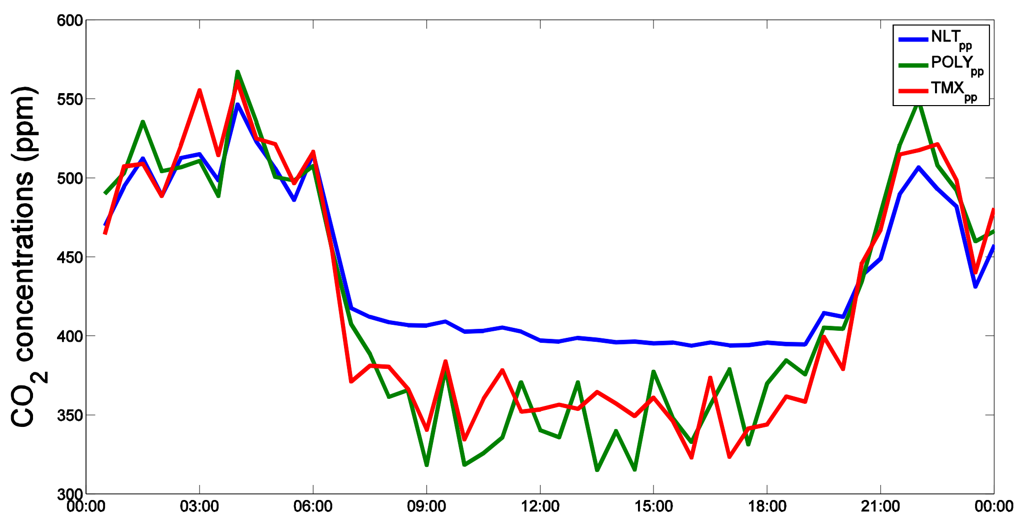

Figure 12. Diurnal CO_2 concentration near the top of the Padrón pepper plant canopies grown without a low tunnel (NLT) (blue), and in POLY (green) and TMX (red) low tunnels.

The effect of low tunnels covered with high-transparency polyethylene plastic film (POLY) on broccoli yield was studied at Mackin Creek Farm during the growing seasons of 2016 and 2017. While 2016 was a particularly warm spring, 2017 was colder with frequent frost events until mid-April 2017. Heavy smoke from forest fires in the Interior BC during the growing season of 2017 after the removal of the low tunnels reduced solar radiation and partly contributed to mild temperatures. Despite being the colder year, broccoli yield was 200% higher in 2017 compared to 2016 (Figure 13). This difference in yield was, partly to increased diffuse radiation due to the smoke, and partly attributed to increased heat and protection of the soil surface from windy conditions, which helped conserve soil moisture for use by the broccoli crop later in the growing season. At Cropthorne Farm, effect of low tunnels covered with high-transparency perforated polyethylene plastic film (POLYperf) on zucchini yield was studied. POLYperf treatment produced 20% more zucchini yield compared to no tunnel control (Figure 14).

