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Differing short-term impacts of agricultural tarping on soil-dwelling and surface-active arthropods

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ABSTRACT

Agricultural tarping, the practice of placing impermeable plastic tarps over crop beds before planting to suppress weeds, is rising in popularity. However, the use of tarps has uncertain effects on soil arthropod communities. We studied the impact of silage (black plastic) tarps and clear plastic tarps on surface-active and soil-dwelling arthropods by tracking immediate impacts and arthropod recovery for 5 weeks after tarps were removed. We also assessed how well environmental and experimental variables explained arthropod diversity and composition. During tarp application, we found that both silage and clear plastic tarps had significant negative impacts on surface-active arthropod diversity, while only clear plastic tarps impacted soil-dwelling arthropods. Surface-active arthropod diversity recovered by 1–3 weeks after tarping, but at 5 weeks after tarping soil-dwelling arthropod diversity was significantly lower in silage tarp and clear plastic plots than control plots. Tarps also led to compositional changes in the arthropod communities, though these changes were only significant during tarp cover. The variables that best explained arthropod diversity and community composition were treatment (i.e., silage tarp, clear plastic tarp, or control) and farm site. Other variables, such as soil moisture and weed coverage, were not consistently strong model predictors. These results imply that tarps may have temporary impacts on surface-active arthropods but potentially longer-lasting impacts on soil-dwelling arthropods. Continuing to monitor impacts of tarps on soil arthropods will better inform the sustainability of this practice.

1. Introduction

Tarping is an agricultural practice that has grown in popularity in the last decade, especially in the northeastern USA, sparking management guides (Lounsbury et al., 2022) and regional research (Lounsbury et al., 2018; Birthisel et al., 2019; Rylander et al., 2020). Tarps have been used globally for decades to kill pathogens and pests (Stapleton and DeVay, 1986; Al-Asa'd and Abu-Gharbieh, 1990; Coelho et al., 1999) and, more recently, have been implemented on small-scale farms as a low-input method to suppress weeds or terminate cover crops while also reducing tillage needs (Rylander et al., 2020). Growers place tarps, often silage (black plastic) tarps or clear plastic tarps, over the soil for several weeks before planting crops. Silage tarps kill weeds via occultation (shading), whereas clear plastic tarps kill weeds via solarization (extreme heating) (Rubin and Benjamin, 1984; Johnson and Fennimore, 2005). Both silage tarps and clear plastic tarps create a barrier over the soil and can increase soil temperatures by around 6 °C or 15 °C (respectively) (Birthisel and Gallandt, 2019), which may affect various aspects of the soil ecosystem.

Relatively little is known about the impacts of tarping on soil arthropods, a diverse group in agriculture including spiders, beetles, ants, mites, and collembolans. In general, the use of plastic films in agriculture has been identified as a threat to soil biodiversity because they seal the soil surface and can alter physical and chemical soil properties (Birthisel et al., 2019; Tibbett et al., 2020). However, literature on tarps' effects is limited: existing studies mostly focus on the effects of clear

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tarps (despite heavy use of silage tarps) and analyze only certain arthropod groups (Seman-Varner, 2005; Gill and McSorley, 2010). In these studies (which both took place in the hot and humid climate of the state of Florida, USA), the use of clear tarps reduced collembolan and mite populations (Seman-Varner, 2005), but did not affect other groups, such as spiders, ants, grasshoppers, crickets, and Elateridae beetles (Gill and McSorley, 2010). Investigating these dynamics in a different climate, comprehensively analyzing the entire arthropod community, and testing the impacts of both silage tarps and clear plastic tarps are therefore needed to expand knowledge around tarps. As well, soil arthropods' roles in providing key ecosystem services for agriculture, such as controlling pests (Kromp, 1999; Lang, 2003; Schmidt et al., 2003; van Lenteren et al., 2018) and improving soil health (Lavelle et al., 2006; Brussaard et al., 2007; Briones, 2018), further emphasize the importance of understanding tarps' impacts on this community.

To produce results that can best inform conservation, research should be designed to capture complexity within the soil arthropod community (Magurran, 2021), for example taking into account that the effects of tarping can differ among taxonomic or ecological groups due to trait differences and environmental factors (Franken et al., 2018; Yekwayo et al., 2018). Literature on the impacts of plastic mulch (thin plastic sheeting used for weed suppression during, rather than before, crop growth) shows that the direction of impacts varies among arthropod groups (Tuovinen et al., 2006; Addison et al., 2013; Schirmel et al., 2018). This suggests that the effects of tarps could also vary, perhaps relating to arthropods' tolerances to heat or preferences for light versus dark environments (Dindal, 1990; Briones et al., 2009; Bokhorst et al., 2012). The impacts of tarps may also differ between surface-active and soil-dwelling arthropods, which vary in their sizes, diets, mobility, and exposure to disturbances (Dindal, 1990). Analyzing both groups can give a more comprehensive understanding of tarps' effects and uncover potentially unique responses between surface and soil communities (Briones et al., 2009; Liu et al., 2018).

