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Cover Crop Windbreaks Can Slow Deterioration of Biodegradable Mulch Film and Increase Bell Pepper Yield

C. Wehrbein and S. E. Wortman
Department of Agronomy and Horticulture, University of Nebraska–Lincoln, 278 Plant Sciences Hall, Lincoln, NE 68583, USA

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Abstract. **Biodegradable mulches are a potentially sustainable alternative to polyethylene mulch film in specialty crops, but they are prone to early deterioration by weathering. Windbreaks could reduce the degrading effect of wind on biodegradable mulches and potentially extend their useful life span in open field conditions. We tested the effect of a cereal rye (*Secale cereale*) annual windbreak on biodegradable mulch durability and plant productivity in a mulched bell pepper (*Capsicum annuum*) crop across two years in Lincoln, NE, USA. Bioplastic and polyethylene mulches were tested during both years, and a paper mulch was included in year two. Windbreaks were oriented perpendicular to the southern prevailing wind direction with mulched beds located north of cereal rye windbreak strips. Data collection across both years included windspeed, gust speed, soil temperature, soil moisture, mulch deterioration, stomatal conductance, leaf greenness (soil plant analysis development), and total fruit yield. Annual wind trends in 2024 were characterized by stronger and more frequent southern winds than those in 2023; as a result, windbreaks were more effective for reducing windspeeds in 2024. Bioplastic and polyethylene mulches increased soil temperatures by 1.9 °C relative to paper mulch, and windbreaks increased soil temperatures by 0.9 °C in 2024 relative to no windbreak, which could contribute to crop earliness and greater total yield. Within 3 weeks of planting, small and large holes in mulch were greatest in bioplastic mulch across both years. In 2024, bioplastic mulches behind windbreak shelter had 42% fewer large holes than unsheltered bioplastic mulches. Stomatal conductance was 27% to 29% greater in pepper sheltered behind a windbreak (relative to unsheltered pepper) across both trial years. Total yield per plant of pepper grown behind a windbreak shelter was 24% greater than that of unsheltered pepper in 2024, but there were no yield differences in 2023. The results suggest that cover crop windbreaks can contribute to greater crop yield, particularly in windy years, by extending the functional lifespan of biodegradable mulch films and increasing crop stomatal conductance. Additional research is needed to evaluate additional biodegradable mulch types and cover crop species as windbreaks as well as the relative effects of windbreak size and distance from the windbreak on crop and mulch performance.**

Agricultural mulches are widely used in specialty crop production to modify the crop and soil microclimate and increase yield potential. Key functions of mulches include their ability to conserve soil moisture, modulate soil temperatures, and physically obstruct weed growth (Kasirajan and Ngouajio 2012; Miles et al. 2017; Tofanelli and Wortman 2020; Wortman et al. 2016). Polyethylene mulch films remain the most used agricultural mulch product because of their low manufacturing costs and reliable performance in open field conditions (Tofanelli and Wortman 2020). Although durable and cheap, polyethylene mulches can have pollutive environmental effects. Polyethylene mulch removal can leave plastic fragments in the field, which can accumulate and inhibit plant growth or be assimilated by future crops (Hou et al. 2019). Removed mulch is typically routed to landfills because recycling soil-contaminated polyethylene can be challenging (Miles et al. 2017).

Biodegradable mulches are a potentially sustainable alternative to polyethylene mulches because they can be biodegraded in ambient soil conditions (Tofanelli and Wortman 2020). These mulches can be entirely biobased and composed of starches, cellulose, or lignin materials, as is common in wood chips, crop residues, or paper-based mulches (Shcherbatyuk et al. 2024). Alternatively, biodegradable plastic mulch films can be derived from a combination of biobased and petroleum-based feed stocks (Miles et al. 2017). Biodegradable plastic mulch films are advantageous because of their ease of application (similar to polyethylene mulch) and ability to be tilled into soils after a growing season (Miles et al. 2017; Tofanelli and Wortman 2020). However, biodegradable mulch films and similar products have been shown to prematurely degrade, especially in environments with high weathering factors (Miles et al. 2012; Tofanelli and Wortman 2020; Wortman et al. 2016). The lack of consistency in mulch durability has been previously identified as a barrier to adoption of biodegradable mulch technology among growers (Goldberger et al. 2015; Tofanelli and Wortman 2020).

Biodegradable mulch durability has been observed to improve when used in protected environments where weathering is mitigated to some extent. In cucumber production, degradation of bioplastic mulches was slower in high tunnels, with mulch products exhibiting visible deterioration that did not exceed 3%, whereas visible deterioration of some products exceeded 20% in open field conditions (Wortman et al. 2016). Paper-based and bioplastic mulches had a higher visible deterioration rate and more rips, tears, and holes when subjected to open field conditions compared with high tunnels across three different tomato production regions (Miles et al. 2012). While high tunnels can greatly reduce mulch exposure to weathering effects (e.g., ultraviolet radiation, wind, and precipitation), the large-scale conversion of open field to high tunnel production would be cost-prohibitive to most growers and is not feasible (Janke et al. 2017). To integrate more sustainable production practices, such as biodegradable mulch use, that preserve the environment and retain yields, alternative practices that reduce mulch weathering potential are needed. These practices should be low-cost and easily implemented by growers for quick and large-scale adoption of sustainable crop production technology.

Windbreaks are traditionally composed of lines of trees, shrubs, or both and reliably reduce wind speeds in agricultural and ecological systems (Brandle et al. 2021; Cleugh 2002). In agriculture, windbreaks can influence microclimatic factors (e.g., increase air temperatures and reduce evaporation) that can lead to increases in crop yield (Cleugh 2002). Windbreaks offer the most shelter on the leeward side of the barrier and can reduce wind speeds on the leeward side up to distances of 10- to 30-times the height of the barrier, depending on the barrier density (Brandle et al. 2021). While traditional windbreaks may be an effective strategy for reducing the weathering effects of wind on agricultural mulch, windbreaks composed of trees or shrubs require a significant amount of time and resource investment to reach maturity (Hodges and Brandle 1996). Furthermore, tree windbreaks are inflexible once established and may require additional ongoing maintenance (Hodges and Brandle 1996).

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S.E.W. is the corresponding author. E-mail: swortman@unl.edu.

Annual herbaceous windbreaks have been noted as a less expensive and flexible solution to reduce wind speeds in adjacent production fields to improve microclimate and potentially enhance yields (Hodges and Brandle 1996). Cover crops such as cereal rye (*Secale cereale*) or winter wheat (*Triticum aestivum* L.) can be established in the fall, overwinter, and then provide shelter in the spring and early summer, which could improve crop health and help reduce the impact of wind-induced weathering of agricultural mulch film. Strips of grass have been cited as effective tools to reduce wind speeds and wind erosion in ecological research and some crop applications (Aase et al. 1985; Rotnicka et al. 2023). Strip cropping research involving corn (*Zea mays*) and soybean (*Glycine max*) found that soybean sheltered by corn had increased leaf area relative to unsheltered soybean, indicating a higher potential for productivity (Radke and Hagstrom 1976). Research of intercropping suggested that strips of a taller herbaceous plant can act as a windbreak and help reduce crop transplant damage and seedling mortality and increase yield (Brainard and Noyes 2012; Gebru 2015; Spieser 1984). Although there are some documented benefits of using herbaceous windbreaks to enhance specialty crop production, limited studies have explored cover crops as annual herbaceous windbreaks. Moreover, no previous studies have quantified the effect of an annual herbaceous windbreak on wind-mediated weathering of biodegradable mulches.

