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Improving Reduced Tillage in Northern Great Plains' Onion Production through Early Season Soil Tarping

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***Abstract. Allium cepa* L., commonly known as onions, are highly susceptible to weed competition due to their minimal canopy cover. Weed management is critical for their production. One potential weed management tool, especially for organic growers, is soil tarping. This study evaluated the impact of two types of early season tarping (solarization and occultation) and duration of tarping (6, 4, and 2 weeks) on weed control in 'Patterson' and 'Candy' onion production. Field experiments were conducted during the 2023 and 2024 growing seasons at the South Dakota State University Specialty Crop Field in Brookings, SD, USA. Solarization was conducted using clear tarps secured with sandbags and buried edges. Occultation was evaluated using white side up and black side up silage tarps, applied at respective weeks before removal and onion planting. Tarp treatments and no tarp controls were arranged in a randomized complete block design with four blocks and ten 7.32 × 3.05 m treatment plots per block. Tarps were placed in April at respective weeks before removal in May. Immediately following tarp removal, clear and control plots were tilled to remove high weed pressure, and all 0.76 × 3.05 m planting beds were harrowed within each plot. Four rows of onion transplants were planted 1 to 2 days following tarp removal in mid or late May, depending on the year. Response variables for data collection included weed type, height, and biomass as well as time to cultivate and onion yield. At tarp removal in both years, all occultation treatments resulted in less weed pressure than the no tarp control. Solarization treatments had varied results based on year. There was no difference in onion yield due to tarping treatment either year, likely due to biweekly hand weeding that evened out treatment effect on weeds over the growing season. Both years, the Patterson onion cultivar yielded more marketable onions than 'Candy'; 40% of 'Candy' onions and 75% of 'Patterson' onions were marketable in 2023; in 2024, 65% of 'Candy' onions and 73% of Patterson onions were marketable. Soil tarping may be an effective option for farmers to reduce early season weeds in onion production; however, it should be used alongside other management strategies to obtain a viable yield.**

Local vegetable production is increasing in the Midwest, and with this increase in specialty crop producers across the region in varying climates and topography, it is important to have a variety of production methods available, especially pertaining to weed management. Interest in low or no-till and reduced herbicide vegetable production is increasing (Burrows 2022). Use of herbicides can result in herbicide-resistant weeds and potential health hazards for humans and ecosystems (Fuchs et al. 2023). Cover crops, crop rotation, mulching, and flame weeding are a few alternative weed management strategies currently used by growers (Brainard et al. 2023; Leavitt et al. 2011; Masasi et al. 2025; Portz and Nonnecke 2011; Rajković et al. 2021; Sportelli et al. 2022). Another method being explored is soil tarping.

Soil tarping is a practice used by farmers across the United States and around the world. Tarps are used not only to reduce weeds but also for sod and cover crop termination (Lounsbury et al. 2022a). They have been used in the production of a variety of specialty crops including cabbage (*Brassica oleracea* L.), beets (*Beta vulgaris* L.), winter squash (*Cucurbita maxima* Duch.), strawberries (*Fragaria ×ananassa* Duch.), and lettuce (*Lactuca sativa* L.) (Aljawasim et al. 2025; Birthisel 2018; Delpeche and Isaac 2013; Hasing et al. 2004; Kubalek et al. 2022; Rylander et al. 2020b). Tarping for weed management in a no-till system decreased weeding labor by 41% when compared with weeding by hand (Maher et al. 2024). Two tarping methods that are commonly used are solarization and occultation. Solarization uses clear plastic to harness energy from the sun and warm the soil (Oz et al. 2017). Solarization is commonly used in warmer climates where temperatures can be raised high enough to kill seeds and seedlings (Stapleton et al. 2005). In the cooler South Dakota climate in early spring, solarization can be used to germinate weed seeds earlier in the season, therefore exhausting the weed seed bank before planting; this can reduce the number of weeds during the growing season (Burrows 2022). Occultation uses opaque material to stop light from hitting weed seeds and therefore stops germination (Birthisel and Gallandt 2019). It can also deprive any existing seedlings or perennial plant parts of light needed for survival. Time of year and length of time a tarp is on the ground impacts how well this practice can reduce weed pressure (Kesler 2022).

Weed management can be especially challenging for onions for a variety of reasons. Because onions are slow growing and have minimal canopy, they do not provide much soil coverage; this makes them highly susceptible to competition with weeds (Khan et al. 2023). Competition with annual weeds has been noted to decrease photosynthetic capacity and bulb size of onions (Hewson and Roberts 1973). It is important to keep weeds well managed for onion crops to maintain a viable yield, especially during the critical weed-free period, which is between 15 and 60 d after onion transplanting (Singh and Singh 1994). Keeping low weed populations can also minimize pest pressure, as the primary onion pest, thrips (*Thysanoptera*), are more prevalent when the crop is subject to higher weed pressure (Lennon et al. 2024). Onions have close plant spacing, sensitive bulb structures, and shallow roots, so care must be taken when managing weeds in onion fields (Sahoo et al. 2017). Research has been conducted on weed management in onions using herbicides, special cultivation equipment, strategic irrigation, cover crops, mulches, crop rotations, flame weeding, and hand weeding (Boyhan et al. 2016; Dechen and Chopra 2020; El-Metwally et al. 2021; Johnson and Davis 2014; Johnson et al. 2012; Sivesind et al. 2012; Souza et al. 2021; Vollmer et al. 2010; Yang et al. 2024). It is helpful for growers to have a variety of weed management options to find what works well for their specific growing location and available resources.

Soil tarping is an accessible, low-cost, reduced-till management option. Studies have noted encouraging results when applying and removing tarps before planting to lessen weed management required during the growing season (Birthisel and Gallandt 2019; Kubalek et al. 2022; Lounsbury et al. 2022b; Maher et al. 2024; Rylander et al. 2020a, 2020b). Because this tool is applicable to various crops and uses, there is increased interest in using tarping in the Midwest (Burrows 2022). While much of the research and usage of tarping has occurred in more humid areas in the eastern United States, few studies have assessed tarping in the Northern Plains (Birthisel and Gallandt 2019; Kinnebrew et al. 2023; Lounsbury et al. 2022a; Maher et al. 2024; Rylander et al. 2020a, 2020b).

The purpose of our research was to study the performance of tarping using clear plastic (solarization) and double-sided black and white silage tarps (occultation) to reduce weed pressure and cultivation time, as well as increase yield under the sunnier, windier conditions of early spring in South Dakota. Occultation treatments with silage tarps placed white side up or black side up were both included in this study to separate occultation tarping effects of temperature (assuming black tarps attract more heat) and lack of soil aeration (both black side up and white side up tarps equally reduce light and soil aeration when covering the ground). In addition to tarp material (clear plastic and opaque silage tarp) and placement (white side up vs black side up), our research studies the impact of tarping duration, using tarps applied for 6, 4, or 2 weeks before onion transplanting. Immediately following tarp removal, onions were planted into all treatments to determine tarping impacts on yield. Because onions are sensitive to weed competition, we hypothesized that onion yield would be negatively affected by weed pressure (Burrows 2022).

Materials and Methods

Location and experimental design. Field research was conducted in the South Dakota State University Specialty Crop Field in Brookings, SD, USA (∼44 19′18″N, 96 46′21″W; elevation: 496 m) during the 2023 and 2024 growing seasons to study the effects of soil tarping on weed pressure and onion yield. Soil type at the research site was a Barnes silty clay loam (Soil Survey Staff 2024). Different locations within the Specialty Crop Field were used each year. Soil tests taken 6 inches deep at the beginning of the season averaged 4% soil organic matter in 2023 and 3% in 2024. In both years, previously fallow fields were tilled in the fall with two passes of a John Deere 2660 VT vertical tillage disk (Moline, IL, USA) chisel plow before spring tarping.

Three types of tarps were evaluated: black silage tarps, white silage tarps, and clear greenhouse plastic, along with a tilled, no tarp control treatment. Each type of tarp was placed at 6, 4, or 2 weeks before onion planting. The experimental design was a completely randomized block design with onion cultivar as a split plot within tarping treatment. There were four 30.48 × 3.05 m blocks with ten 7.32 × 3.05 m treatment plots within each block.