It is also important to consider that tarping may have long-term and indirect effects – for example, Birthisel et al. (2019) found that the impact of tarps on soil microorganisms intensified in the weeks after tarp removal. Such lingering effects could relate to tarps' impacts on the ecosystem, such as on soil temperature, soil moisture, and weed coverage (Birthisel et al., 2019), which change habitat suitability to soil biological communities (Altieri et al., 1985; Schirmel et al., 2018). Arthropod diversity and composition could also vary due to elements of experimental design, including sampling at different sites or times (Campbell et al., 2011; Kirse et al., 2021). Identifying predictors of arthropod diversity and composition during and after tarping will help explain tarps' impacts and uncover sources of complexity within our system.

In this study, we tested the impact of agricultural tarping on surface-active and soil-dwelling arthropod communities. We specifically asked: 1) how do tarps impact the diversity and community composition of soil arthropods?, 2) how do soil arthropod communities respond after tarps are removed?, and 3) how do the experimental and environmental factors in our system explain variability of the soil arthropod community? We hypothesized that both tarp types would decrease soil arthropod diversity, with more negative effects under clear plastic tarps due to the higher temperatures found there. We also hypothesized that tarps' effects would differ depending on taxonomic groups, creating unique arthropod composition under tarps. Finally, we hypothesized that treatment would best predict soil arthropod diversity during tarp application, but that environmental factors, like soil moisture and weed coverage, would become more predictive after tarps were removed. Monitoring the effects of tarps on soil arthropods is an important step to assessing the sustainability of this practice.

2. Methods

2.1. Site descriptions

We conducted this experiment in western Chittenden County in Vermont, which is situated in the northeastern United States and has a temperate climate. Our study took place at three farms: Intervale Community Farm (ICF; 44.49820 N, 73.20567 W, 30 m above sea level), Diggers' Mirth Farm (Diggers'; 44.49888 N, 73.20991 W, 30 m above sea level), and Catamount Farm (Catamount; 44.43237 N, 73.20083 W, 70 m above sea level). ICF and Diggers' are relatively close to one another (separated by 300 m), while Catamount is 8 km south of ICF and Diggers'. All three farms are located adjacent to semi-natural areas: ICF and Diggers' are situated near a network of recreational forested areas within the Intervale floodplains west of the Winooski River, and Catamount is located within a residential area but is surrounded by large strips of forest and grassland/shrubland. All three farms mainly grow annual vegetables (Catamount also grows perennial fruits) and have used tarps for weed suppression.

The three farms had key environmental and management differences. To understand baseline soil differences, we collected soil using an auger (2 cm diameter, 15 cm depth) and composite sampling (18 soil samples from each farm, taken from the center of each 4.5 m by 1.5 m plot; see Section 2.2). Soils were analyzed by the UVM Agricultural and Environmental Testing Lab (https://www.uvm.edu/extension/agricultural-and-environmental-testing-lab) and tested for soil texture, pH, available phosphorus, available nitrate, soil organic carbon (SOC), and effective cation exchange capacity (Table 1). One key difference among sites was that Catamount's soils were classified as sand, Diggers' soils were loam, and ICF's soils were sandy loam. Each farm also had a different composition of major weeds, with Catamount dominated by *Portulaca oleracea* L. (common purslane) and *Digitaria* grasses (crabgrass), ICF containing high cover of *Chenopodium album* L. and *Chenopodium glaucum* L. (white and oak-leaved goosefoot), and Diggers' containing mostly *Amaranthus retroflexus* L. (redroot pigweed). These ecological differences allow us to understand how tarps function in contrasting environments. We also used irrigation and fertilizer schemes typical to each farm (rather than homogenizing management among farms) because these practices are honed to each farm's environment, reflect the operational capacities of each farm, and represent realistic

Table 1
Baseline soil characteristics for the three farm sites. Soil series were determined from the Web Soil Survey (NRCS USDA, 2022).