To address this knowledge gap, we aimed to study the effectiveness of a cereal rye windbreak to reduce ground-level wind speeds adjacent to a mulched bell pepper crop. Our objectives were to quantify changes in microclimate, biodegradable mulch durability, and pepper growth as influenced by seasonal wind shelter from an annual herbaceous windbreak.

Materials and Methods

Field history and study design. Field trials were conducted between Sep 2022 and Aug 2024 at the University of Nebraska–Lincoln East Campus Research Farm, Lincoln, NE, USA (lat. 40°50′12″N, long. 96°39′48″W). Research fields were formerly used for matted-row strawberry production research from Spring 2021 to Sep 2022. Dominant weed species in the field include pigweed (*Amaranthus* sp.), field bindweed (*Convolvulus arvensis*), and crabgrass (*Digitaria* sp.). Soil organic matter in the field ranged between 3.5% to 4.0%, there was a small field slope (<1%), and there were no nearby structures or vegetation providing wind shelter.

A randomized complete block split-plot design was used, with four replicates in 2022–23 and five replicates in 2023–24. Whole plots (length × width: 54 ft × 6 ft) included the presence/absence of a cereal rye (*Secale cereale*) windbreak located south of split-plot rows. Whole plot areas were oriented east to west lengthwise. Split plots (length × width: 12 ft × 3 ft) tested different mulch types and were located within the protected leeward area north of whole plots (Fig. 1). Mulch types tested included 1.5-mil (0.038-mm) black polyethylene mulch film (Rain-Flo Irrigation, East Earl, PA, USA), black bioplastic mulch film (Bio 360; Johnny's Selected Seeds, Winslow, ME, USA), and a bare soil control without mulch. During 2023–24, the control was replaced with paper mulch (WeedGuardPlus®; Sunshine Paper Co., Aurora, CO, USA). Split-plot treatments were oriented east to west lengthwise within raised bed rows (Fig. 1).

Study management. Organic cereal rye seed [Winter rye (Common); Johnny's Selected Seeds, Winslow, ME, USA) was broadcast-seeded and lightly disked into whole plots on 9 Sep 2022 and 18 Sep 2023 to prepare for the 2023 (year 1) and 2024 (year 2) field studies, respectively (Table 1). Aisle buffers were planted with oats (*Avena sativa* L.) and white clover (*Trifolium repens*) on 9 Sep 2022, and with cereal rye on 18 Sep 2023. Whole plots received supplemental irrigation using oscillating lawn sprinklers to aid cereal rye establishment in both trial years because of uncharacteristically dry fall weather. Before forming raised beds, split-plot areas received an equivalent of 120 lb/acre nitrogen (N) for the year 1 study as compost (Soil Dynamics; Ashland, NE, USA). In the second trial year, 100 lb/acre N was applied to raised beds as urea. Raised beds were formed with a bed shaper/mulch layer (RB-448; Nolt's Produce Supplies, Leola, PA, USA). A single drip line (0.55 gal/min/100 ft of drip tape; Irritec, Fresno, CA, USA) was laid before split-plot treatments were applied. Plastic and bioplastic films and paper mulches were mechanically applied to split plots using the same bed shaper/mulch layer. Bare soil control whole-plot treatment areas were mowed at the time of applying split-plot treatments. Cereal rye windbreak whole-plot treatments remained unmanaged for the duration of each trial year, and plants were left to grow to physiological maturity.

Two rows of bell pepper plants (cv. Mercer; Stokes Seeds, Thorold, Ontario, Canada) were staggered within raised beds and spaced 1.5 ft apart within rows and 1.25 ft between rows. No trellising was used to support the pepper plants. Raised beds were irrigated 3 d per week to deliver approximately 0.8 acre-inches of water weekly. Weeds were removed once weekly from bare soil plots during the first experimental year using a combination of stirrup hoes and hand weeding. In both years, weeds were removed by hand from planting holes of mulch treatments every 2 weeks. Fallow areas north of whole plots as well as whole plot treatment areas lacking a windbreak were mowed weekly using a flail mower to maintain vegetation heights below 6 inches to mitigate potential effects on windspeed. Peppers were planted and all data-collecting sensors were installed 25 May 2023 and 29 May 2024.

Data collection. Cereal rye density and height measurements were collected in whole-plot treatments 1 week before planting peppers. A 1-× 1-ft^2 quadrat was used to collect 10 plant density counts within each whole plot containing cereal rye. Ten cereal rye plants were measured from ground level to the tip of the developing seed head (not including the awns) using a meter stick in 2024 only. Plant height in 2023 was estimated using Photoshop (Adobe Inc., San Jose, CA, USA).

A 3-cup anemometer data logger (S-WSB-MOO3; Onset, Bourne, MA, USA) and micrologging station (H21-USB; Onset, Bourne, MA, USA) were used to measure average wind speeds and gust speeds. One anemometer was placed in each whole plot and mounted 1 ft above ground level. Anemometers were placed adjacent to the middle of whole-plot treatments lengthwise and approximately located 1 ft south of the raised beds used for split-plot mulch treatments. Additional control anemometers were placed in open conditions adjacent to the study at 1 ft above the soil surface to collect near-field windspeeds unaffected by the windbreaks. Average wind speeds and top gust speeds were recorded in 5-min intervals. Wind speed and gust speed measurements were collected until the termination of each experiment. Supplemental weather station data (lat. 40°49′48″N, long. 96°39′36″W) from the Nebraska Mesonet were used to determine predominant wind velocity and frequency of occurrence during 2023 and 2024, as well as categorization of wind directions from experimental wind measurements (NEMesonet 2023, 2024). Mesonet data recorded wind directions and windspeeds at a height of 2 m. Mesonet data were limited to dates between 15 May and 16 Aug in both trial years. The distance of the Mesonet station from the study was approximately 0.47 mi (∼0.76 km).

Soil water tension was measured periodically throughout the season using soil moisture sensors (200SS WATERMARK Sensor; Irrometer Co., Riverside, CA, USA). One sensor was installed in the middle of each split plot and buried to an 8-inch soil depth. Soil temperatures were recorded using pendant data loggers (MX2201; Onset). One pendant data logger was buried per split plot at 2 inches below the soil surface. Pendant data loggers were set to record average soil temperatures in 4-h intervals. Soil moisture and temperature data were combined into season-long averages for analysis.