Soil tarping. Opaque silage tarps with one side black and one side white were used for occultation treatments (6-mil black/white plastic sheeting; Farm Plastic Supply, Addison, IL, USA). Clear greenhouse plastic (ultraviolet-resistant 6-mil; Farm Plastic Supply) was used for solarization treatments. All tarps were purchased from Farm Plastic Supply and cut into 7.32 × 3.05 m rectangles to fill the entire treatment plot area. Tarps purchased and used in 2023 were washed and reused in 2024. In 2023, tarps were placed over the soil on 18 Apr, 5 May, and 17 May so each tarp type covered the soil for durations of roughly 6, 4, and 2 weeks before removal on 30 May. In 2024, tarps were placed over soil to cover treatment plots on 5 Apr, 19 Apr, and 2 May and all were removed on 14 May. In 2023, tarp application was 2 weeks later than 2024 due to slow snow melt causing field inaccessibility. Black side up and white side up tarps were secured with 25 to 30 sandbags, each sandbag weighing roughly 6.8 kg. Clear tarps were secured with sandbags as well as burying the edges in the soil to align with practices that producers are currently using in our region.

Before each tarp application, in each year, Onset HOBO MX Soil Moisture and Temperature Data Loggers (MX2307; Bourne, MA) were installed to record soil temperature and moisture at 10 cm soil depth in each of the 10 plots beneath tarps within two of the four replicate blocks. Wooden stakes (0.61 m tall) were pounded into the soil at the center of the 3.05 m tarp side edge of each treatment plot. Sensors were mounted to the wooden stakes using zip ties and wires were run over the soil 2.9 m from the plot edge into the plot so moisture and temperature probes collected data where onions would be planted. HOBO Pendant MX Water Temperature Data Loggers (MX2201) were used in each treatment plot in the two replicated blocks that did not have the more robust soil sensors. Temperature pendants were buried at a 10 cm soil depth in the same location as moisture sensors so they would collect temperature data where onion rows would be established. All sensors within the four replicated blocks were set to collect temperature data hourly. Sensors were read out and removed before tarp removal on 29 May 2023 and 14 May 2024.

Weed type, count, height, and biomass were assessed at tarp removal. This was done by randomly throwing three 50 × 50 cm polyvinyl chloride (PVC) quadrats into each treatment plot. Weeds within each quadrat were separated by broadleaves and grasses. For each weed type, three weeds were randomly selected to be measured for height. All weeds within the quadrats were clipped to soil level, counted separately by broadleaves and grasses, dried for 3 d at ∼60 °C, and weighed to measure biomass. In 2023, weed count, height, and weight data were only collected on living weeds within the quadrat; however, in 2024, weight and count weed data collected included both living and nonliving weeds that had died from tarping. To observe the effects of high thistle populations in the 2024 field location, thistle and dandelion counts were recorded separately.

After data collection, clear tarp and control treatment plots were tilled to clear out the high amounts of germinated weeds in these treatment plots before planting. In 2023, a walk behind BCS 749 (BCS, Oregon City, OR, USA) with a tiller attachment was used for tillage to a depth of 6 cm. To reduce time and labor in 2024, a tractor with a 655 iMatch AutoHitch (John Deere, Moline, IL, USA) rotary tiller was used. Tillage was maintained at a depth of 6 cm to avoid bringing up more weed seeds to the soil surface. Black and white tarped plots did not need to be tilled at removal of tarps, as there were minimal weeds in these treatment plots both years.

Planting onions. ‘Barolo,’ ‘Patterson,’ and ‘Candy’ (Johnny’s Selected Seeds Winslow, ME, USA) (Fig. 1) onions were seeded in 128-cell trays in the South Dakota State University greenhouse on 28 Feb 2023, and 29 Feb 2024. Greenhouse temperatures were set 20 to 23.3 °C for daytime and 17.7 to 21.1 °C for nighttime and 400 W high-pressure sodium lights were used each day from 6:00 AM to 10:00 PM in 2023 and 7:00 AM to 6:00 PM in 2024. In 2023, ‘Candy’ and ‘Patterson’ onion seedlings in the greenhouse slowed vegetative growth and began forming bulbs prematurely. Premature bulbing can occur as an onion stress response to high temperature, insufficient water, or exposure to long daylight. As an attempt to avoid this issue in 2024, hours of artificial lighting were reduced to 11 h each day. Despite these efforts, onion seedlings bulbed prematurely in 2024; the premature bulbing may have been due to poor greenhouse temperature consistency or soil over-drying between waterings. Onions were watered on an as-needed basis. The seeds began germinating on 8 Mar 2023 and 6 Mar 2024. Once onions reached ∼2 inches in height, the seedlings were fertigated using a water-powered Dosatron injector (D14MZ2; Clearwater, FL, USA) with

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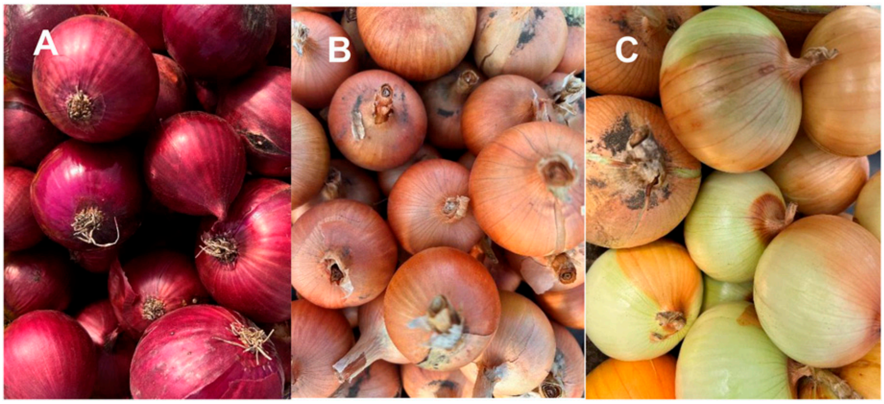


Fig. 1. Mature ‘Barolo’ (**A**),‘Patterson’ (**B**), and ‘Candy’ (**C**) onions after harvest, curing, and grading. Onion seeds were purchased from Johnny’s Selected Seeds (Winslow, ME, USA) and grown to maturity in South Dakota State Specialty Crop Field in Brookings, SD, USA.

Nature’s Source Organic Plant Food 3N–1P_2O_5–1K_2O (Nature’s Source, Sherman, TX, USA) one to two times a week. On 24 May 2023 and 9 May 2024, onions were placed outdoors in a holding area to acclimate before planting into treatment plots. Once placed outside in cooler temperatures, the onions halted premature bulb growth and reverted to growing healthy vegetative leaves.

To prepare tarped field plots for onions, 0.68 kg (2023) and 1.36 kg (2024) Multi-K GG KNO_3 (13N–0P_2O_5–46K_2O, Haifa, Israel) granular fertilizer was hand-broadcast within each 23.23 m^2 onion bed. Fertilizer rates were based on preseason soil tests and nutrient recommendations for onions from the 2023 Midwest Vegetable Production Guide (Phillips 2023). Guard rows were fertilized in 2023, but not in 2024. To loosen soil for transplanting and evenly distribute fertilizer, a BCS 749 (BCS) with power harrow attachment was run through all 0.76 × 3.05 m onion beds at a depth of 8 cm.

Onion planting beds and walkways were established within each treatment plot. Four rows of ‘Patterson’ onions were spaced 15 × 23 cm apart to fill 0.76 × 3.05 m onion beds. The same was done for ‘Candy’ onions. Two guard rows of ‘Barolo’ onions spaced 15 × 23 cm were each 0.38 m wide, and a 0.91 m wide walkway was left on the edges of the plots. Two lines of drip tape were laid for each four-row test cultivar and one line for each two-row guard row. Onions were transplanted by hand on 31 May in 2023 and 16 May in 2024.

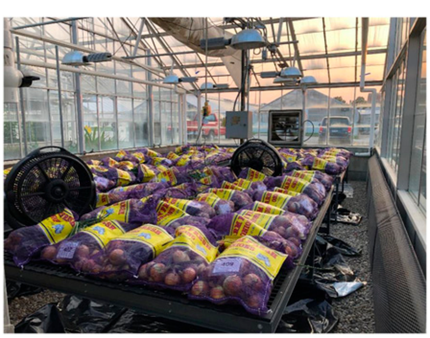


Fig. 2. Onions curing in greenhouse in Brookings, SD, USA, for roughly 1 month after harvest on 28 Aug 2023.