	Catamount	Diggers'	ICF
Soil texture	Sand (87% sand, 9% silt, 4% clay)	Loam (44% sand, 48.5% silt, 7.5% clay)	Sandy loam (70.5% sand, 27% silt, 2.5% clay)
Soil series (with Great Group)	Mix of Scarboro (Humaquept), Adams (Haplor-thod), and Windsor (Udipsamments)	Winooski (Dystrudept)	Hadley (Udifluvent)
World Reference Base soil classification	Fluvisol	Cambisol	Cambisol
pH	6.8	7.0	7.0
Available phosphorus (ppm)	19.4	104.9	29.5
Available nitrate (mg N / kg)	17.6	17.2	21.6
Soil organic carbon (%)	2.3	3.1	1.5
Effective cation exchange capacity (meq/100 g)	6.5	12.1	7.5

scenarios. Catamount used drip irrigation due to its sandy, well-drained soil, while ICF and Diggers' used a combination of sprinklers and hand watering, and each farm received different water amounts depending on the appropriate levels for their soil type.

Weather conditions during our experiment were hotter and drier than historical means for the month of June (when tarps were on the field), with a mean precipitation of 0.2 cm per day and a mean temperature of 22 ℃. In July, after tarps were removed, weather conditions were wetter and cooler than historical means, with a mean precipitation of 0.5 cm per day and a mean temperature of 21 ℃ (NOAA, 2021).

2.2. Treatments and experimental design

We tested two types of plastic tarps, silage tarps and clear plastic tarps, along with an uncovered hoed control. We chose to study silage tarps and clear plastic tarps because they are commonly used in New England (Birthisel et al., 2019; Lounsbury et al., 2022) and have key material and functional differences (e.g., clear plastic tarps create hotter soil conditions than silage tarps and are translucent, while silage tarps are opaque). In control plots, we suppressed weeds by hoeing the plots weekly for the duration that the tarps were on the fields. This method is a common organic practice for weed control and was identified as a likely alternative practice to tarping. We chose this control rather than an unmanaged control (e.g., not applying disturbance) because it is not realistic that a farmer would grow crops without any weed suppression practice. Therefore, results comparing soil arthropod communities in tarped areas versus undisturbed areas would not yield useful information to farmers weighing certain management practices.

The three treatments were replicated six times on each farm, with the experimental units organized as a completely randomized design (18 plots on each farm; 54 plots total across the three farms). Plots were 4.5 m by 1.5 m (1.5 m is the width of a crop bed), with a buffer space of 0.5 m between plots. The study site at each farm consisted of 2–3 adjacent crop rows.

Our silage tarps were 0.13 mm thick polyethylene plastic with a black up-facing side and white down-facing side (Klerks Hyplast Inc., Chester, South Carolina, USA). Our clear plastic tarps were 0.15 mm thick polyethylene plastic (Poly-Ag Corp, San Diego, California, USA) and were donated from a local farm where they had been used on a hoophouse. Repurposing clear plastic from hoophouses represents realistic farm practices (Birthisel et al., 2019).

Before treatments were applied, the study site at each farm was tilled and prepared with fertilizer. Additionally, we irrigated the study sites 1–2 days before applying the tarps to stimulate weed germination and increase effectiveness of tarps for killing weeds (Lounsbury et al., 2022). We installed the tarps in late May (late spring) and secured the tarps by burying roughly 15 cm of the tarp edges under around 3 cm of soil. These buried areas were not considered part of the treatment plot. The tarps were installed for 25 days (Table A1; more information on field management is available in Kinnebrew et al., 2022).

After tarp removal, we did not remove weeds in any plots (tarped or control) for the remainder of the experiment. This reflects the reality of many small organic farms, which do not have the time, labor, or expenses for extensive hand weeding (Fennimore, 2014). We additionally direct seeded two rows of lettuce (*Lactuca sativa*; Encore Lettuce Mix, Product ID: 2366 G from Johnny's Selected Seeds; Winslow, ME, USA) in each plot using a Jang seeder (Jang Automation Co., LTD, South Korea) a week after tarp removal. This mimics the use of tarps to prepare beds for crops. The lettuce was not harvested until after the experiment ended (more information on crop yields is available in Kinnebrew et al., 2022).

2.3. Arthropod sampling and identification

We sampled soil arthropods 5 times throughout the field season (Table A1). First, we sampled before tarps were applied to capture baseline diversity patterns in our field areas (mid-May). We then sampled 3 weeks into tarp placement and 1, 3, and 5 weeks after tarp removal (mid-June to mid-July; 5 total sampling periods). We chose sampling dates where weather was clear to capture arthropods when they are most active and to avoid sample losses from rain.

We sampled soil arthropods using two methods: pitfall traps and the Berlese Funnel method. We term arthropods caught by pitfall traps "surface-active arthropods" and arthropods captured with the Berlese funnel method "soil-dwelling arthropods." Our pitfall traps consisted of plastic collection cups (95 mm diameter lid, 120 mm deep) placed in the soil with their lids level to the soil surface (Southwood and Henderson, 2009). This method captures active litter- and surface-dwelling arthropods that fall and become trapped in the cups as they move across the soil surface.