Early-season mulch durability was measured by collecting large and small hole counts in plots containing mulch products. Hole counts were collected within the entire plot area of each split plot for the first 3 weeks after transplanting bell peppers. Holes ≥1 inch in diameter were categorized as large holes, and small holes were those <1 inch in diameter.

Pepper plant health and productivity were assessed by measuring chlorophyll content, stomatal conductance, and yield. A chlorophyll meter (SPAD 502Plus; Konica Minolta, Tokyo, Japan) was used to measure the most recently matured leaf on a pepper plant by clamping the measuring head onto the adaxial leaf surface. Chlorophyll content was estimated 3 weeks after planting in both trial years, and 10 measurements were taken per

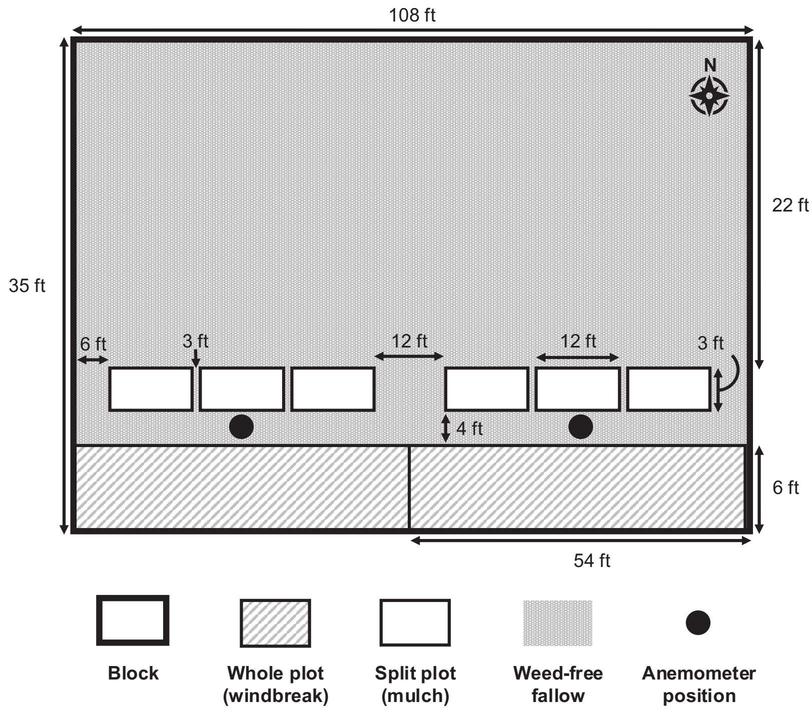

Fig. 1. Field layout and plot dimensions used during the 2023 and 2024 trials. Whole plot areas outlined in the figure depict the cereal rye (*Secale* cereale) windbreak planting location. Whole-plot treatments include the presence/absence of a cereal rye windbreak. Split-plot mulch treatments included 1.5-mil polyethylene film mulch, bioplastic film mulch, or no mulch control. During the 2024 field trials, the no mulch control treatment was replaced with paper mulch. Anemometers were placed 1 ft south of the outside edge of split-plot mulch beds. 1 ft = 0.3048 m.

split plot and averaged. Stomatal conductance was measured using a leaf porometer (SC-1 Leaf Porometer; Meter Group, Pullman, WA, USA) in 2023, and using a combined porometer/fluorometer (LI-600; LI-COR, Lincoln, NE, USA) in 2024. Porometer devices were used by attaching the clamping mechanism onto the adaxial surface of mature pepper leaves fully exposed to sunlight, and four samples per plot were averaged. In 2023, stomatal conductance was measured on 19 Jun; in 2024, measurements were taken on 12, 21, and 27 Jun and 11 Jul. Measurements taken in 2023 were recorded on days with sunny, clear conditions and a prevailing southern wind, whereas measurements taken in 2024 were recorded on days with sunny, clear conditions and a mix of southern wind and nearly still conditions. All measurements were recorded between 1000 and 1400 HR.

Total pepper yield was recorded per split plot and adjusted to total yield per pepper plant to account for slight variations in plant population per split plot attributable to transplant shock and pests. Peppers were harvested when fruit size was greater than 2.5 inches in diameter and 2.5 inches in length. Harvests continued weekly until at least five harvest events had been completed in each year.

Statistical analysis. Windspeed data were compiled and sorted using R software into a windrose via the "climatol" package (Guijarro 2024). Similarly, windbreak density and height summary statistics were calculated to characterize windbreak differences between years (excluding heights from 2023, which were estimated using Photoshop). All other data were analyzed by performing an analysis of variance (ANOVA) in R (R Core Team 2023) using the "lme4" package (Bates et al. 2015). Multiple comparison tests were conducted using the "emmeans" package (Lenth 2023). Trial year, windbreak presence, mulch type, and their interactions were analyzed as fixed effects. Block and the interaction between block × whole plot were treated as random effects. Mulch type was not considered an effect for the analysis of windspeed and gust speed, and only wind measurements from the southeastern, southwestern, or south direction were considered in the analysis (i.e., those potentially affected by the windbreak). Data from different trial years were analyzed separately if trial year interacted with another fixed effect. Soil plant analysis development (SPAD) data were not pooled for analysis because of the change from bare soil to paper mulch treatments across trial years. Stomatal conductance data were not pooled for analysis because of the difference in instruments between trial years. When a fixed effect was significant, multiple comparison tests were performed using Tukey's honestly significant difference test ($\alpha = 0.05$). All significant interactions, or main effects when there were no interactions, are described in the text with accompanying P values; all other effects were nonsignificant.

Table 1. Seeding rates and fertilizer applications applied to cereal rye windbreaks and windbreak characteristics for the 2023 and 2024 field season.

Trial yr	Seed rate (lb/acre)	Fertilizer applied (lb N/acre)[i]	Rye density (plants/ft^2)[ii]	Rye ht (inches)[ii]
2023	60	0	12.8 ± 4.6	36.3
2024	60	25	39.6 ± 11.6	41.3 ± 6.2

[i] N = nitrogen. Fertilizer was applied to cereal rye in the form of composted turkey litter. Fertilizer was applied during the fall before each experimental year. No fertilizer was applied to rye in Fall 2022 for the 2023 trial year.

[ii] Rye density and rye heights were collected 1 week before planting in the spring of each trial year. Rye heights in 2023 were digitally estimated; therefore, no standard error was available for 2023 heights.

Results and Discussion

Windbreak characteristics and annual wind trends. Rye windbreak establishment was better in 2024, with an average stand density of 39.6 ± 11.6 plants/ft^2, compared with that in 2023, which had a stand density of 12.7 ± 4.6 plants/ft^2. Rye plant heights averaged 41.3 ± 6.2 inches at the time of pepper planting in 2024. Rye height in 2023 was estimated as approximately 36.3 inches in height.