Onion irrigation and fertilization. Onions were irrigated weekly as needed, with a rainfall equivalent target rate of 2.5 cm per week. In 2023, total rainfall June through August was 14 cm (South Dakota Mesonet 2024). Precipitation occurred on 26 d during the 3 months, the greatest amount occurring on 5 Aug at 3 cm. Summer of 2024 was much wetter, with a total rainfall of 32 cm June through August; precipitation occurred on 31 d during the 3 months, with the greatest amount occurring on 31 Jul at 10 cm (South Dakota Mesonet 2024).

Nature’s Source 10N–4P_2O_5–3K_2O fertilizer was applied using a water-powered Dosatron injector (D14MZ2) to distribute fertilizer through the drip irrigation lines in 2023 on 11 Jun, 12 Jul, and 21 Jul at a rate of 624.8 $L\cdot ha^{-1}$. In 2024, fertilizer was distributed through two fertigation applications 6 Jun and 2 Jul at a rate of 954.1 $L\cdot ha^{-1}$. In 2023, a conservative amount of fertilizer was used; because onions need high nutrients for large bulb size, conservative fertilizer application resulted in a high number of small onions in 2023. Fertilizer was increased to the maximum recommended amount by the Midwest Vegetable Guide in 2024 to increase onion bulb size (Phillips 2023).

Growing season data collection and cultivation. During the growing season, weed growth was measured biweekly (2023: 12 Jun, 5 Jul, 18 Jul, 1 Aug, and 17 Aug; 2024: 3 Jun, 19 Jun, 1 Jul, 18 Jul, 31 Jul, and 8 Aug), followed by a combination of stirrup hoe and hand weeding. Two 25 × 25 cm square PVC quadrats were thrown randomly within the center 8 feet of each cultivar row. Within each quadrat, weeds were separated by broadleaf and grass type. Three random heights were collected for each weed type. The number of each type of weed was counted and weeds were clipped at the soil level, bagged, dried for 3 d at ∼60 °C, and weighed. After each data collection event, cultivation of the center 8 feet of each bed was timed and number of laborers to cultivate each bed was recorded. In 2024, weeding was skipped after data collected on 19 Jun and 31 Jul due to rain and wet field conditions.

Insect pressure and weed species were noted throughout the growing season. Insects observed in plots included ladybugs (*Coccinellidae*), bees (*Anthophila*), lacewings (*Chrysoperla carnea*), and thrips (*Thysanoptera*). In 2023, minimal insect damage was noted on onion leaves during the growing season. Thrips damage was noted on onion leaves on 18 Jul in 2024. By 25 Jul, thrips pressure had become very high. Overhead irrigation was used to discourage thrips activity. This management strategy was minimally effective as the overhead irrigation was light and brief. A violent and heavy rain event on the evening of 31 Jul, however, greatly reduced thrips pressure. Onion guard rows and data rows were then sprayed with Sevin (Zeta Cypermethrin, Concentrated, Palatine, IL) to prevent thrips populations from increasing again. Sevin (0.18 L) was mixed with 5.7 L water in a backpack sprayer to cover the entire 278.71 m^2 area of onion beds.

The most prevalent weeds in 2023 were Venice mallow (*Hibiscus trionum*) and redroot pigweed (*Amaranthus retroflexus*), which are both warm season annuals. In 2024, the most prevalent weeds were Canada thistle (*Cirsium arvense*), which is a cool season perennial, as well as crabgrass (*Digitaria sanguinalis*) and Venice mallow, which are both warm season annuals. Cheatgrass (*Bromus tectorum*), a winter annual, was very prevalent in spring of 2024 at tarp removal.

Onion harvest and curing. Onions were harvested on 28 Aug 2023 and 27 Aug 2024, once 50% to 80% of all onion leaves for each cultivar collapsed in the field. Both years, Candy onions matured and showed collapsed leaves slightly earlier than Patterson onions. Before harvest, five onions of each cultivar within each treatment plot of blocks one and three were randomly chosen to measure onion leaf height and count. ‘Patterson’ and ‘Candy’ onions were harvested from the center 6 feet of each treatment plot. This resulted in 48 onions per cultivar in each 1.39 m^2 treatment bed. Onions were bagged with corresponding plot number tags and transported to a curing location. In 2023, onions cured in the South Dakota State University campus greenhouse (Fig. 2). The greenhouse was set to ambient humidity and 23.9 to 26.7 °C. Onions were placed in one layer in netted onion sacks to cure on sterilized greenhouse benches for ∼1 month. In 2024, ‘Candy’ onions had minimal healthy foliage at harvest due to thrips damage from earlier in the season, and some had completely rotted leaves from disease thriving on thrips-wounded leaves. Diseased onions were separated from healthy onions at harvest. The onion curing location for 2024 was the Specialty Crop Field high tunnel (Fig. 3); this was done to avoid infesting the greenhouses with any thrips that could have been lingering on onions. High tunnel sides were left open to allow for natural air flow through the tunnel and closed when high winds or rain were anticipated. Onions were hung in netted onion bags from high tunnel trusses and left to cure for ∼1 month. Watch Dog (Spectrum, Aurora, IL, USA) humidity and temperature sensors placed in the high

Fig. 3. Onions curing in Specialty Crop Field high tunnel in Brookings, SD, USA, for roughly 1 month after harvest on 27 Aug 2024.

tunnel recorded a maximum temperature of 40 °C and maximum relative humidity (RH) of 99%. The minimum temperature reached was −1.1 °C and minimum RH was 21%. The average temperature over the month the onions were in the tunnel was 66 °F and average RH was 64%.

Onion yield data collection. Once the onions were finished curing, yield data were collected one block at a time 26 Sep through 12 Oct in 2023 and 2 Oct through 7 Oct in 2024. Onions were separated into marketable and culled categories. USDA size standards were used to develop a grading system (US Department of Agriculture 2014). A ruler with wood blocks was used to create a caliper for sizing onions. Marketable onions were weighed, counted, and separated into four size categories: packer (3.8 to 5 cm diameter), medium (5 to 7.6 cm diameter), large (7.6 to 10 cm diameter), and colossal (diameter larger than 10 cm). Unmarketable onions were weighed, counted, and the following cull categories were noted: insect damage, disease and rot, less than 1 inch diameter, misshapen, and green leaf.

Statistical analysis. Analysis of variance and means separation was conducted using the PROC GLIMMIX procedure in SAS (Version 9.4; SAS Institute, Cary, NC, USA) to determine the fixed effects of year, cultivar, and tarp treatment on marketable and unmarketable onion count and weight, as well as weed height, count, and weight at tarp removal. Interactions among year, tarp, and cultivar response variables were also tested. Block and all interactions with block were random factors in analyses. Repeated measures analysis was used to detect differences among tarp treatments and date for weed height, count, weight, and cultivation time over the length of the growing season. Means were separated according to Fisher's protected least significant difference test ($\alpha \leq 0.05$) using the "lsmeans" function. Normality was checked for all data collected using Q-Q plot, histogram, boxplot, and linear predictor.