We installed one pitfall trap in the center of each plot (at least 0.75 m from the tarp edge and 2 m from the nearest adjacent pitfall trap). Each pitfall trap consisted of two stacked cups. The upper cup was used to collect arthropods, while the purpose of the lower cup was to hold the soil in place and avoid repeatedly digging new holes (and disturbing the soil) at each sampling period. When the pitfall traps were not in use (between sampling periods), we removed the upper cups and covered the lower cups with lids and a thin layer of soil. During collection times, we used a killing agent of 50% propylene glycol and 50% water, and left pitfall traps out for 3 days (we collected all aggregated arthropods on the third day). We chose 3 day intervals for the pitfall traps due to high catch rate and because high frequency of rain storms (which are destructive to samples) made it logistically difficult to plan longer trapping intervals. The 3 days were consecutive for almost all samplings. An exception was the last sampling (5 weeks after tarp removal), when we collected arthropods after 2 days, waited 1 day while a heavy storm passed, and then set out new traps for 1 day. We pooled the data from these 3 days. To sample arthropods under the tarps, we cut a 0.5 m hole in the tarp, set up the pitfall trap (and collected soil for the Berlese funnels), and then sealed the tarp using either black duct tape for the silage tarps or clear tape for the clear plastic tarps. Our collection of arthropods from pitfall traps in this sampling coincided with the end of the tarp treatment.

The Berlese funnel method reflects soil-dwelling arthropod presence. For this method, we took 3 soil cores (5 cm diameter, 10 cm deep) from each plot and composited them. We sampled in a stratified random pattern, taking 1 core from each of 3 regions in each plot. Subsequently, we extracted arthropods by placing collected soil in a funnel apparatus and exposing it to a 60-Watt light bulb for 72 h (Woolley, 1965; Southwood and Henderson, 2009). Arthropods were collected and preserved in 95% ethanol.

Because pitfall traps are biased towards catching larger and more mobile organisms while Berlese funnels are biased towards capturing smaller and less mobile organisms (Sabu et al., 2011), we only analyzed macrofauna from pitfall traps and mesofauna from Berlese funnels. Macrofauna are generally defined as organisms larger than 2 mm (including small insects), while mesofauna are between 0.2 and 2 mm (Lavelle et al., 1997; Gongalsky, 2021). Orders we included from pitfall traps were Araneae, Opilliones, Coleoptera, Hemiptera, Lepidoptera (caterpillars), Orthoptera, Psocoptera, Thysanoptera, Diplopoda, Dermaptera, Isopoda, and Lithobiomorpha. Orders we included from the Berlese funnels were Symphypleona, Astigmata, small insect larva, Protura, Entomobryomorpha, Oribatida, Mesostigmata, Poduromorpha, Prostigmata, and Symphyla. We did not include ants (Hymenoptera) from either sampling method because ants' central foraging behavior drives their organization on the landscape and can make these sampling methods inadequate for determining their abundance (Higgins and Lindgren, 2012). Abundance results for ants are included in the Appendix (Fig. A1).

In the lab, we used a stereo microscope to classify all soil arthropods to morphospecies. While identifying organisms to species is valuable (Ward and Stanley, 2004), using morphospecies can be an efficient and effective method to monitor arthropod communities, often yielding similar numbers to species (Hackman et al., 2017).

We taxonomically identified all soil arthropods to the order level, while some were identified to family, genus, or species level as resources, time, and expertise allowed (for example, all beetles were identified to family). We identified arthropods using keys within Dindal (1990) (for all arthropods), and Evans (2014) and Bousquet (2010) (for beetles). We also utilized taxonomic resources and community identification on online sites bugguide.net (Iowa State University, 2021) and iNaturalist.org (iNaturalist, 2021).

2.4. Environmental variables

We collected data on soil temperature, soil moisture, and weed coverage to further understand their indirect effects on soil arthropod community composition. We chose these variables because they represent major documented effects of tarps (Birthisel and Gallandt, 2019) and are known to affect soil arthropod communities (Philpott et al., 2014; Gkisakis et al., 2016).

Soil temperature was automatically monitored every 30 min while tarps were on the fields using iButtons (Thermochron, Baulkham Hills, NSW, Australia). Two iButtons were buried in each plot — one at the surface (below 1 cm of soil) and one 10 cm below the surface. We removed the iButtons at the time of tarp removal. We measured soil moisture using a FieldScout TDR 350 Economy Soil Moisture Meter (Spectrum Technology, Inc., Aurora, IL, USA) with 12.2 cm probe tips. We took point samples of soil moisture 3 weeks into the tarp experiment, when arthropods were sampled, and subsequently every time arthropods were sampled (1, 3, and 5 weeks after tarp removal; Table A1).

