Research Article

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Insulative effect of plastic mulch systems and comparison between the effects of different plant types

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Abstract: To address agricultural needs of the future, a better understanding of plastic mulch film effects on soil temperature and moisture is required. The effects of different plant type and mulch combinations were studied over a 3.5-month period to better grasp the consequence of mulch on root zone temperature (RZT) and moisture. Measurements of (RZT) and soil moisture for tomato (*Solanum lycopersicum*), pepper (*Capsicum annuum*) and carrot (*Daucus carota*) grown using polyolefin mulch films (black and white-on-black) were conducted in Ontario using a plot without mulch as a control. Black mulch films used in combination with pepper and carrot plants caused similar RZTs relative to uncovered soil, but black mulch film in combination with tomato plants caused a reduction in RZT relative to soil without mulch that increased as plants grew and provided more shade. White-on-black mulch film used in combination with tomatoes, peppers or carrots led to a reduction in RZT relative to soil without mulch that became greater than the temperature of soil without mulch. This insulative capability was similarly observed for black mulch films used with tomato plants. Apart from white-on-black film used in combination with tomatoes, all mulch film and plant combinations demonstrated an ability to stabilize soil moisture relative to soil without mulch. RZT and soil moisture were generally stabilized with mulch film, but some differences were seen among different plant types.

Keywords: vegetable crops, plasticulture, microclimate stabilization, moisture retention, insulation, root zone temperature

1 Introduction

Plastic mulch film made from polyolefins has been extensively studied and its use is known to increase crop yields, extend growing seasons, decrease requirement for water and decrease weeds (Lamont et al. 1993). The recent review by Gao et al. (2019) provides a detailed analysis for the interested reader of how different crops and water use can be affected. Many of the benefits of these films are associated with changes to root zone temperatures (RZTs), which have been suggested to be affected by soil moisture (Díaz-Pérez 2010). However, despite many studies of how soil temperature is affected by the use of polyolefin mulches, results relating to the effect of film colour are inconsistent. Although many articles find that using black polyolefin mulch film causes soil temperatures to increase when compared to bare soil, and using white-on-black polyolefin mulch causes the opposite effect (Díaz-Pérez et al. 2005; Lamont 2005; Chakraborty et al. 2008; Díaz-Pérez 2009, 2010), there are a variety of studies that have results contradicting this information (for specific examples, refer to Snyder et al. (2015)). Conflicting reports of the effect of mulch colour on soil temperature suggest that it is likely an oversimplification to assume black films warm and white films cool the soil they cover.

Previously, measurements were reported that indicated plastic mulch films of different colours have the ability to insulate soil against temperature change, rather than simply increasing or decreasing the soil temperature relative to unprotected soil (Snyder et al. 2015). Since studies of soil temperature under mulch often report average temperatures for a short interval in a season (e.g. 2 weeks), this insulating effect may not be apparent (Decoteau et al. 1990; Díaz-Pérez and Batal 2002; Díaz-Pérez et al. 2004; Gordon et al. 2008;

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Díaz-Pérez 2010; Gordon *et al.* 2010). This insulating effect has been reported for mulch not made out of polyethylene: in 1996, Larsson and Båth observed an insulating effect of organic mulch films, and, based on their data, spun polypropylene and paper films (Larsson and Båth 1996). The authors' data on black polyethylene films in the same study showed that over time the soil under the black film had a higher weekly mean temperature than the soil in the bare plot (as opposed to an insulating effect) (Larsson and Båth 1996). This insulating effect was seen by Li *et al.* (2016) who reported a difference in instantaneous soil heat flux in soil with plastic mulch compared to bare soil.

The qualitative similarity between the ability of mulch to insulate soil against temperature change and its ability to stabilize moisture content of soil has also been reported previously (Snyder *et al.* 2015). Other researchers have also observed that soil covered by films tends to have lower watering needs and a decreased risk of flooding (Bolton and Aylesworth 1973; Larsson and Båth 1996; Ramalan and Nwokeocha 2000; Ramakrishna *et al.* 2006; Chakraborty *et al.* 2008), and Snyder *et al.* (2015) reported that similar to their effect on soil temperature, the use of mulch films stabilizes soil moisture: the same film that causes increased soil moisture during dry periods will protect soil from excess moisture when unprotected soil is wettest. More recently, Qin *et al.* (2018) determined that soil water evaporation decreases during the day with the use of plastic mulch, but increases at night compared to bare soil. It has been suggested (Díaz-Pérez 2010) that mulch films' ability to insulate against temperature change may be a direct result of generally higher moisture levels in soil protected by mulch, since high specific heat capacity of water should act to stabilize temperature.