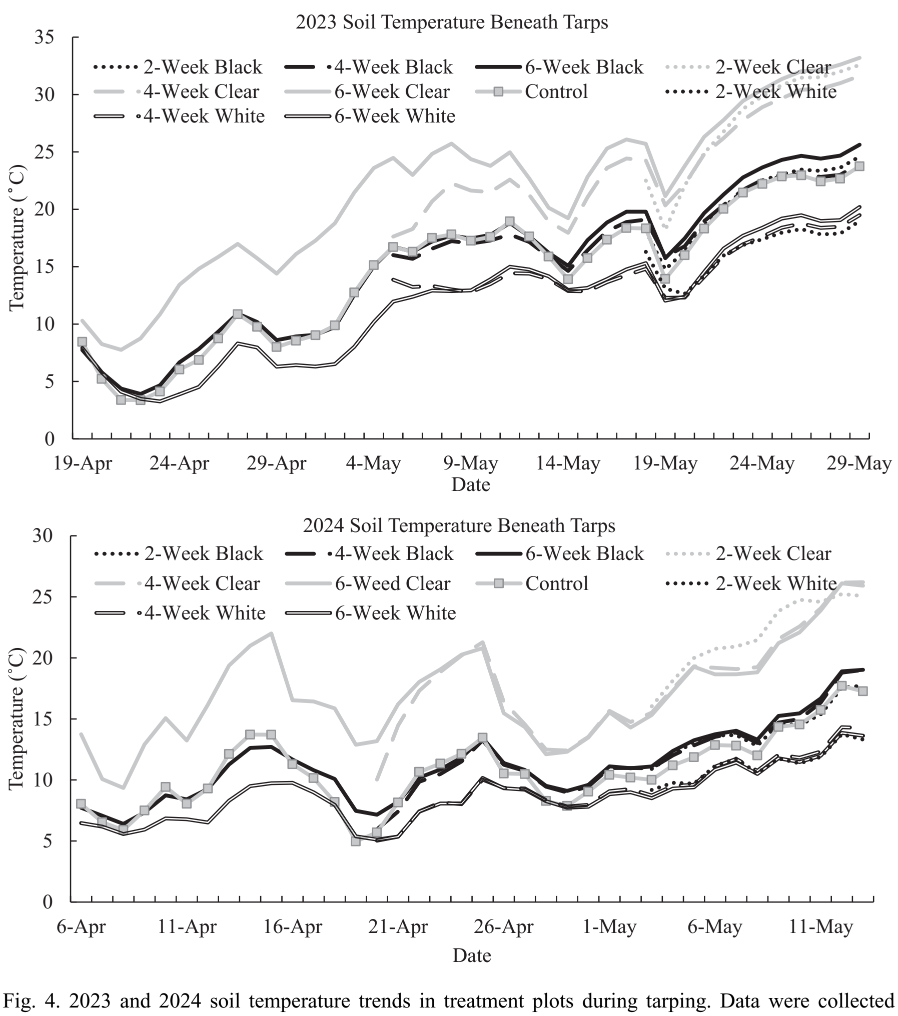


Fig. 4. 2023 and 2024 soil temperature trends in treatment plots during tarping. Data were collected with Onset HOBO moisture and temperature data loggers and temperature pendants (MX2201, MX2306; Bourne, MA, USA) to collect temperature at a soil depth of 10 cm. Data were averaged from four blocks of treatment replications each year.

Results

Soil temperature and moisture. Data from soil temperature and moisture sensors placed during tarping and the growing season provided interesting trends and insights. In both 2023 and 2024, clear treatments showed soil temperatures that trended higher than black, control, and white tarp treatments, respectively (Fig. 4). Both years, soil moisture was more consistent beneath the tarps than the control with no tarp, which fluctuated with precipitation events. Differences of soil moisture levels beneath the tarp treatments varied with year (Fig. 5).

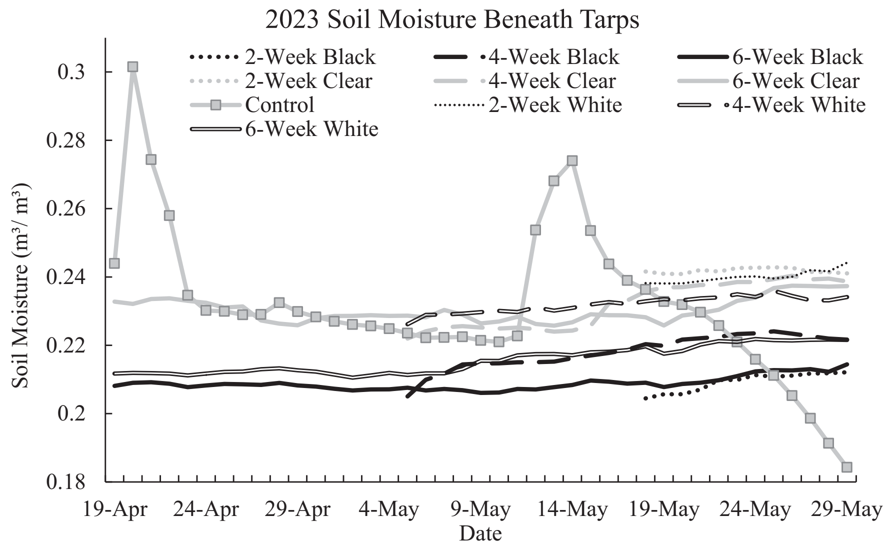
Weed pressure tarp removal. At tarp removal, there were visible differences among treatments both years (Figs. 6 and 7). Tarping effects on weed pressure varied by year for broadleaf and grass height and count. The field location in 2024 had higher thistle and overall weed pressure than the 2023 tarping plot area. Only broadleaf and grass weights showed consistent trends between the years.

Broadleaf weed height, weight, and count at tarp removal. Effects of treatments on broadleaf height differed by year with an average of 2.3 cm in 2023 and 7.1 cm in 2024 ($P = 0.017$; Table 1). In 2023, the 6 week clear tarp and control treatment plots had higher broadleaf height averages than all other treatments except the 2 week clear ($P < 0.001$). No treatment differences were seen in broadleaf heights within 2024.

Averaged across all treatments, broadleaf weights in 2024 were six times greater than broadleaf weights in 2023 ($P = 0.037$). Both years, however, showed similar trends. The control averaged 20 times more broadleaf weight than the 6 week black and two times more than the 2 week clear. All tarp treatments showed lower broadleaf weights than the control (Table 2).

In 2023, the control averaged 277 broadleaf weeds per square meter, more than all other treatments ($P < 0.001$; Table 1). The 2 week clear averaged 205 broadleaf weeds per square meter, which was twice that of the 4 and 6 week clear. All occultation treatments had considerably fewer broadleaves than control and clear treatments (Table 1). In 2024, 4 and 2 week clear produced just over 100 weeds per square meter, higher than all occultation treatments except for 2 week white ($P = 0.031$). No treatment in 2024 showed a significant difference from the control, which averaged 42 weeds per square meter.

Grass height, weight, and count at tarp removal. In 2023, grass height at tarp removal averaged 2.9 cm, compared with 11.1 cm in 2024 ($P = 0.009$; Table 1). Grass height responded differently in clear and control treatments based on year ($P = 0.043$). In both years, however, the control had taller grass



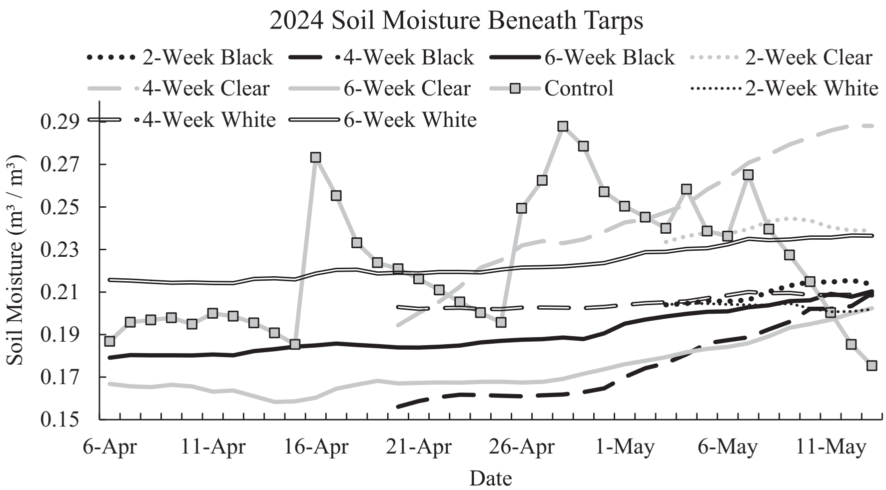


Fig. 5. 2023 and 2024 soil moisture trends in treatment plots during tarping. Data were collected with Onset HOBO moisture and temperature data loggers (MX2306; Bourne, MA, USA) to collect temperature at a soil depth of 10 cm. Data were averaged from two blocks of treatment replications.

weeds than the black and white tarp treatments (Table 1). In 2023, the control averaged 11.9 cm, taller than grass in all tarp treatments ($P < 0.001$). All occultation treatments, aside from 6 week white, had shorter grass than all clear treatments, which varied from 4 to 8 cm (Table 1). In 2024, grass in the control plots (21.7 cm) was taller than the 2 week clear but not the 4 and 6 week clear. The 4 week and 6 week black and white tarp treatments were lower than the control and 4- and 6-week clear ($P < 0.001$).

Grass weight in all occultation treatments except for the 2 week white was lower than the control ($P = 0.021$; Table 2). The control averaged just under 80 g per square meter, significantly higher than the 2 week clear tarp (16.32 $g \cdot m^{-2}$), but not the 4 and 6 week clear tarps, which were both ∼45 g per square meter (Table 2).