We surveyed weeds weekly after tarps were removed (Table A1). For each treatment plot, we placed a 1×2 m sampling frame in the center of each plot. We visually estimated percent cover for each present weed species using the following classes: less than 1%, 1–5%, 5–15%, 15–25%, 25–50%, 50–75%, and 75–100% (Peet et al., 1998). For analysis, we converted cover ranges to the midpoint of the range. We then calculated weed richness (total weed species per plot) and total weed coverage by summing the cover for each species. Total weed cover could exceed 100% when multiple layers of vegetation were present. Weeds were identified using Uva et al. (1997).

2.5. Statistical analyses

We performed all statistical analyses in R version 4.0.4 (R Core Team, 2021) and used $P < 0.05$ to indicate significance. We first tested how abundances of dominant taxonomic groups differed among treatments during tarp application. We determined the 7 most abundant orders (>95% of all captured individuals) for surface-active and soil-dwelling arthropods each during tarp application and tested how their abundance differed among treatments. To analyze data at a finer resolution, we additionally tested how the abundance of the 7 most abundant surface-active Coleoptera families (>95% of captured Coleoptera individuals) differed between treatments during tarp application. We tested for significance using either linear mixed models or generalized linear mixed models fit with the Poisson distribution, depending on residual structures, with farm as a random effect with random intercepts (lmer and glmer in the lme4 package; Bates et al., 2015). We made pairwise comparisons using estimated marginal means tests (emmeans in the emmeans package; Lenth et al., 2018).

To understand how tarps impacted arthropod diversity, we calculated richness, Shannon's diversity (vegan package; Oksanen et al., 2007), and total abundance separately for surface-active and soil-dwelling arthropod morphospecies and at each sampling time (pre-tarps, during tarping, and 1, 3, and 5 weeks after tarping). We used repeated measures linear mixed effects models (lmer function from the lme4 package) for richness and Shannon's diversity data, and repeated measures generalized linear mixed effects models fit with a negative binomial distribution (glmer.nb function in the lme4 package) for abundance data. All models included farm site as a random effect (with random intercepts). Model types were chosen based on which yielded normality of residuals, which was tested using quantile-quantile plots and histograms. We made multiple comparisons among treatments at each sampling period using estimated marginal means tests with the emmeans package.

We then tested how morphospecies composition related to treatment using Principal Coordinates Analysis (PCoA) of Bray-Curtis dissimilarities. We ran separate PCoAs for each sampling period to see the impact and recovery of tarps on arthropod composition. We chose PCoA because it performs well with species abundance data (McArdle and Anderson, 2001). We ran the PCoA using the vegdist (vegan package) and wcmdscale functions, and then tested how well treatment explained the composition data with a permutational multivariate analysis of distance matrices (adonis function with "bray" distance method in vegan package). Pairwise differences between treatments were also computed with the pairwise.perm.manova function in the RVAideMemoire package (Hervé, 2018).

Finally, we created models to test how environmental and experimental variables, including treatment, farm, soil moisture, soil temperature, weed coverage, and sampling time (1, 3, or 5 weeks after tarps were removed), related to the soil arthropod communities. "Treatment" specifically refers to whether plots were treated with silage tarps, clear plastic, or the control, and "farm" indicates at which of the three farms (Catamount, ICF, or Diggers') the plots were located. Our primary model structures were based off a priori assumptions of the ecological system. In models representing conditions during tarp cover, we included an interaction term between treatment and farm to understand whether tarps' effects on arthropods differed by farm site; for models representing the sampling periods after tarps were removed, we included an interaction between treatment and sampling time to see if tarps' effects changed through time. We tested model structures with AIC to find the most parsimonious models and avoid overfitting (confirming at this step to only include one interaction term per model). We then assessed collinearity among explanatory variables using variance inflation factors (VIF; vif function in the car package; Fox et al., 2012), and removed variables with $GVIF^{(1/2*DF)}$ scores of over 5 (Fox and Monette, 1992). The only variables we eliminated were soil surface temperature and soil (10 cm below the surface) temperature, due to high collinearity with treatment (Fig. A2). Final variables of interest when tarps were on the fields included treatment, farm, soil moisture, and the interaction between treatment and farm. Variables of interest when tarps were removed included treatment, farm, soil moisture, weed coverage, sampling time, and the interaction between treatment and sampling time.