While most studies of the use of mulch film focus on its effect on different plants and crop yield, studies which attempt to evaluate the effect of different plants on soil microclimate underneath mulch films are very limited. While the separate contributions to changes in soil microclimate due to plants and mulch can be approximated by growing plants without mulch and using mulch without plants, since there are very likely significant synergistic effects between mulch films and the plants they help grow (Tarara 2000) and since it is ultimately the combined effect of plant and mulch that is of interest to farmers, it is sensible to perform measurements on soil under mulch with plants and to focus on the effect of soil rather than the crop yield. Ma *et al.* (2018) demonstrated the importance of understanding the effects of plastic mulch through their meta-analysis on the effects of plastic mulch on yield using three parameters with three different crops, as the effects depend on the unique circumstances of the crop.

The purpose of this research project was to study long-term changes in temperature and moisture in soil protected by black and white-on-black mulch films over one growing season with different plant species. Compared to the previous research done at the same site by Snyder *et al.* (2015), this research is novel as it focused on whether plant type combined with mulch colour had an effect on soil microclimate in a new growing season (thus with different weather patterns). Brault *et al.* (2002) observed what they suspected was an effect on soil temperature due to the crops they were growing, but as their study was focused on one crop (lettuce *cv. Ithaca*) they were unable to compare the soil temperatures for different crops. Though they concluded that the leaves from the crops were the cause of the lower temperatures, as far as we are aware no studies demonstrate this, though there is a comparison of soil temperatures when crops with large leaves are grown versus crops with small leaves, which allows a broader comparison than previous research.

2 Materials and methods

2.1 Site selection and preparation

The site setup has been described previously in Snyder *et al.* (2015). The following changes were made to accommodate the new growing season and desire to include different plant types: The site was tilled and remulched on the 22 May 2014; 13 rows were designed as previously described, with 12 containing polyethylene-based agricultural mulch film and one bare soil; film thickness was between 20 and 25 microns; two pigments of film were studied, black and black-on-white.

Vegetables were planted using a split plot design, where the two units were taken as vegetables and mulch colour. The experimental design dictated that the mulch colour (or lack of mulch) was the whole plot treatment while the vegetables planted were the subplots. Black films were replicated in sets of three but due to material limitations, replications for white films were not possible. Therefore, data between different vegetables in white-on-black films were compared to black films with the same plant treatment, while considering this limitation. Vegetables planted included Scarlet Nantes carrot (*Daucus carota*), Better Boy tomato (*Solanum lycopersicum*) and California Wonder sweet pepper (*Capsicum annuum*). The plot with no mulch was not replicated,

due to space limitations. All vegetables were planted on the 29 May 2014. Carrot seeds were planted approximately 1 cm apart, 1 cm deep with rows 30 cm apart. Tomato seedlings were planted approximately 1 m apart. Sweet pepper seedlings were planted approximately 30 cm apart with rows 30 cm apart.

2.2 Local climate

The growing season for Central Ontario in 2014 was typical for the area. Data including monthly averages, maxima and minima of temperature and total rainfall are displayed in Table 1. Generally, central Ontario has a mild summer with temperatures peaking at 30°C with a high humidity. Temperatures typically cool to below 20°C at night.

2.3 Measurement of environmental and soil parameters

Soil thermometers (Rapitest model 1618, Lusterleaf brand, Woodstock, IL) were used to measure the RZT of each plot at a depth of 7–10 cm. Film temperature was measured using an infrared thermometer (Mastercraft Model 057-4554-4, Canadian Tire, Canada). Soil and film measurements were repeated until less than 5% variation between three consecutive measurements was obtained, to account for any lag in the thermometers. Such measurements presented below are averages of three measurements after equilibrium was achieved. Moisture levels were recorded using soil moisture meters (Rapitest model 1820, Lusterleaf brand, Woodstock, IL). Measurements were recorded Monday, Wednesday and Friday at 2:00 pm from 29 May to 10 September 2014.

Before the study began, halfway through the study and at the end of the study, the moisture meters were calibrated by comparing the measurements with soil samples for which moisture content was determined gravimetrically by measuring the soil before and after drying in an oven. Each plot had a semi-permanent meter in it which allowed consistent measurements for the same part of the plot. In order to eliminate some associated errors, meters were rotated every month.

Measurements of rainfall and other environmental parameters were recorded and verified based on results obtained from a nearby weather station. Irrigation occurred on May 28th and May 30th, in equal amounts for all plots, in order to help establish transplants.