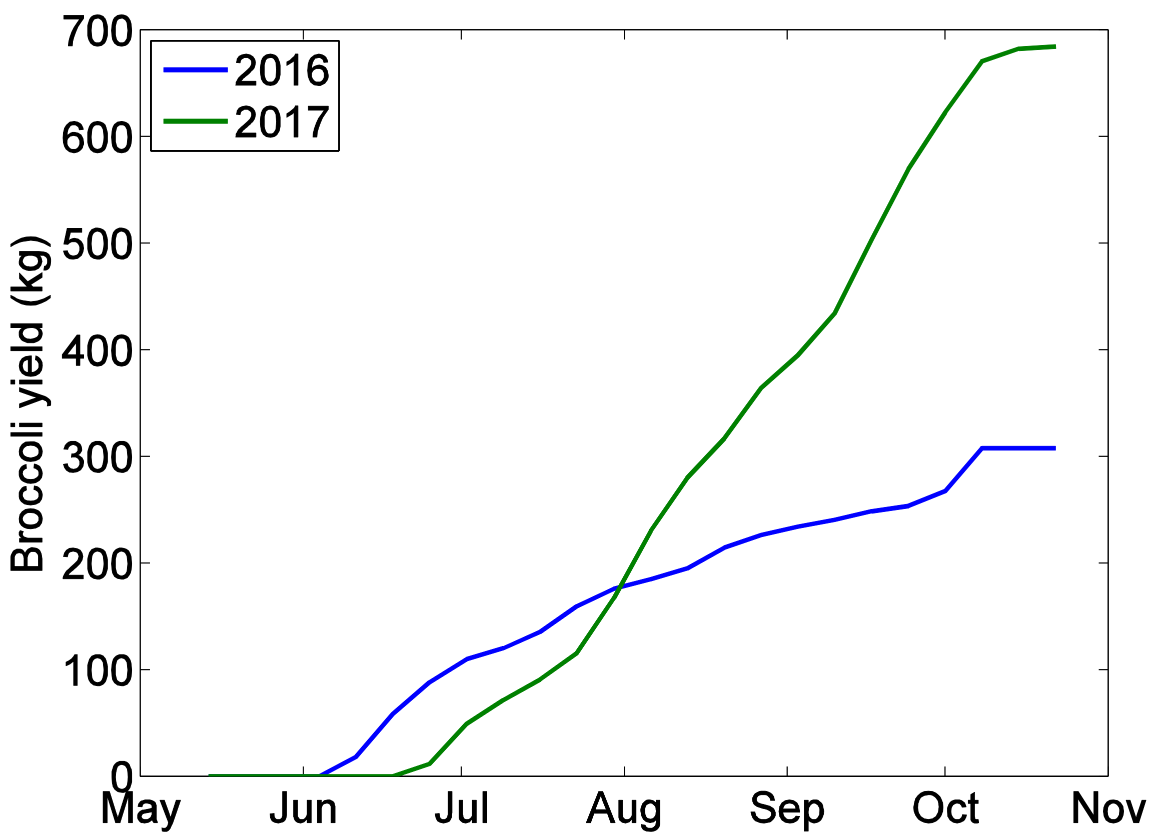

Figure 13. Effect of low tunnels covered with high transparency polyethylene (POLY) on broccoli yield during 2016 and 2017.

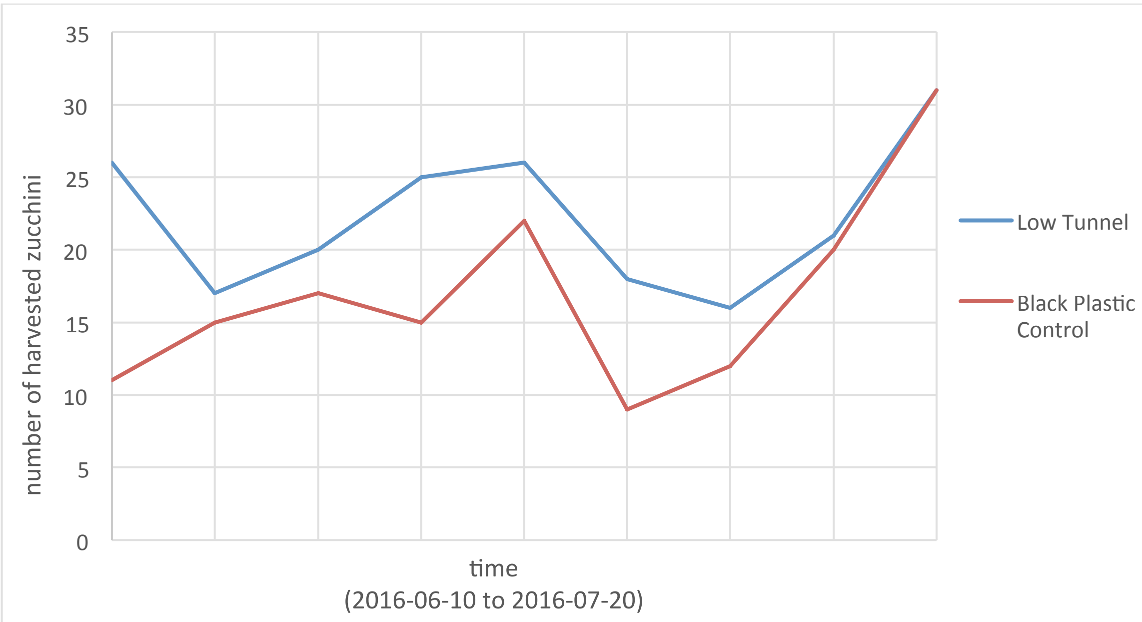

Figure 14. Comparison of number of zucchinis produced by plants grown in low tunnels and plants grown outside (no tunnel), both with black plastic mulch.

Conclusions

We have shown that (1) black and clear plastic mulches (with low longwave transmissivity) can increase soil temperature near the soil surface by ~40%, whereas high reflectivity plastic mulches can cool soils by ~20%; and (2) use of a low longwave transmissivity plastic films can increase low tunnel heating by ~33% compared to high longwave transmissivity plastic films, and can increase crop productivity. While Padron pepper yield in low tunnels covered with POLY and TMX was increased by ~12% compared to that in NLT at UBC Farm, POLY low tunnels increased zucchini and broccoli yields by 20% and 200% at the Cropthorne Farm and Mackin Creek Farm, respectively.

This research is beneficial to make decisions for choosing appropriate films depending upon how much increase or decrease in soil temperature would help in maximizing crop performance in different seasons and eco-climate regions in BC. Similarly, our work on using different plastic films in low tunnels will help farmers in advancing and/or extending the growing season for early and late season crop harvests, respectively, thereby enabling them to achieve a higher remuneration. Future studies should focus on water and carbon balances in low tunnel grown crops to better understand how and when irrigation and CO_2 fertilization should be applied or how frequently the tunnels need to be ventilated to make up for the depletion of CO_2 within the tunnels.

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