From the Nebraska Mesonet station data, wind trends in both summers of 2023 and 2024 were characterized by predominantly southern winds (Fig. 2). Wind speeds were lower in 2023, with speeds greater than 5 mph accounting for 19.5% of all recorded data between 15 May 2023 and 16 Aug 2023. Between 15 May 2024 and 16 Aug 2024, wind speeds greater than 5 mph accounted for 29.6% of all recorded wind data. Relative to the Nebraska Mesonet data, windspeeds collected from control anemometers had a lower frequency of winds greater than 5 mph, which occurred 0.7% of the time in 2023 and 10.9% of the time in 2024. Wind speeds measured at 1-ft heights by the control anemometers were lower than those measured at 2-m heights by the Nebraska Mesonet data, thus demonstrating how wind speeds can differ between measured heights. Differences in wind shear and ground-surface roughness can influence surface-level wind speeds (Justus and Mikhail 1976).

Sustained windspeeds from the southeastern, southwestern, or southern direction were analyzed together because of the lack of interaction among trial year. Sustained windspeeds were 73% lower, on average, behind rye windbreaks compared with those with no rye windbreak treatments ($P < 0.002$) (Fig. 3A). Gust speeds from the southeastern, southwestern, or southern direction were analyzed separately because of the interaction between trial year × windbreak presence. In 2023, gust speeds were similar among rye and no rye windbreak treatments. However, gust speeds measured in 2024 were reduced by 42% behind

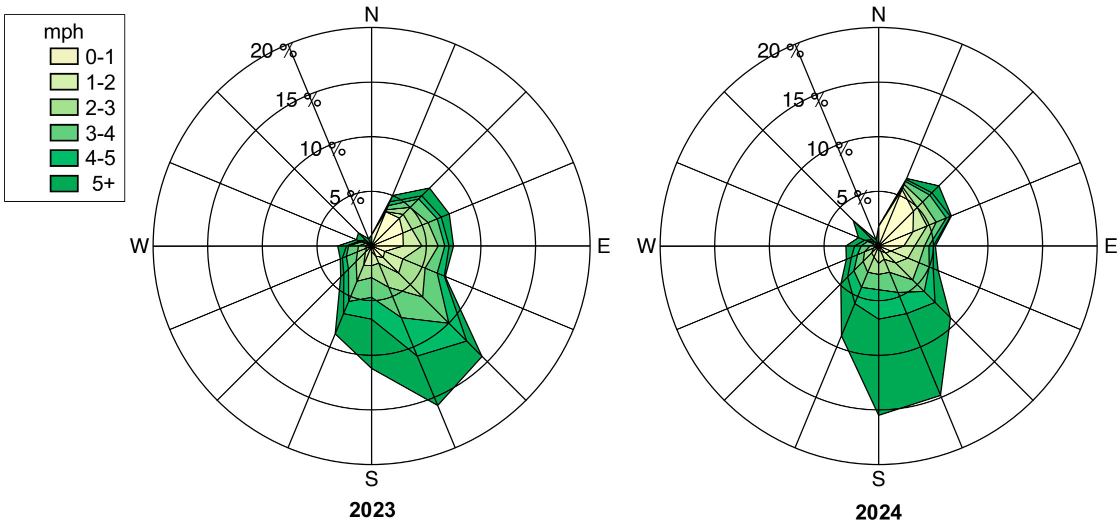

Fig. 2. Summary of annual wind intensity and frequency of occurrence during the 2023 and 2024 Summer field trials. Data were supplied by the Nebraska Mesonet weather data station (lat. 40°49′48″N, long. 96°39′36″W) at Lincoln, NE, USA. 1 mph = 1.6093 km·h^{-1}.

rye windbreaks compared with those with no rye treatments ($P < 0.002$) (Fig. 3B).

Seasonal wind velocity patterns are driven by differences in air pressure between regions as a result of uneven heating of geographical surface features. Historical US wind trends (between 1961 and 1990) measured from ground heights between 6.1 and 21.3 m have shown a predictable flow of southern-originating winds into the summer starting no later than June (Klink 1999). Klink (1999) also suggested that the majority of mean monthly windspeeds between May and August were typically greater than 4 m·s^{-1}, with the exception of one sampled station location. Historical data (between May and August) that suggested that late spring and summer winds are predominantly from the southern direction are comparable to both the Nebraska Mesonet station data and our experimental control data.

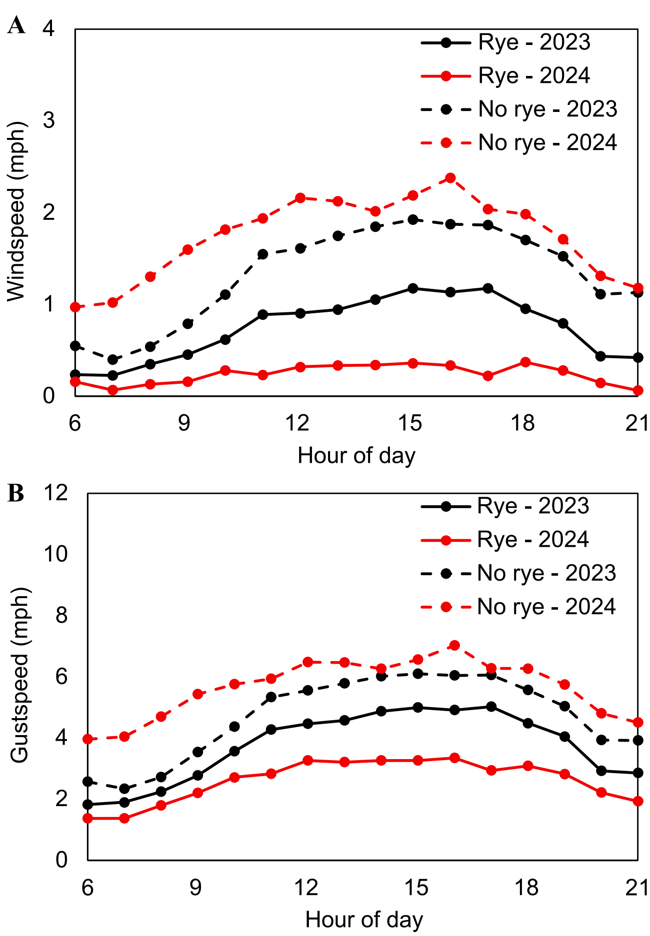

Fig. 3. The effect of shelter provided by rye strips during the 2023 and 2024 pepper field trials on (**A**) sustained windspeeds and (**B**) gust speeds. Wind measurements were taken 1 ft above the soil surface and located 3 ft north of whole plot rye strips (or bare soil controls). 1 mph = 1.6093 km·h^{-1}.