Treatment effects on grass count differed depending on year ($P = 0.011$; Table 1). In 2023, the control and 2 and 6 week clear average grass counts were higher than all occultation treatments which had almost no grass present ($P = 0.002$). The 2 week clear, with 157 grass weeds per square meter, was greater than the control, which averaged 132 weeds per square meter (Table 1). In 2024, 4 week clear (672 weeds/m^2) had more grass weeds than all occultation treatments and the control (240 weeds/m^2) ($P = 0.001$). Occultation treatments, and 2 and 6 week clear were not significantly lower than the control.

Weed pressure during the growing season. In both years, broadleaf and grass weed pressure differed by date during the growing season. Broadleaf and grass weeds had a trend of decreasing as the season progressed. Repeated measures analysis was used for all weed growth and cultivation time (data not shown) collected during the growing season. Tarping effect on broadleaf and grass weeds varied by year (Tables 3 and 4).

Broadleaf height, weight, and count. There were no differences in broadleaf weight among tarp treatments over the length of the growing season in 2024 ($P = 0.727$), but there were differences in 2023 ($P = 0.054$; Table 5). In 2023, broadleaf weight was higher in all clear and 4 and 6 week black treatments than 4 and 6 week white tarps. Differences due to date data were collected both years ($P < 0.001$). No differences were seen among tarp treatments over the length of the growing season for broadleaf count or height in either year (data not shown).

Grass height, weight, and count. No differences among tarping treatments were seen over the length of the season in 2023 for grass count ($P = 0.098$) or grass weight ($P = 0.094$). No differences were seen among treatments over the length of the season for grass height in 2023 or 2024 (data not shown).

However, in 2024, there were interactions between date and tarp treatment for grass counts ($P = 0.021$) and grass weights ($P = 0.053$) over the length of the growing season (Tables 3 and 4). For grass weight, the only significant difference among solarization treatments and the control was the control averaging almost three times the amount of the 6 week clear grass weight on 1 Jul. Grass counts showed a similar trend, with the 6 and 2 week clear showing lower grass counts than the control on 1 Jul. The 2 and 4 week clear also showed lower grass counts than the control on 19 Jun. No differences were seen between occultation treatments and the control for grass counts or weights over the length of the growing season except for 31 Jul, where the 2 week black showed significantly fewer grass weeds than the control. There were differences among dates over the growing season for both grass count and weight ($P < 0.001$).

Weed cultivation time. No differences were seen among treatments for weeding times over the length of the growing season in 2023 ($P = 0.753$) or 2024 ($P = 0.823$). There were, however, differences seen in weeding times among dates over the growing season ($P < 0.001$); both years showed decreasing time needed to weed plots as the season progressed (data not shown). This lines up with the trend of decreasing grass counts as the growing season in 2024 progressed.

Onion yield. Tarping treatments had no impact on total onion bulb yield, leaf count, or height either year. However, there was a difference in yield and leaf data due to cultivar.

Marketable yield: Total count, total weight, and size count and weight. Interaction was seen between year and cultivar for marketable onion count ($P = 0.021$). In 2023, 40% of ‘Candy’ onions and 75% of ‘Patterson’ onions planted were considered marketable ($P = 0.022$). In 2024, 65% of ‘Candy’ onions and 73% of Patterson onions were marketable ($P = 0.016$; Table 6).

There was an interaction between year and cultivar for marketable onion weight ($P = 0.003$). In 2023, average marketable yield weight was 1.99 $kg \cdot m^{-2}$ for ‘Candy’ onions and 4.44 $kg \cdot m^{-2}$ for ‘Patterson’ ($P = 0.023$). In 2024, ‘Candy’ yielded 4.68 $kg \cdot m^{-2}$ and ‘Patterson’ yielded 3.50 $kg \cdot m^{-2}$ ($P = 0.086$; Table 6).

An interaction between cultivar and year occurred for onion count in the small size

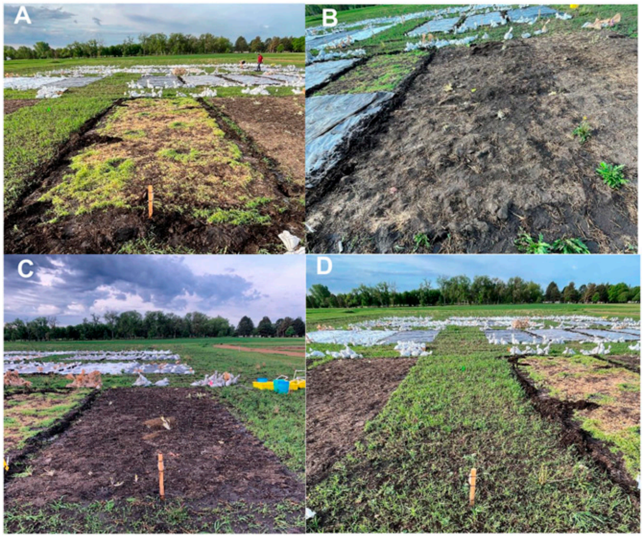


Fig. 6. Treatment plots at tarp removal on 30 May 2023 that were covered for 6 weeks with clear (**A**), white (**B**), and black (**C**) tarps compared with a control treatment with no tarp (**D**) in the South Dakota State University Specialty Crop Field. Tarping materials (6-mil black/white plastic sheeting and ultraviolet-resistant 6-mil clear greenhouse plastic) were purchased from Farm Plastic Supply (Addison, IL, USA). All tarps were secured with 25 to 30 6.8-kg sandbags; edges of clear tarps were buried in soil.

category ($P = 0.035$) but no differences were seen between cultivars for either year (Table 6). No interaction was seen between year and cultivar for medium onions. 'Patterson' averaged 54% medium onions while 'Candy' averaged 23% ($P < 0.001$) (data not shown). Interaction was again seen between cultivar and year for large onion count ($P = 0.001$). In 2023, 'Candy' averaged 6% large onions and 'Patterson' averaged 19% ($P = 0.049$). In 2024, 'Candy' averaged 31% large onions and 'Patterson' averaged 4% ($P = 0.010$). 'Candy' yielded more colossal onions than 'Patterson' over both years ($P = 0.007$).

Interaction between cultivar and year was seen for onion weight in the small size category ($P = 0.033$) but no differences were seen between cultivars for either year (Table 6). Medium-sized 'Patterson' onions averaged a weight of 2.78 $kg \cdot m^{-2}$ plot and 'Candy' averaged 1.23 $kg \cdot m^{-2}$ ($P < 0.001$). Interaction was again seen between cultivar and year for large onion weight ($P = 0.001$). No yield differences for large onion weight were seen between cultivars in 2023 ($P = 0.067$), but in 2024, 'Candy' averaged 2.98 $kg \cdot m^{-2}$ large onions and 'Patterson' averaged 0.33 $kg \cdot m^{-2}$ ($P = 0.003$). 'Candy' yielded a higher weight (0.11 $kg \cdot m^{-2}$) of colossal onions than 'Patterson' (0 $kg \cdot m^{-2}$) over both years ($P = 0.007$).

Cull count, weight, and cull category count. There was an interaction between year and cultivar for cull onion count ($P = 0.017$). In 2023, an average of 58% of 'Candy' onions and 21% of 'Patterson' planted were counted as cull; there was no difference between cultivars in 2024 (Table 7). Average cull weight over both years was 2.62 $kg \cdot m^{-2}$ for 'Candy' and 1.12 $kg \cdot m^{-2}$ for 'Patterson' ($P = 0.006$) (Table 7).

Interaction between cultivar and year was seen for onion insect damage count ($P = 0.040$), but no differences in insect damage count were seen between cultivars either year (Table 7). For disease and rot onion count, 'Candy' averaged 23% and 'Patterson' averaged 15% ($P = 0.011$). No differences were seen between cultivars for onions that were counted as too small. 'Candy' averaged more mishappen bulbs than 'Patterson' ($P = 0.026$). Interaction between cultivar and year was seen for green leaf ($P = 0.002$). 'Patterson' had more counts of green leaf in 2023 (0.049) and 'Candy' had more in 2024 ($P = 0.022$).

Onion living leaf count and height at harvest. In 2024, 'Candy' onions had minimal healthy foliage at harvest due to thrips damage from earlier in the season, and some leaves exhibited complete decay as opportunistic pathogens colonized wounds caused by thrips feeding. 'Patterson' showed higher living leaf count with an average of six leaves per onion plant than 'Candy', which showed an average of three leaves per plant ($P = 0.015$). The same trend was observed for onion leaf height. 'Patterson' showed an average height of 30.68 cm and 'Candy' showed an average height of 21.83 cm at harvest ($P = 0.013$) (Table 8).