With these variables, we used multiple linear regression models to predict soil arthropod richness and redundancy analysis (RDA, a multivariate regression analysis and constrained ordination technique; vegan package) to predict arthropod composition (we chose to build models for richness rather than Shannon's diversity because the results were very similar and richness is a more intuitive metric). We created separate models for when tarps were on and off the fields because these times reflect different dynamics and numbers of samplings, thus having different explanatory variables. We additionally created separate models for surface-active and soil-dwelling arthropods, due to these groups being caught with different methods and representing different ecological groups.

Within our final models, we tested for significance of the multiple linear regression models using Type 3 ANOVAs from the car package. We chose Type 3 ANOVAs to test variables regardless of their order in the model and to take into consideration interaction terms (Shaw and Mitchell-Olds, 1993). We additionally assessed the relative importance of variables in the linear regression models with the "lmg" method within the relaimpo package (Grömping, 2007). The "lmg" method computes the average R^2 over all possible model structures (orders of variables), and we hereafter call this statistic "variable importance" (Lindeman, 1980). For the RDA models, we tested significance using permutational ANOVAs (anova.cca function from the vegan package), using the "margin" option to obtain Type 3 effects.

3. Results

3.1. Summary of arthropod data

We collected 8027 surface-active (macrofauna) arthropods in total in the pitfall traps (2710 from Catamount, 2591 from Diggers', and 2726 from ICF), comprising 102 morphospecies and 12 orders. At the order level, the most abundant group were beetles with 5559 total individuals. Beetles were also the order with the most morphospecies. Of the 75 identified beetle morphospecies, all were identified to family, 43 were identified at least to genus (57.9% of the beetle specimens), and 15 were identified to species (14.7% of the beetle specimens).

In the Berlese funnel samples, we collected 823 soil-dwelling (mesofauna) arthropods, comprising 20 morphospecies and 10 total orders. Collembolans, mostly from the order Entomobryomorpha, comprised 48% of the Berlese samples, while mites, mostly Prostigmata, made up 39% of the samples.

3.2. Taxa abundance during tarping

Tarp application significantly affected many surface-active arthropod taxa. At the order level, most orders — including Araneae, Coleoptera, Hemiptera, Thysanoptera, and Lithobiomorpha — had significantly lower abundances in the tarped plots than control plots (Fig. 1A, Table A2). Changes amongst Coleoptera families were less consistent. Compared to the control, Carabidae and Scarabidae were both less abundant in the silage tarp ($P = 0.001$ & $P < 0.001$, respectively) and clear plastic tarp plots ($P < 0.001$ & $P = 0.031$), while Anthicidae were less abundant in the silage tarp plots ($P < 0.001$) but not in the clear plastic tarp plots ($P = 0.296$). Conversely, Staphylinidae individuals were more than twice as abundant in silage tarp plots than control or clear plastic tarp plots (both $P < 0.001$). Other families, like Coccinellidae, Elateridae, and Tenebrionidae, had lower abundances and did not significantly differ among treatments (Fig. 1B, Table A2).

For soil-dwelling arthropods, clear plastic tarps had a negative impact on several orders. We found lower abundances in clear plastic than in control plots for Prostigmata ($P = 0.004$) and Poduromorpha springtails ($P = 0.035$), but there were no other significant differences between treatments for these groups. Entomobryomorpha springtails