Table 1: Weather data during the time samples were taken. Averages were typical for that of a Central Ontario climate

	May	June	July	August	September
Average temp. (°C)	12.1	17.3	17.5	17.5	14.3
Max. temp. (°C)	26.6	29.3	28.7	30	29.9
Min. temp. (°C)	−0.2	4.8	7.5	6.9	2.1
Total rainfall (mm)	45.2	124.1	65.9	115.7	81.7

3 Results and discussion

3.1 Soil temperature vs air temperature

A comparison of RZT measured in all plots (those with black mulch, white-on-black mulch and no mulch) shows that all soil temperatures were generally warmer than the temperature of ambient air. The only exception to this was observed for tomatoes grown under black mulch in the second and third months since planting (when plant foliage is greatest). During those times, when air temperature was above 25°C the RZT under the mulch was sometimes lower, by as much as 2°C.

3.2 Soil temperature: soil under mulch vs soil without mulch

In Figure 1, RZT measured in soil underneath mulch films is shown as a function of RZT measured in the plot without mulch. A solid line with slope equal to 1 is added for clarity, such that points falling above the line indicate warmer RZT under mulch films than in soil without mulch, and points falling under this line indicate cooler temperatures under mulch than in soil without mulch. Simple linear fits (dotted lines) are shown for all data, and slopes less than 1 indicate plots where insulation against temperature change relative to soil without mulch is demonstrated.

3.3 Effect of colour and plant type

All measurements under white-on-black film (Figure 1b, d and f) indicate insulation and generally cooler RZT relative to soil without mulch. The extent of cooling provided by the combination of mulch and plant increased for higher temperatures in soil without mulch, such that at a temperature of approximately 20°C the RZT measured

Figure 1: RZT measured in plots covered by mulch as a function of RZT measured in the bare ground plot. Measurements are separated according to the colour of mulch and the plant grown: (a) black film with tomatoes, (b) white-on-black film with tomatoes, (c) black film with peppers, (d) white-on-black film with peppers, (e) black film with carrots and (f) white-on-black film with carrots. In each plot, a solid line with slope equal to 1 is shown, and simple linear fits (dotted lines) to each dataset are shown, such that data with lines of slope less than 1 indicate plots with temperatures that were less susceptible to ambient temperature change than the uncovered plot. The greatest difference between slopes for the black films is 43% compared to only a 3% difference in slopes for the white-on-black films, suggesting that RZTs under white-on-black films are not susceptible to sunlight but air temperature.

Figure 2: Photographs of a representative plot in which tomatoes were grown on black mulch (Figure 1a) taken in June, July and August. Seeds and seedlings were planted on May 29th.

under the mulch film was similar to that of the uncovered soil, but when the highest uncovered soil temperature of 32°C was measured, the RZT measured under white-on-black mulch film was approximately 5°C cooler. The extent of insulation and cooling is insensitive to whether the plant grown is tomato, pepper or carrot (Figure 1b, d and f have similar slopes, despite having different plants), suggesting that for white-on-black films, the temperature of the soil under the film is dependent on the air temperature and not the sunlight.

The RZT measured under black mulch film where peppers (Figure 1c) and carrots (Figure 1f) were grown was similar to the RZT measured in uncovered soil, and neither set of data indicated significant insulation against temperature change, cooling nor warming relative to uncovered soil, except in the month of May where a slightly higher RZT was measured in the mulched plots. The RZT measured under black mulch film where tomatoes were grown indicates insulation and cooling similar to that observed under white-on-black mulch film, and when data are isolated based on time since planting (Figure 1a), the effect of changing tomato plant foliage is clear: initial measurements of RZT made during the first month since planting indicate temperatures similar to uncovered soil temperatures, RZTs measured during the second and third months since planting show cooling and insulation, and RZTs measured during the fourth month after planting indicate a return to RZT values similar to soil without mulch. Photographs made of the tomato plants at different times since planting show that foliage increases dramatically in

June and July, then decreases in August (Figure 2), suggesting that increased shade provided by plants is responsible for the cooling and insulation observed. Similar effects were not observed in carrots and peppers.

3.4 Film temperature

The effect of plant foliage is most evident when film temperature is examined and compared with the temperature of the uncovered plot surface and with the RZT underneath the film. For all plots except those containing tomato plants, the film temperature was consistently higher than that of the surface of the uncovered soil due to absorption of UV radiation. The temperature of black mulch film reached above 65°C on several occasions, and that of white-on-black mulch film reached temperatures higher than 45°C at times (Figure 3). For both white-on-black mulch films and black mulch films planted with peppers and tomatoes, the film temperature was always higher than or equal to the temperature of the surface of uncovered soil (Figure 3c–f) and was similarly always higher than or equal to the RZT measured underneath the mulch film (data not shown).