Characteristics of windbreak height and porosity (or density) are key factors that influence the degree of wind protection offered on the leeward side of a windbreak (Brandle et al. 2021; Heisler and Dewalle 1988). The distance over which a windbreak offers protection is often measured in increments of windbreak height (commonly abbreviated as *H*), and wind reductions have been found both upwind and downwind from a windbreak position (Heisler and Dewalle 1988). Protection on the windward side of traditional windbreaks have stretched to 2 to 5 *H* upwind, with larger protection offered downwind, and extended to 10 to 30 *H* on the leeward side (Brandle et al. 2021). In systems using tall wheat–grass strips, windspeeds measured at 1 ft above the ground were reduced by 45% compared with those in open field conditions across a measured area of between 1.25 and 10.9 *H* on the leeward side of the grass strips (Aase et al. 1985). Similarly, anemometers in our study were positioned approximately 1 *H* north of rye windbreak strips, and they were able to detect considerable wind speed reductions from southern winds in both trial years. Windbreak density also influences the proportion of air that passes through the barrier. Increasing densities have been attributed to reduced airflow through the barrier, with 40% to 60% density considered to reduce windspeeds the most over extended distances in traditional windbreaks (Brandle et al. 2021; Heisler and Dewalle 1988). Studies that evaluated sand transport over Marram grass (*Ammophila arenaria*) suggested that airflow through a canopy is density-dependent, with more dense stands reducing the amount of airflow penetrating through the plant canopy (Rotnicka et al. 2023). In our experiment, the lower rye plant densities observed in 2023 and more frequent and higher wind intensities in 2024 could partially explain the greater reduction in sustained wind speeds among windbreak treatments in 2024 relative to 2023 (Fig. 2).

Gust speeds from the south were greater in magnitude than sustained wind speeds as they measured the highest wind speed at a given moment within a measured interval (Fig. 3). At high wind velocities, the plants are prone to bending over as they yield to the wind (Aase et al. 1985; Brandle et al. 2021; Rotnicka et al. 2023), and the degree of protection offered by a vegetative windbreak is subject to change under very intense wind velocities. This may reduce the performance of an herbaceous windbreak, compared with woody windbreaks, thus offering a partial explanation for the lower-magnitude reductions in gust speed among treatments relative to wind speeds (Fig. 3). In 2023, no differences in gust speeds were apparent among treatments, possibly because of the lower rye stand densities and generally mild wind patterns (Figs. 2 and 3B).

Soil temperature and moisture. Season-long soil moisture data were analyzed separately by year because of the interaction between trial year × windbreak presence. However, the soil moisture data were similar among all treatments within both trial years, although the windbreak effect in 2024 was approaching significance ($P = 0.06$). Soil water tension in both years ranged between 0 and 50 cb among treatments. Evaporation from soils and plant water demands are key drivers that influence soil moisture losses. Bare soils generally show the highest levels of evaporation potential with reductions based on percent residue coverage of a soil surface (Klocke et al. 2009). Agricultural mulches can reduce soil moisture evaporation by creating a barrier that prevents soil water evaporative loss, although this is dependent on the permeability of the agricultural mulch used (El-Beltagi et al. 2022; Kasirajan and Ngouajio 2012). Cucumber (*Cucumis sativus*) field experiments have shown biodegradable mulch films, and semi-permeable mulches had 8.2% greater soil moisture than bare soil (Wortman et al. 2016).

Wind speed can also influence soil moisture, and reducing wind speed may reduce evaporative losses. Previous research that explored soil moisture and evaporation rates in a wind tunnel experiment attributed greater evaporative losses on surface soils to increasing wind velocities (Négyesi et al. 2021). Field experiments that used native savannah vegetation suggested that evaporation potential was decreased by 15% with reduced windspeeds, although gains in soil moisture were not apparent as a result of moisture competition between adjacent windbreaks and field crops (Banzhaf et al. 1992).

Sampling depth could explain the similarity in soil moisture among mulch types and windbreak presence in our experiment. Studies that sampled soil moisture at 3-inch depths were able to detect differences among irrigated mulch treatments, possibly because soil moisture near the surface is more prone to evaporation from increased temperatures and wind exposure (Wortman et al. 2016; Xiao et al. 2011). The frequent irrigation coupled with deeper sensor placement (8-inch depth) in this study may explain the lack of observed differences.

Season-long soil temperature data were analyzed separately because of the interaction among trial year × mulch type. Soil temperatures were influenced by mulch types in 2023; the soil temperatures of bare soil plots were, on average, 0.7 °C lower than those of polyethylene mulches ($P < 0.03$) (Fig. 4A). The soil temperatures of paper mulches in 2024 were also lower than those of both bioplastic and polyethylene mulches by approximately 1.9 °C ($P < 0.001$) (Fig. 4A). In 2024, soil temperatures protected by a windbreak were, on average, 0.9 °C higher than those of treatments without a windbreak ($P < 0.001$) (Fig. 4B). Relative to plastic mulches, bare soils generally result in lower soil temperatures (Ibarra-Jiménez et al. 2008). Previous research suggested that polyethylene and biodegradable mulches can increase soil temperatures between 0.1 and 5.9 °C relative to bare soils, depending on the measurement period after planting (Moreno and Moreno 2008). The black color and limited gas exchange of the polyethylene mulch absorb solar radiation and trap it near the soil surface, allowing for greater surface temperatures and longer retention of heat compared to bare soil. Bioplastic mulch soil temperatures were comparable to both polyethylene mulches and bare soil plots in 2023 (Fig. 4A). Starch–polyester biomulches typically have lower soil temperatures relative to polyethylene mulches, which has been attributed to differences in mulch thickness and material durability (Tofanelli and Wortman 2020). Mulch degradation can compromise heat adsorption and transfer from mulching materials to underlying soils by increasing mulch permeability and reducing mulch–soil contact, causing soil temperatures to be more akin to bare soil temperatures (Moreno and Moreno 2008; Tarara 2000; Tofanelli and Wortman 2020).

The paper mulch used in 2024 was a lighter color relative to either the polyethylene or the biodegradable mulch treatments. Lighter-colored mulches reflect more solar radiation compared to darker-colored mulches, and they accumulate less heat as a result (Ibarra-Jiménez et al. 2008). Moreover, compared with polyethylene mulch, kraft paper mulches tend to have a soil-cooling effect of approximately 1 °C during daytime, relative to bare soils (Schonbeck and Evanylo 1998). Lower radiation absorbance potential between black plastic and paper mulches could have contributed to lower soil temperatures among paper mulch treatments in 2024.

In traditional windbreaks, soil temperatures in sheltered zones are elevated relative to unsheltered zones because of reduced wind-mediated heat transfer away from soil surfaces (Brandle et al. 2021). The level of heat transfer away from the soil surface is related to wind intensity, with higher windspeeds resulting in a greater transfer of heat (Cleugh 2002). In our study, we expected higher soil temperatures behind rye windbreaks because the measurements were taken in the quiet zone (within 2 *H* of the windbreak) where we anticipated lower windspeeds. However, soil temperatures were not different among windbreak treatments in 2023, indicating that the relatively modest windspeed reductions by the rye windbreaks did not confer reductions in soil–atmosphere heat transfer. In contrast, soil temperatures in 2024 were greater when protected by a rye windbreak, which also correlated with greater reduction in windspeed behind the windbreak in 2024 compared with 2023 (Fig. 4B).