Discussion

Our results support the idea that soil tarping can reduce weed pressure as compared with conventional tillage and hand weeding management, but contrary to other tarping study results, there was no effect on vegetable yield (Lounsbury et al. 2022a; Maher et al. 2024; Rylander et al. 2020a, 2020b). This could be because all treatment plots were cultivated biweekly throughout the growing season, so there was less impact of weed pressure on onion yield.

Solarization impacts on weed pressure at tarp removal. There was an obvious difference in weed pressure among treatments at tarp removal. In 2024, a slightly warmer, wetter spring (April-May average air temperature being 7 °C and total precipitation being 26 cm), the clear treatments showed higher grass counts, but lower weights than the control. This supports the idea that clear treatments resulted in the germination of more, but smaller weed seedlings before tarp removal, exhausting the weed seed bank sooner in the season. If a grower has time to tarp in early spring, they may reduce the amount of weeding required during the growing season. In 2023, a slightly colder and much drier year (April–May average air temperature being 6 °C and total precipitation being 9 cm), the clear treatments showed high broadleaf counts,

Fig. 7. Treatment plots at tarp removal on 14 May 2024 that were covered for 6 weeks with clear (**A**), white (**B**), and black (**C**) tarps compared with a control treatment with no tarp (**D**) in the South Dakota State University Specialty Crop Field. Tarping materials (6-mil black/white plastic sheeting and ultraviolet-resistant 6-mil clear greenhouse plastic) were purchased from Farm Plastic Supply (Addison, IL, USA). All tarps were secured with 25 to 30 6.8-kg sandbags; edges of clear tarps were buried in soil.

Table 1. Average broadleaf and grass count and height within treatments at tarp removal for 2023 and 2024. To collect data, three square 50 × 50 cm polyvinyl chloride quadrats were thrown randomly into each treatment plot; within each quadrat, all broadleaf and grass weeds were counted; three broadleaf and three grass weeds were randomly selected to measure height. In 2023, only living weeds from treatment plots were included in weed data collection. Both living and dead weeds from treatment plots were included in weights in 2024. Data were analyzed using analysis of variance and means separation using the PROC GLIMMIX procedure in SAS (Version 9.4; SAS Institute, Cary, NC, USA).

	Broadleaf weed count/m^2	Grass weed count/m^2	Broadleaf ht (cm)	Grass ht (cm)
	2023			
Treatment				
2-week black	2 d[i]	0 b	1.67 cd	0.00 e
4-week black	2 d	0 b	0.78 cd	0.00 e
6-week black	2 d	0 b	0.47 cd	0.00 e
2-week clear	205 b	157 a	2.89 bc	4.17 cd
4-week clear	109 c	75 ab	2.50 cd	3.78 cd
6-week clear	94 c	139 a	5.95 a	8.03 b
Control (no tarp)	277 a	132 a	5.06 ab	11.86 a
2-week white	0 d	0 b	0.00 d	0.00 e
4-week white	3 d	0 b	1.92 cd	0.00 e
6-week white	2 d	9 b	2.22 cd	0.89 de
P value	<0.001	0.002	<0.001	<0.001
	2024			
2-week black	15 bc	54 c	6.47	12.92 bcd
4-week black	6 c	32 c	5.64	4.81 ef
6-week black	9 bc	5 c	3.47	0.36 f
2-week clear	104 a	467 ab	4.45	12.72 bcd
4-week clear	113 a	672 a	0.00	15.89 abc
6-week clear	81 ab	521 ab	5.92	18.97 ab
Control (no tarp)	42 abc	240 bc	9.14	21.72 a
2-week white	42 abc	304 bc	9.56	11.14 cde
4-week white	27 bc	54 c	6.81	6.47 def
6-week white	16 bc	25 c	11.67	6.14 def
P value	0.031	0.001	0.413	<0.001
Year				
2023	70	51	2.34 b	2.87 b
2024	45	237	7.08 a	11.11 a
Significance of effect				
Treatment	<0.001	<0.001	0.134	<0.001
Year	0.203	0.066	0.017	0.009
Treatment x year	<0.001	0.011	0.213	0.043

[i] Values within the same column followed by a different letter are statistically different according to Fisher's protected least significant difference (α ≤ 0.05).

Table 2. Average broadleaf and grass weight within treatments at tarp removal with both years (2023 and 2024) of data combined. To collect data, three square 50 × 50 cm polyvinyl chloride quadrats were thrown randomly into each treatment plot; within each quadrat, all broadleaf and grass weeds were clipped to soil level, separately bagged, and dried for 3 d at 60°C. In 2023, only living weeds from treatment plots were included in weed weights. Both living and dead weeds from treatment plots were included in weights in 2024. Data were analyzed using analysis of variance and means separation using the PROC GLIMMIX procedure in SAS (Version 9.4; SAS Institute, Cary, NC, USA).

	Broadleaf wt (g/m^2)	Grass wt (g/m^2)
Treatment		
2-week black	8.833 bc[i]	11.252 b[i]
4-week black	2.022 bc	3.583 b
6-week black	1.618 c	0.250 b
2-week clear	16.087 b	16.320 b
4-week clear	14.867 bc	44.000 ab
6-seek clear	10.737 bc	44.217 ab
Control (no tarp)	31.919 a	79.267 a
2-week white	8.002 bc	38.835 ab
4-week white	3.417 bc	7.500 b
6-week white	4.417 bc	1.605 b
Year		
2023	2.880 b	2.40 b
2024	17.503 a	46.95 a
Significance of effect		
Treatment	0.003	0.021
Year	0.037	0.094
Treatment × year	0.267	0.053

[i] Values within the same column followed by a different letter are statistically different according to Fisher's protected least significant difference (α ≤ 0.05).

but fewer broadleaves than the control. This could be due to clear treatments germinating high amounts of weed seedlings and then many of the seedlings dying due to high temperatures beneath the tarp. In 2023, average temperatures reached beneath the clear tarps trended higher than 2024 (Fig. 4). This may be because tarping was conducted later in the spring in 2023, so solarized plots may have been exposed to sunnier, warmer conditions as summer approached. The warmer temperatures beneath the clear tarps during 2023 also may have been due to less weed growth, which allowed the soil to be exposed to more sun and higher temperatures (Singh et al. 2022). The greater weed coverage in 2024, most likely due to higher moisture, may have shaded the soil and reduced soil temperature (Gupta et al. 1983; Kahimba et al. 2008; Singh et al. 2022; Yang et al. 2021). Increased moisture slows down soil warming and cooling, so the drier year of less soil moisture in 2023 may have exposed the plots to more extreme temperature fluctuations (Al-Kayssi et al. 1990).

Occultation impacts on weed pressure at tarp removal. Results from 2023 showed the use of both white and black tarps reduced annual weeds at removal when compared with plots with no tarps; this is in alignment with results of a study conducted in the Northeast United States (Rylander et al. 2020b). Treatments with the same color tarp did not differ due to the amount of time the tarp was applied, which also aligns with previous research (Rylander et al. 2020b). During 2023, spring precipitation was minimal (March through April was 9 cm; South Dakota Mesonet 2024), and 6 week tarps were placed when very minimal weed growth was present in fields. More weed growth was present in the field location right before 4 and 2 week tarps were placed, especially in 2024; there was much more weed pressure in 2024 than in 2023. In 2024, our study site had higher spring precipitation (March through April was 25.5 cm) and much earlier weed growth, despite tarping 2 weeks earlier than the previous year. There were much higher weed populations of pregerminated perennial weeds such as Canada thistle (*Cirsium arvense*) and dandelion (*Taraxacum officinale*), as well as very high amounts of the winter annual cheatgrass (*Bromus tectorum*) up to 4 weeks before tarp removal, with excessive weed pressure increasing as tarp removal date drew closer. The jumpstart on growth before tarping for these resilient weeds may be the cause of occultation being less effective in 2024.

Perennial and annual weed growth responses to solarization and occultation. Studies have shown tarping does not reduce perennial weeds such as Canada thistle and dandelion because of deep underground rhizomes that can survive higher surface-level soil temperatures from occultation and solarization; encouraged growth from warmer temperatures only strengthens underground storage reserves (Lounsbury et al. 2022b). Cheatgrass can germinate at just above freezing temperature with optimum plant growth occurring

Table 3. Grass weight tarp and date interactions analyzed over the length of the 2024 growing season through repeated measures. To collect data biweekly, two square 25 × 25 cm polyvinyl chloride quadrats were thrown randomly into each onion cultivar bed within each treatment plot; within each quadrat, all grass weeds were clipped to soil level, bagged, and dried for 3 d at 60°C. Data were analyzed using repeated measures, analysis of variance, and means separation using the PROC GLIMMIX procedure in SAS (Version 9.4; SAS Institute, Cary, NC, USA).