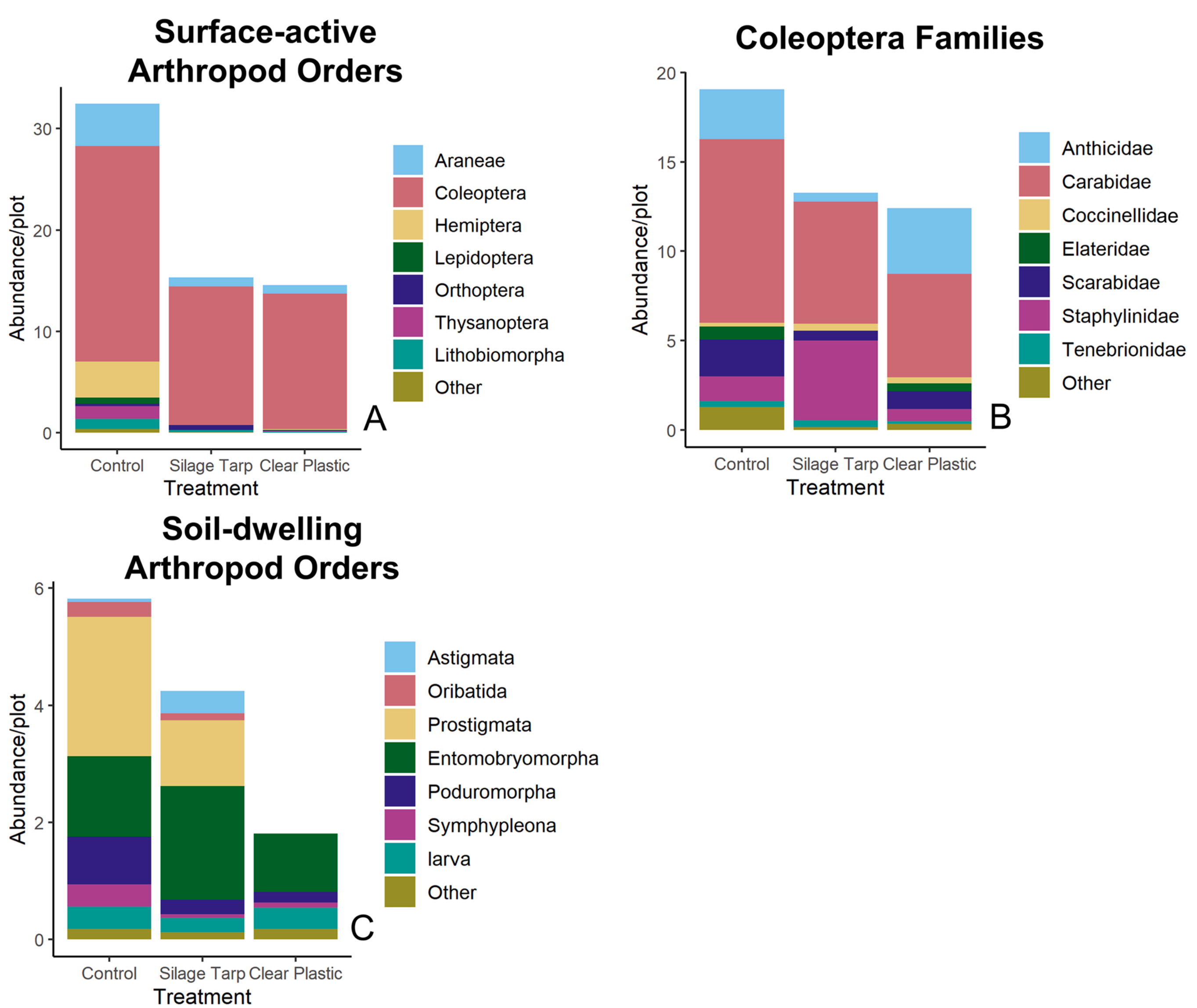

Fig. 1. Abundances of individuals within surface-active arthropod orders (A), Coleoptera families (B), and soil-dwelling arthropod orders (C) among the treatments when tarps were on the field. "Abundance/plot" relates to the average number of individuals captured per pitfall trap (A, B) or Berlese funnel sample (C).

were most abundant under silage tarps and least abundant under clear plastic tarps (silage tarp - clear plastic P = 0.008). There were no differences among treatments for Symphypleona springtails or insect larva (Fig. 1C; Table A2).

3.3. Diversity and abundance

For surface-active arthropods, during the tarping treatment both silage tarps and clear plastic tarps had significantly lower richness, Shannon's diversity and total abundance than the control plots (all P < 0.001; Fig. 2A,C,E; all statistics in Table A3). One week after we removed the tarps, silage tarps had lower richness than control plots (P = 0.044), but there were no other significant differences. At 3 and 5 weeks after tarp removal, there were no significant differences for richness, Shannon's diversity, or abundance among the treatments.

During the tarping treatment, richness and Shannon's diversity of soil-dwelling arthropods were significantly lower in the clear plastic tarp plots than in the control plots (both P < 0.001; Fig. 2B,D; Table A3). Abundance of soil-dwelling arthropods during the tarp treatment was also significantly lower in the clear plastic tarps compared to both control (P = 0.002) and silage tarp plots (P = 0.034; Fig. 2F). Soil-dwelling arthropod abundance remained significantly lower in the clear plastic tarp plots than the control 1 week after tarp removal (P = 0.033). While there were no differences in richness or Shannon's diversity values 1 and 3 weeks after tarp removal, 5 weeks after tarp removal silage tarp and clear plastic tarp plots had significantly lower richness (P = 0.011 & P = 0.050) and Shannon's diversity values (P = 0.003 & P = 0.045) than control plots. Additionally, abundance was significantly lower in silage tarp plots than control plots 5 weeks after tarp removal (P = 0.004; Fig. 2F; Table A3).