Mulch durability. Accumulated small and large hole densities were analyzed separately by trial year given the interaction with mulch type. Small hole densities were more than six-times greater in bioplastic film compared with polyethylene in 2023 ($P < 0.001$) (Table 2); similarly, in 2024, small holes in bioplastic film were more than five-times greater than in polyethylene mulch ($P < 0.001$) (Table 2). Large hole density in 2023 was also greater in bioplastic film, accumulating approximately three additional large holes per plot compared with polyethylene mulch ($P < 0.001$) (Fig. 5A). In 2024, large hole density was affected by mulch type ($P < 0.001$) and the interaction between mulch type × windbreak presence ($P < 0.03$) (Fig. 5B). Compared with either polyethylene or paper mulch plots in 2024, bioplastic film had approximately seven additional large holes per plot. Paper mulch and polyethylene treatments were similar regardless of windbreak protection. Within bioplastic treatments, large hole density was 73% greater in open relative to windbreak-sheltered plots (Fig. 5B).

The ability of a mulch to modulate soil temperatures, retain soil moisture, or block weed growth is tied to how intact the mulch remains (Kasirajan and Ngouajio 2012; Tofanelli and Wortman 2020). The rate at which mulches degrade can be heavily influenced by the nearby environment and the material composition of the mulch. Simulated weathering experiments demonstrated that bioplastic mulches (which are commonly starch-based) lose a greater amount of mulch mass and mechanical properties from field aging relative to polyethylene mulches (Hayes et al. 2017). As a result, bioplastic mulches are typically more susceptible to accumulating holes and tearing from weathering and premature degradation than plastic mulches, reducing their weed-suppressive ability (Tofanelli and Wortman 2020). In field cucumber, bioplastic mulch films showed signs of visible deterioration 34 d after transplanting; by day 69, deterioration of 8.9% to 28.7%, depending on the bioplastic mulch used, was observed (Wortman et al. 2016). Another study reported similar deterioration in bioplastics, where rips, tears, and holes were significantly greater than those in black plastic at the end of each field season in Mount Vernon, WA, USA and Lubbock, TX, USA (Miles et al. 2012). Our data add support to the existing evidence of the relatively low durability of commercial bioplastic mulch

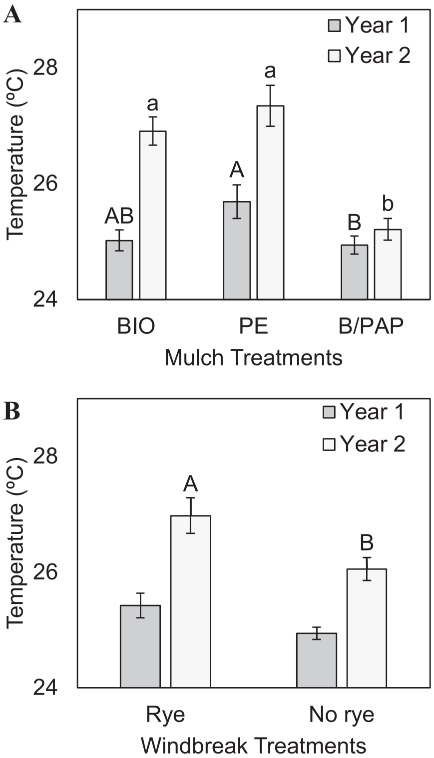

Fig. 4. Effect of mulch type (**A**) and windbreak presence (**B**) on season-long soil temperatures in 2023 and 2024. Soil temperatures were recorded at 2-inch depths at 4-h intervals between 25 May 2023 and 8 Aug 2023 during year 1, and between 29 May 2024 and 20 Aug 2024 during year 2. Error bars are ±1 standard error of treatment means. Different letters above error bars indicate significant differences at α = 0.05. Lowercase and uppercase letters are is used to separate comparisons of means within years within each figure. B/PAP = either bare soil (year 1) or paper mulch (year 2); BIO = Bio360 bioplastic mulch; PE = black polyethylene mulch. °F = (°C × 1.8) + 32.

films, showing a greater accumulation of small holes (diameter <1 inch) in bioplastic mulch relative to polyethylene just 21 d after transplanting.

Table 2. Total small holes accumulated after a 3-week counting period among mulch types during the 2023 and 2024 field season.

Mulch treatment by year[i]	Total accumulated small holes (holes/plot)[ii]
2023	
BIO	56.9 ± 11.9 A
PE	7.6 ± 1.7 B
B	—
2024	
BIO	236.7 ± 47.6 a
PE	37.1 ± 10.3 b
PAP	0 ± 0 b

[i] B = bare soil; BIO = Bio360 bioplastic mulch; PE = black polyethylene mulch; PAP = WeedGuardPlus® paper mulch.

[ii] Means with the same letter within trial year are not statistically different at α = 0.05. Standard errors are reported following treatment means (mean ± standard error). 1 hole/plot = 0.0278 hole/ft².

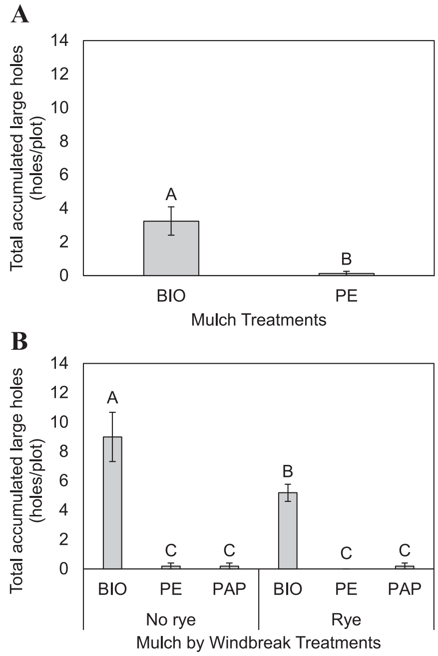

Fig. 5. (**A**) Total large holes accumulated among mulch types during the 2023 Summer field season. (**B**) Total large holes accumulated among mulch types and rye strip presence during the 2024 Summer field season. Error bars are ±1 standard error of treatment means. Different letters above error bars indicate significant differences at α = 0.05. BIO = Bio360 bioplastic mulch; PAP = paper mulch (year 2); PE = black polyethylene mulch. Zero large holes were detected in PE treatments protected by rye strips during the 2024 Summer field season. 1 hole/plot = 0.0278 hole/ft².

Large holes (diameter >1 inch) are more likely to form from excessive pulling or shear force on the mulch material because small holes become greater in diameter or merge with adjacent holes (Miles et al. 2012). The high frequency of small holes and low resistance to weathering could have caused a greater accumulation of large holes in bioplastic mulches during both trial years (Fig. 5). Wind can facilitate large hole formation by lifting loose or exposed mulch material, essentially creating a pulling action on the mulch material. Therefore, greater windspeed reductions by rye windbreaks in 2024 could have caused fewer large holes to accumulate in bioplastic mulches at 21 d after transplanting, relative to unprotected bioplastic mulches (Fig. 5B). Miles et al. (2012) found greater hole count densities and percent visible deterioration of bioplastic mulches in open field environments compared with protected high tunnel environments, likely because of greater wind and solar radiation in the open field. Similar comparisons between high tunnel and open field environments in cucumber production showed that visible deterioration of bioplastic mulches decreased to less than 4% in high tunnels from reduced exposure to open field weathering (Wortman et al. 2016).