	2024 grass weight (g/m^2)					
	3 Jun	19 Jun	1 Jul	18 Jul	31 Jul	8 Aug
Treatment						
2-week black	6.24 A b[i]	17.2 A a	15.53 CD a	6.61 C abc	0.04 B c	2.09 NS bc
4-week black	3.17 AB b	17.7 A a	25.08 ABC a	20.73 AB a	0.86 AB b	3.16 NS b
6-week black	2.94 AB c	11.3 AB b	27.23 AB a	15.08 ABC ab	0.07 B c	1.42 NS c
2-week clear	1.49 B c	5.25 B bc	15.8 BCD a	12.64 ABC ab	0.22 AB c	0.79 NS c
4-week clear	2.25 AB b	5.57 B b	17.67 ABCD a	9.48 BC ab	1.08 A b	0.94 NS b
6-week clear	1.7 B d[i]	8.61 AB bc	10.89 D ab	21.95 A a	0.65 AB d	0.9 NS cd
Control (no tarp, tilled)	3.2 AB cd	10.4 AB b	26.85 ABC a	11.86 ABC bc	0.83 AB d	2.15 NS d
2-week white	5.42 A b[i]	9.96 AB b	28.31 A a	7.69 C bc	0.35 AB c	4.28 NS b
4-week white	3.21 A b[i]	11.6 AB a	17.92 ABCD a	11.25 ABC ab	1.01 AB c	1.07 NS c
6-week white	4.26 A b[i]	5.46 B bc	28.71 A a	10.44 ABC b	0.25 AB c	1.63 NS bc
Significance of effect						
Treatment	0.094					
Date	<0.001					
Treatment × date	0.053					

[i] Uppercase letters signify differences among tarp treatments within date and lowercase letters signify differences among dates. Values within the same column followed by a different letter are statistically different according to Fisher's protected least significant difference (α ≤ 0.05). NS = not significantly different.

between 3 and 31 °C (Martens et al. 1994; Young and Evans 1973; Zouhar 2003). Temperature was maintained within this optimum range for all treatments during 2024, when cheatgrass populations were high. Because solarized treatment temperatures were generally higher than other treatments, but still within optimum growing range for this species, cheatgrass thrived in these treatments. The lower grass heights in solarized treatments compared with the control in 2023 and 2024 was likely due to the weight of the plastic and buried edges reducing upright plant growth; in addition, by tarp removal, many weeds within the solarized plots were very chlorotic and necrotic, likely due to temperature stress. Lower weed height seen in solarization and occultation may have potential to reduce risk of weeds getting caught and wrapped up in tillage equipment or mowers at bed preparation, therefore reducing labor of cleaning weeds from equipment.

Growing season broadleaf weed weight. Over the length of the growing season in 2023, broadleaf weed weight was higher in all clear and 4 and 6 week black treatments than 4 and 6 week white tarps, but no treatments were different from the control. This suggests that solarization and occultation did not have any significant impact on broadleaf weeds during the growing season. Minimal differences noted in growing season weed growth may have been due to the biweekly hand weeding events conducted during the growing season that sufficiently decreased weed populations.

Growing season grass weed weight and count. Over the length of the growing season in 2024, grass weights and counts were lower in varying clear treatments than the control. This suggests that regardless of tarp duration, solarization successfully exhausted the seedbank at the beginning of the season and reduced weed pressure during the growing season. Minimal to no differences were seen between occultation treatments and the control for grass counts or weights over the length of the growing season, which suggests that occultation did not impact weed pressure during the growing season. It is important to note that in our study, white tarp treatments showed trends of higher grass pressure than all other treatments, although not statistically significant. Contrary to our results, previous studies have shown occultation treatments to have less biomass at the end of the growing season for beet production (Rylander et al. 2020b). This study was conducted in the Northeast where spring soil moisture is commonly very high, and they may have had success in warming up the moist soil to create an environment perfect for germinating non-photoblastic weed seeds and then depriving those seedlings of light to conduct photosynthesis with the black tarp coverage, therefore killing germinated weed growth (Rylander et al. 2020b).

Table 4. Grass count tarp by date interactions analyzed over the length of the 2024 growing season through repeated measures. To collect data biweekly, two square 25 × 25 cm polyvinyl chloride quadrats were thrown randomly into each onion cultivar bed within each treatment plot; within each quadrat, all grass weeds were counted. Data were analyzed using repeated measures, analysis of variance, and means separation using the PROC GLIMMIX procedure in SAS (Version 9.4; SAS Institute, Cary, NC, USA).

	2024 grass (count/m^2)					
	3 Jun	19 Jun	1 Jul	18 Jul	31 Jul	8 Aug
Treatment						
2-week black	635 AB a[i]	397 A a	410 AB a	69 AB b	3 B c	14 AB c
4-week black	810 AB a	289 ABC b	461 A a	130 A c	22 AB d	22 AB d
6-week black	661 AB a	243 ABCD b	322 ABCD ab	103 AB c	6 AB c	29 A c
2-week clear	298 B NS	89 D NS	132 D NS	46 B NS	11 AB NS	8 AB NS
4-week clear	370 B abcd	110 CD cd	206 BCD b	67 AB bc	21 AB cd	8 AB d
6-week clear	368 B ab	142 BCD a	145 CD ab	80 AB a	9 AB b	4 B b
Control (no tarp, tilled)	780 AB a	311 AB b	368 ABC b	108 AB c	28 A d	13 AB d
2-week white	880 AB a	359 A b	354 ABCD b	120 A c	11 AB d	6 B d
4-week white	876 AB a	327 AB b	273 ABCD b	103 AB c	27 A d	15 AB d
6-week white	1101 A a	212 ABCD b	370 ABC c	87 AB d	15 AB e	13 AB e
Significance of effect						
Treatment	0.098					
Date	<0.001					
Treatment × date	0.012					

[i] Uppercase letters signify differences among tarp treatments within date, while lowercase letters signify differences among dates. Values within the same column followed by a different letter are statistically different according to Fisher's protected least significant difference (α ≤ 0.05). NS = not statistically significant.

Table 5. Average broadleaf weight analyzed over the length of the 2023 growing season through repeated measures. To collect data, two square 25 × 25 cm polyvinyl chloride quadrats were thrown randomly into each onion cultivar bed within each treatment plot; within each quadrat, all broadleaf weeds were clipped to soil level, bagged, and dried for 3 d at 60°C. Data were analyzed using repeated measures, analysis of variance, and means separation using the PROC GLIMMIX procedure in SAS (Version 9.4; SAS Institute, Cary, NC, USA).

	Broadleaf wt (g/m^2)
Treatment	
2-week black	24.98 ab[i]
4-week black	36.34 a
6-week black	31.94 a
2-week clear	32.7 a
4-week clear	31.12 a
6-week clear	33 a
Control (no tarp, tilled)	22.98 ab
2-week white	25.4 ab
4-week white	14.14 b
6-week white	16.16 b
Date	
12 Jun	8.34 b
5 Jul	117.77 a
18 Jul	2.66 cd
1 Aug	3.68 c
17 Aug	1.93 d
Significance of effect	
Treatment	0.054
Date	<0.001
Treatment × date	0.3125

[i]Values within the same column followed by a different letter are statistically different according to Fisher's protected least significant difference (α ≤ 0.05).

This Northeast study did not conduct any biweekly weeding in treatment plots during the growing season, so the higher cumulation of weeds over the growing season may have shown greater differences among treatments when weed biomass was collected at harvest as compared with our work (Rylander et al. 2020b).

Growing season cultivation time within each tarp treatment. No differences were seen among treatments for weeding times over the length of the growing season in our study. However, the time needed to weed all plots decreased as the season progressed, aligning with our data showing decreasing grass weight and counts as the season progressed in 2024. Our results of no differences among treatments for weeding labor contradicted previous studies that have noted a reduction in weeding labor in tarped plots (Maher et al. 2024; Stapleton et al. 2005). A study conducted in New York noted that using black tarps in a no-till system reduced labor costs and produced similar weed control to conventional tillage management for cabbage and winter squash crops (Maher et al. 2024). Another study in California found that solarized treatments reduced weed labor 48% or greater when compared with an untreated control plot in strawberry production (Stapleton et al. 2005). These studies used crops with greater leaf canopy than onions that may have been able to better compete with weeds as the season progressed, therefore reducing labor.