For films used in combination with tomatoes, the effect of increasing foliage and associated shading of the film is clear when film temperature is isolated based on month since planting (Figure 3a and b). For black mulch film, the film temperature (and the corresponding uncovered soil temperature) is highest immediately after planting, and

Figure 3: Film temperature measured for each plot as a function of the temperature of the soil surface in the bare plot. Measurements are separated according to the colour of mulch and the plant grown: (a) black film with tomatoes, (b) white-on-black film with tomatoes, (c) black film with peppers, (d) white-on-black film with peppers, (e) black film with carrots and (f) white-on-black film with carrots.

remains higher than that of the surface of uncovered soil throughout the month of June and is consistently lower than the temperature of the surface of uncovered soil

throughout the month of July, when plant foliage is greatest (Figure 2). During the month of August, after the plants had begun to die off and foliage decreased dramatically, film

temperatures were again mostly higher than the corresponding temperature of the surface of uncovered soil.

Film temperature for white-on-black film with tomato also showed a similar dependence on plant growth observed in black film (though a quantitatively smaller effect) and had a consistent effect on RZT, irrespective of plant type. Film temperatures in May, June and August were all close to or higher than that of the surface of uncovered soil, but film temperatures measured in July were consistently lower. That shading caused by changing amounts of foliage had a stronger effect on film temperature than on RZT under the film is expected: the primary means by which sunlight affects RZT is through conduction from the film that warms with increasing exposure to sunlight. This is not the only input to soil temperature, and since heat exchange via pathways such as conduction from deeper soil (Ramalan and Nwokeocha 2000) that are not strongly affected by shade will also affect RZT, it is reasonable to expect RZT to be less responsive to changing shade than film temperature.

3.5 Soil moisture: under mulch vs uncovered soil

The moisture measured in plots underneath mulch films was compared with the moisture measured in the uncovered plot (see Supplementary data), and all plots indicated similar insensitivity to moisture fluctuations in the bare soil. The moisture measured in soil covered by mulch films is neither generally higher nor lower than that measured in uncovered soil at the same time. This is likely due to several factors including: hindrance of rainfall hitting soil in plots with mulch due to mulch and foliage, increased evapotranspiration in plots with mulch due to large crops, yet decreased evapotranspiration from mulch protecting the crops and decreased runoff from mulched plots. The rainfall that occurred during the study could fall naturally and was not directed to a specific location.

The lack of correlation between moisture in the mulch-covered soil and that in uncovered plots contradict the assumption that moisture affects soil temperature. Because of the large specific heat capacity of water, one might expect that in two plots that are nominally identical (in the type of plant grown and mulch colour) when one plot has soil with measured moisture content much higher than that of the other, the plot with high moisture content would have a temperature farther from ambient. Close inspection of such data shows that this is not the case, and that even when moisture content differs by as much as 12%, there is very little difference in soil temperature. Additionally, there is no observed dependence of soil moisture on plant type or

mulch colour (both of which were observed to have some effect on soil temperature). Since all the soil moisture (after May) occurred from rainfall, this is likely because the mulch blocked the rainfall equally in each plot, regardless of the plant type or colour. Finally, soil moisture measured under mulch film was generally uncorrelated with that measured in uncovered soil, such that it was at times much higher than that in uncovered soil and other times much lower. If the heat capacity of water strongly affected the soil's ability to resist temperature change, one would then expect the soil temperature under the mulch film to be similarly uncorrelated with the temperature of uncovered soil, which is not the case.

4 Conclusions

1. The data presented here are consistent with previous reports that mulch films (in combination with plants) do not simply cool or warm soil, nor do they simply decrease the requirement for water by increasing soil moisture content. Instead, the use of mulch films allows soil to resist changes in temperature and moisture.
2. In general, lower temperatures were observed mid-day in soil covered by white-on-black mulch, and in soil covered by black mulch when tomato plants are grown and at a size large enough to provide a significant degree of shade. Measurement of film temperature for both black and white-on-black films provides further evidence that shade caused by increasing tomato plant foliage strongly affects both soil and film temperatures. Future studies related to plant leaf area and soil temperatures with mulch film will further define this relationship.
3. Mulch films generally provide stable soil moisture (though not necessarily higher levels of soil moisture than uncovered soil) and this stabilized soil moisture seems insensitive to mulch colour and plant type.
4. Measurements of both soil temperature and moisture content suggest that stabilization of soil temperature under mulch films is not strongly dependent on soil moisture content.

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