Pepper health and productivity. Bell pepper SPAD values in 2023 in bare soils were reduced by 8% relative to plastic mulch treatments ($P < 0.001$) (Table 3). In 2024, bell pepper growing in paper mulches had 12% lower SPAD values than polyethylene mulches ($P < 0.05$), whereas bioplastic performed similarly to both polyethylene mulches and paper mulches (Table 3). There were no effects of windbreak treatments on SPAD values in pepper in either year.

Table 3. SPAD values of bell pepper growing in different mulched conditions between the 2023 and 2024 field seasons.

Mulch treatment by trial yr[i]	SPAD index value[ii]
2023	
BIO	58.2 ± 0.5 A
PE	57.8 ± 0.7 A
B	53.6 ± 1.2 B
2024	
BIO	56.5 ± 1.4 ab
PE	59.2 ± 1.3 a
PAP	53.1 ± 1.8 b

[i] B = bare soil; BIO = Bio360 bioplastic mulch; PAP = WeedGuardPlus® paper mulch; PE = black polyethylene mulch.

[ii] Unitless index. Means with the same letter within trial year are not statistically different at α = 0.05. Standard errors are reported following treatment means (mean ± standard error).

Chlorophyll content in crops is commonly estimated using SPAD; additionally, SPAD can be used as a proxy to estimate plant-available or soil-available N or weed competition (Shafagh-Kolvanagh et al. 2008; Uchino et al. 2009). In soybean, weed competition reduced SPAD values up to 14.7% (Shafagh-Kolvanagh et al. 2008). Uchino et al. (2009) tested the effect of the cover crop seeding date in relation to corn and soybean planting. The SPAD values were markedly lower in both corn and soybean when cover crops were planted 14 d before the main crop, indicating nutrient competition between the cover crops and the main crop (Uchino et al. 2009). Although weeds were removed from bare control plots on a weekly basis during the 2023 field study, there was considerable weed competition that occurred between weeding events that may have stunted pepper growth and resulted in lower SPAD values.

Similarly low SPAD values were observed in 2024 in the paper mulch plots. While the paper mulch effectively reduced weed competition, it may have contributed to N immobilization. Previous research attributed soil N reductions by untreated paper mulches and other organic materials to either enhanced soil leaching (relative to plastic and oiled paper mulch treatments) or the high ratio of carbon to N of the material (Schonbeck and Evanylo 1998). Applications of a polylactic acid mulch fabric (which also has a high ratio of carbon to N) have reduced mean soil N availability during early crop growth by approximately 88% relative to bare ground control plots as a result of immobilization (Wehrbein et al. 2024). It is also possible that soil N mineralization rates were greater beneath the plastic and bioplastic films compared with paper mulch because of the observed

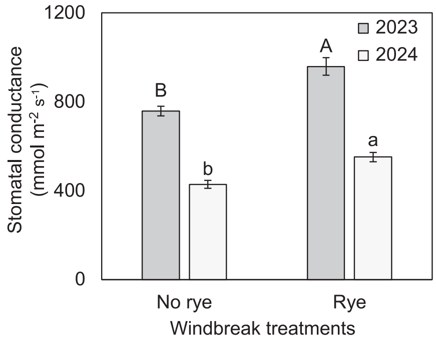

Fig. 6. Pepper plant stomatal conductance as protected by rye strips during field seasons of 2023 and 2024. The 2023 measurements were recorded on clear condition days with south-driven wind. The 2024 measurements were recorded on either south-driven winds or calm conditions. Error bars are ±1 standard error of treatment means. Different letters above error bars indicate significant differences at $\alpha = 0.05$. Lowercase and uppercase letters are indicative of comparisons made within specific contrast groups.

differences in temperature (Fig. 4A), which could have led to greater soil N availability and pepper uptake (Zhang et al. 2024). Overall, pepper grown in bare soil (2023) and paper mulch (2024) plots likely had lower SPAD values because of reduced soil N availability.

Stomatal conductance was 27% greater for peppers behind a windbreak compared with open field in 2023 ($P < 0.03$), and it was 29% greater behind a windbreak in 2024 ($P < 0.001$) (Fig. 6). Stomata are primarily responsible for regulating both plant water loss and gas exchange; therefore, they are sensitive to environmental conditions. Factors including light intensity, carbon dioxide concentration, temperature, and relative humidity can influence stomatal development and conductance (Driesen et al. 2020). Under shelter with reduced wind, evaporative water losses are reduced, and humidity is higher because of reduced water vapor flux away from soil and plant surfaces (Brandle et al. 2021). As a consequence of reduced wind speeds and increased vapor pressure around the stomata aperture, stomata protected by shelter tend to stay open longer and have greater gas exchange than stomata not under shelter (Driesen et al. 2020). In our experiment, stomatal conductance was likely elevated in pepper protected by rye strips because of reduced wind-mediated stress around the leaves; increased wind can reduce humidity around the leaf and induce water stress upon the plants. Skidmore et al. (1974) found that a slat-fence wind barrier reduced stomatal resistance (the opposite of stomatal conductance) in durum wheat (*Triticum durum*) in the most sheltered area. Brenner et al. (1995) reported that unsheltered millet (*Panicum miliaceum* L.) had reduced stomatal conductance relative to sheltered millet under nonirrigated conditions, although this effect was attributed to a greater leaf area of sheltered plants.

Total yield was analyzed separately by trial year because of the interaction between mulch type × year effects. Mulch type influenced pepper yield in 2023 ($P < 0.001$) (Fig. 7A), with pepper plants in bare soil yielding 49% less than those grown in bioplastic mulch plots and 54% less than polyethylene plastic plots. In 2024, total yield was affected by the windbreak effect ($P < 0.002$) (Fig. 7B). Pepper plants grown behind a windbreak had a total yield 24% greater than that of peppers grown without a windbreak.

Pepper yield can be greatly influenced by the nearby growing environment and is often increased as a result of growing in mulches. Weed growth can reduce yields through competition for resources such as light and nutrients. Weeds growing in the planting holes of a plasticulture pepper crop reduce fruit set (and subsequently yields) as early as 6 weeks after transplanting, depending on weed competitiveness (Norsworthy et al. 2008). Mulches can enhance crop yields by reducing weed competition through the physical exclusion of weed growth and light penetration to the soil surface (Teasdale and Mohler 2000; Tofanelli and Wortman 2020). Polyethylene mulches are effective at consistently reducing weeds in multiple cropping systems, whereas biodegradable mulch weed suppression can be variable (Schonbeck 1999; Tofanelli and Wortman 2020; Zhang et al. 2019). Although weed suppression was not quantified in this study, we observed that bare ground control plots during the 2023 field trials had a considerably higher grass weed density than either mulch type, potentially reducing SPAD values in 2023 (Table 3). Thus, the elevated weed pressure in control plots during the 2023 field trials could have lowered pepper yields as a result of competition for nutrient and light resources (Fig. 7A).