Onion yield differences among tarp treatments. Contrary to previous studies showing increased yield for cabbage, beets, strawberries, and squash, our study resulted in no difference in onion yield due to tarp treatment (Lounsbury et al. 2022a; Maher et al. 2024; Rylander et al. 2020b; Stapleton et al. 2005). Our contradictory results may be due to the biweekly hand weeding during the growing season evening out weed pressure among treatments as the season progressed and minimizing any weed pressure effects on yield. Another reason our study showed differing yield results compared with other studies may be because onions are slow growing with minimal canopy, so they were unable to compete with weeds coming up during the growing season; previous studies that noted higher yields in tarped treatments used faster growing crops with larger canopies and therefore greater potential to compete with and shade out later season weeds (Maher et al. 2024; Stapleton et al. 2005). Although we expected increased onion yield due to weed reduction from tarping, we noted minimal onion yield differences among tarping treatments (Burrows 2022). Tarping my provide a tool for growers to balance weed management in a reduced-tillage system without harming yield.

Yield difference between onion cultivars. Although there was no difference in yield due to treatment, there was a difference in yield between Candy and Patterson cultivars. 'Candy' produced more large and colossal onions, which aligns with previous onion studies (Russo 2008). 'Patterson' onions produced more medium-sized onions than 'Candy'. 'Candy' trended toward having higher insect pressure and rot than 'Patterson' and produced significantly more rotten onions than 'Patterson' in 2023. The thick, papery skin surrounding the 'Patterson' onion bulb may have played a role in protecting the 'Patterson' onions from insect and disease damage, allowing it to produce a higher number of marketable onions than the minimally skinned 'Candy' onions. Despite high thrips damage to onion leaves in 2024, onion bulbs succumbed to very minimal insect damage. The main reason for unmarketable onions for 2024 was disease and rot. This may have been because of the high amounts of rain received as well as extreme temperature and moisture fluctuations during high tunnel curing. Studies have found that high temperature, moisture, and curing too long can increase chances for onions to succumb to disease and rot (Coolong and Williams 2014; Schwartz 2011; Tho et al. 2019; Vahling-Armstrong et al. 2016).

Conclusion

This research provides evidence that tarping can reduce weed pressure early in the season.

Table 6. Total onion marketable average weight and count of 48 planted onions and weight and count within each size category. In 2023, onions were harvested 28 Aug, cured in the South Dakota State University (SDSU) campus greenhouse until analyzed for yield 26 Sep through 12 Oct. In 2024, onions were harvested 27 Aug and cured in the SDSU Specialty Crop Field high tunnel until yield was analyzed 2 Oct through 7 Oct. Data were analyzed using analysis of variance and means separation using the PROC GLIMMIX procedure in SAS (Version 9.4; SAS Institute, Cary, NC, USA).

	Weight (kg/m^2)					Count/48 onions				
Cultivar	Total	Small	Medium	Large	Colossal	Total	Small	Medium	Large	Colossal
2023										
Candy	1.993 b[i]	0.284	0.961 b	0.695	0.054	19 b	6	6 b	3 b	0
Patterson	4.444 a	0.210	2.519 a	1.715	0.000	36 a	5	23 a	9 a	0
P value	0.023	0.199	0.004	0.067	0.193	0.022	0.231	0.006	0.049	0.182
2024										
Candy	4.679	0.053	1.493 b	2.978 a	0.155 a	31 b	2	13 b	15 a	1 a
Patterson	3.495	0.129	3.035 a	0.330 b	0.000 b	35 a	3	30 a	2 b	0 b
P value	0.086	0.090	0.008	0.010	0.044	0.016	0.079	0.008	0.010	0.043
Significance of effect										
Treatment	0.570	0.354	0.695	0.151	0.649	0.748	0.293	0.229	0.189	0.717
Year	0.296	0.170	0.275	0.318	0.102	0.421	0.268	0.240	0.281	0.076
Cultivar	0.137	0.965	<0.001	0.041	0.007	0.002	0.816	<0.001	0.056	0.007
Treatment × cultivar	0.173	0.832	0.992	0.282	0.649	0.176	0.598	0.930	0.464	0.717
Treatment × year	0.869	0.722	0.832	0.547	0.673	0.961	0.804	0.472	0.781	0.625
Cultivar × year	0.003	0.033	0.962	0.001	0.102	0.021	0.035	0.282	0.001	0.076
Treatment × cultivar × year	0.747	0.724	0.182	0.763	0.673	0.597	0.438	0.404	0.720	0.625

[i]Values within the same column followed by a different letter are statistically different according to Fisher's protected least significant difference (α ≤ 0.05).

Table 7. Onion total cull weight and count and reason for cull count categories. In 2023, onions were harvested 28 Aug and cured in the South Dakota State University (SDSU) campus greenhouse until analyzed for yield 26 Sep through 12 Oct. In 2024, onions were harvested 27 Aug and cured in the SDSU Specialty Crop Field high tunnel until yield was analyzed 2 Oct through 7 Oct. Data were analyzed using analysis of variance and means separation using the PROC GLIMMIX procedure in SAS (Version 9.4; SAS Institute, Cary, NC, USA).

	Weight (kg/m²)	Count/48 onions					
Cultivar	Total cull wt	Total cull count	Insect damage	Disease and rot damage	Too small <1 inch	Mishappen	Green leaf
2023							
Candy	2.935 a[i]	28 a	16	9 a	5	1	0 b
Patterson	1.024 b	10 b	2	4 b	2	0	1 a
P value	0.053	0.018	0.077	0.032	0.153	0.178	0.049
2024							
Candy	2.295	16	1	13	1	1	1 a
Patterson	1.212	11	1	11	1	0	0 b
P value	0.058	0.094	0.888	0.279	0.661	0.084	0.022
Significance of effect							
Treatment	0.547	0.820	0.855	0.615	0.519	0.854	0.352
Year	0.832	0.435	0.018	0.439	0.142	0.699	0.839
Cultivar	0.006	0.002	0.038	0.011	0.097	0.026	0.755
Treatment × cultivar	0.373	0.099	0.759	0.603	0.038	0.338	0.760
Treatment × year	0.572	0.728	0.799	0.827	0.782	0.721	0.832
Cultivar × year	0.290	0.017	0.040	0.131	0.133	0.893	0.002
Treatment × cultivar × year	0.555	0.629	0.498	0.784	0.092	0.220	0.396

[i] Values within the same column followed by a different letter are statistically different according to Fisher's protected least significant difference (α ≤ 0.05).

Table 8. Onion leaf height and leaf count data collected before onion harvest 28 Aug 2023 and 27 Aug 2024. To collect data, five onions within each onion bed in each treatment plot were selected in a zigzag pattern; leaves were counted and the tallest living leaf was measured for height. Data were only collected in two of four blocks both years. Data were analyzed using analysis of variance and means separation using the PROC GLIMMIX procedure in SAS (Version 9.4; SAS Institute, Cary, NC, USA).

	Count	Height (cm)
Cultivar		
Candy	3 b[i]	21.83 b
Patterson	6 a	30.68 a
Year		
2023	5	38.41
2024	4	14.10
Significance of effect		
Treatment	1.000	0.880
Year	0.390	0.066
Cultivar	0.015	0.013
Treatment × cultivar	0.938	0.291
Treatment × year	0.548	0.862
Cultivar × year	0.939	0.290
Treatment × cultivar × year	0.837	0.816

[i] Values within the same column followed by a different letter are statistically different according to Fisher's protected least significant difference (α ≤ 0.05).

Although fewer weeds were noted in occultation treatments at tarp removal, perennial weeds like Canada thistle and dandelions survived early spring occultation. Solarized treatments showed reduced weed pressure later in the growing season; however, other weed management practices still needed to be used along with tarping to maintain a viable yield of onions. The effort taken to tarp did not increase the overall yield of onions, but also did not negatively impact yields. Occultation can reduce early season weed competition and may work more effectively with faster growing crops that grow a larger canopy to shade out weeds later in the season. Further research could be conducted to observe tarping used later in the season in Midwest climates, as this may increase heat potential for solarization to kill more weed seeds in the soil.

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