Practices that promote root zone temperatures between 25 and 27.5 °C are the most favorable for accelerating pepper growth and yield (Díaz-Pérez 2010). Mulches are a common method of modifying root zone temperatures. Bell pepper plants grown in black polyethylene mulch yielded 49.9% more than peppers grown in paddy-straw and 84.1% more than those grown in no mulch treatments as a result of greater root zone temperatures during the colder months in Ludhiana, India (Dhaliwal et al. 2017). In warmer climates with above-optimal root zone temperatures, Díaz-Pérez (2010) found that mulches that reflect radiation and accumulate less heat in the root zone led to yield increases when compared with mulches that absorb more radiation. Elevated pepper yields behind rye windbreaks could be partially explained by increased soil temperatures compared with pepper grown without rye (Figs. 4B and 6B).

Higher yields among peppers protected by windbreak treatments could have been a consequence of greater stomatal conductance. In nonlimiting irrigated water conditions, increasing stomatal conductance in C3 plants can increase photosynthetic rates and enhance plant cooling (Roche 2015). Therefore, pepper plants with higher stomatal conductance can achieve greater yield potential because of greater leaf carbon dioxide concentrations and more favorable temperatures for photosynthesis. A comparison of wheat cultivars indicated that grain yield increases were positively associated with increases in stomatal conductance (Fischer et al. 1998). Positive correlations were also observed between stomatal conductance, canopy temperature depression, and photosynthetic activity, indicating that leaf cooling via transpiration may play a key role in enhancing photosynthesis (Fischer et al. 1998; Lu et al. 1998).

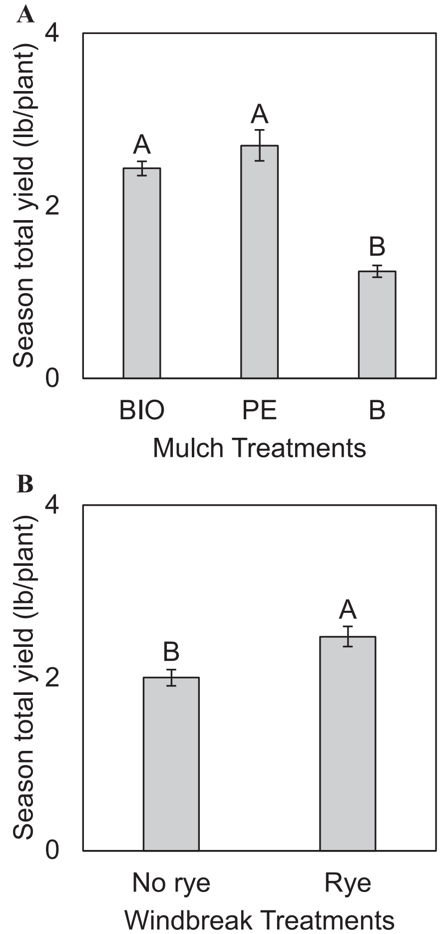

Fig. 7. (**A**) Yield per pepper plant as affected by mulch type during the 2023 Summer field trials. (**B**) Yield per pepper plant as protected by rye strips during the 2024 Summer field trials. Error bars are ±1 standard error of treatment means. Different letters above error bars indicate significant differences at $\alpha = 0.05$. B = bare soil (year 1); BIO = Bio360 bioplastic mulch; PE = black polyethylene mulch. 1 lb/plant = approximately 14,520 lb/acre = approximately 16,302 kg·ha^{-1} assumes two rows of peppers with 1.5-ft plant spacing and 4 ft between bed row spacing.

Conclusions

Annual herbaceous cover crop windbreaks are a quick, low-cost, and low-risk option growers can use to reduce the potentially negative effects of wind on cash crops. The effectiveness of the annual windbreak is dependent on both annual wind trends as well as the characteristics of the barrier. Annual windbreaks oriented perpendicular to the prevailing wind with a dense establishment population are more likely to reduce windspeeds and confer associated cropping system benefits. In this pepper plasticulture system, we found that windbreaks were associated with greater soil warming, fewer large holes in bioplastic mulches, and greater plant productivity under irrigated conditions. Growers in cooler climates may benefit from combining annual windbreaks and plasticulture to achieve warmer production temperatures for extending the production season. Therefore, using cover crops to reduce wind incidence on adjacent crop production could mitigate risks associated with crop loss in open field crop production (Shrefler et al. 2015; Simonne and Hochmuth 2005).

Cereal rye was an attractive species to test as an annual windbreak because it can accumulate a large amount of biomass before installing mulches and planting in the spring. This biomass helped to shelter mulches and reduce wind-mediated mulch weathering in the spring. Preservation of mulch integrity is important during the spring, when weed suppression is most valuable during the critical weed-free period (Amador-Ramírez 2002; Frank et al. 1992), compared with later in the season, where mature crop canopies can suppress weeds in lieu of damaged mulches. Transplants and newly emerged seedlings are especially vulnerable to damage from desiccating winds, mechanical damage incurred by winds (i.e., sandblasting), or injury from herbicide drift. Therefore, wind reductions in newly planted mulches may facilitate greater establishment and survival of crops.

Our research demonstrated the potential to preserve biodegradable mulch integrity when applied directly adjacent to a cereal rye windbreak (within 1–3 *H*). While this study considered only a single bed-row of production, commercial growers could fit two or three bed-rows within the expected protected leeward area of a 3-ft-tall cereal rye strip (dependent on bed width and row spacings). However, future research should consider the effect of the barrier over extended distances of *H* to confirm the scalability of cover crop windbreak protection in plasticulture systems. Extending the number of biodegradable mulches tested may reveal how different mulch polymers vary in susceptibility to wind shear damage and abrasive damage by airborne soil particles. Previous reviews also consider how annual windbreak composition and width may affect wind exposure of adjacent production and influence arthropod diversity (Hodges and Brandle 1996). Thus, additional research could explore annual windbreaks and their effect on both reducing windspeeds and providing habitat for pest and beneficial insects. Finally, research that explores the effects of wind shelter on different specialty crop types will help identify and quantify additional benefits (e.g., reducing sand blasting in cucurbit crops or reducing lodging and stem curvature in cut flower crops).

Although beneficial for reducing wind adjacent to crop production, nearby cover crops may compete with the cash crop for soil resources and light. Thus, it is important to understand how close to space an annual windbreak to plastic mulched beds to prevent potential yield loss related to crop–windbreak resource competition. Ongoing research is exploring how the distance of a cover crop from the edge of a plastic mulch bed affects soil moisture availability and crop yield.

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