3.4. Composition analyses

In the principal coordinates analyses (PCoA), treatment significantly explained surface-active communities during the tarp treatment (P < 0.001; $R^2 = 0.12$), with significant pairwise differences among all treatment pairs (control – silage tarp P < 0.001; control – clear plastic P < 0.001; silage tarp – clear plastic P = 0.039; Fig. 3B). Treatment was also a significant predictor of soil-dwelling arthropod communities during the tarp treatment (P = 0.039; $R^2 = 0.04$), but there were no differences between treatment pairs (control – silage tarp P = 0.064; control – clear plastic P = 0.064; silage tarp – clear plastic P = 0.381; Fig. 3G). After tarps were removed, treatment no longer significantly explained arthropod composition in the PCoAs for either surface-active

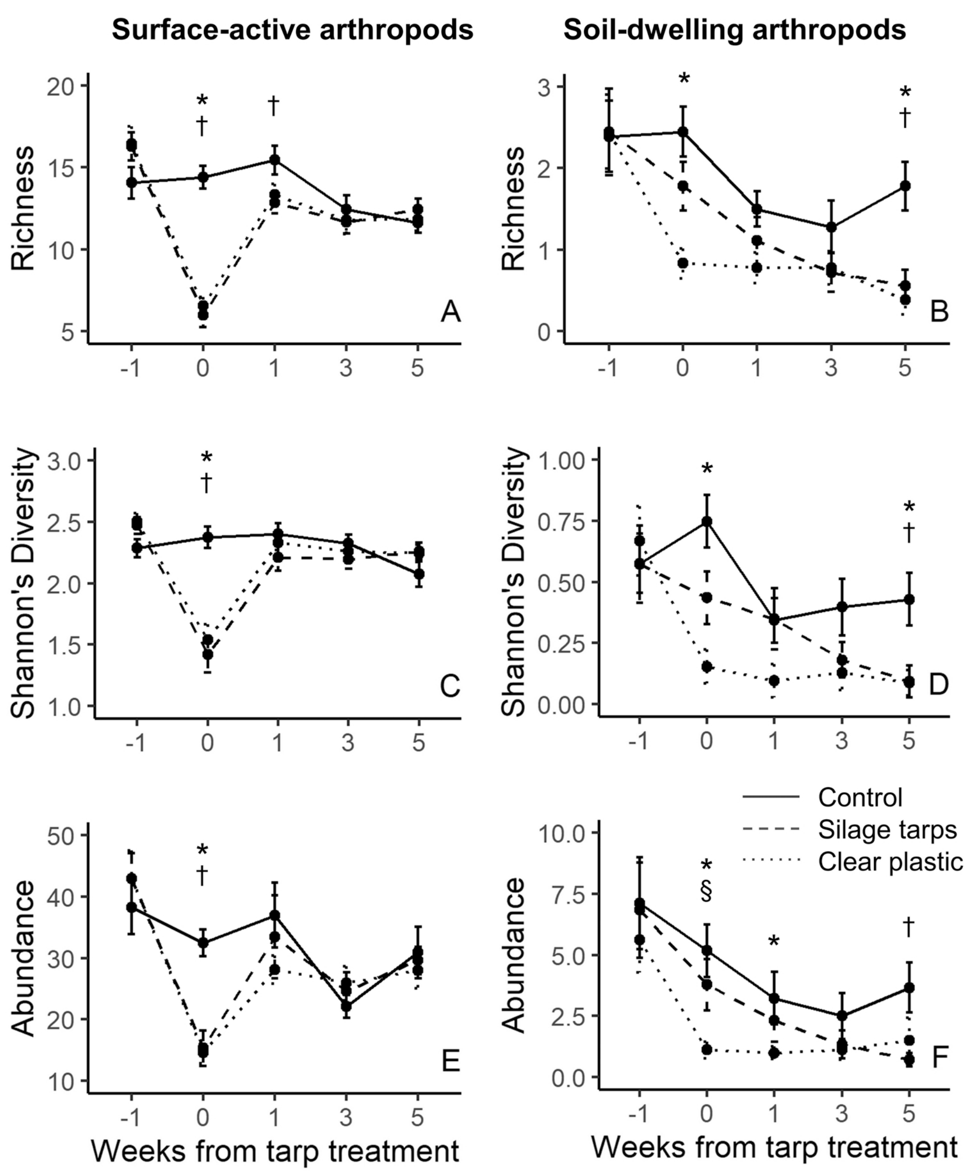

Fig. 2. Impact of tarps on richness, Shannon's diversity, and abundance for surface-active and soil-dwelling arthropod morphospecies. A cross (†) indicates a significant difference between control and silage tarp plots, an asterisk (*) indicates a significant difference between control and clear plastic plots, and § indicates a significant difference between silage tarp and clear plastic plots. "– 1" represents the week before tarps were applied, "0" represents sampling the last week of the tarp treatment, and "1", "3", and "5" indicate weeks since tarp removal.

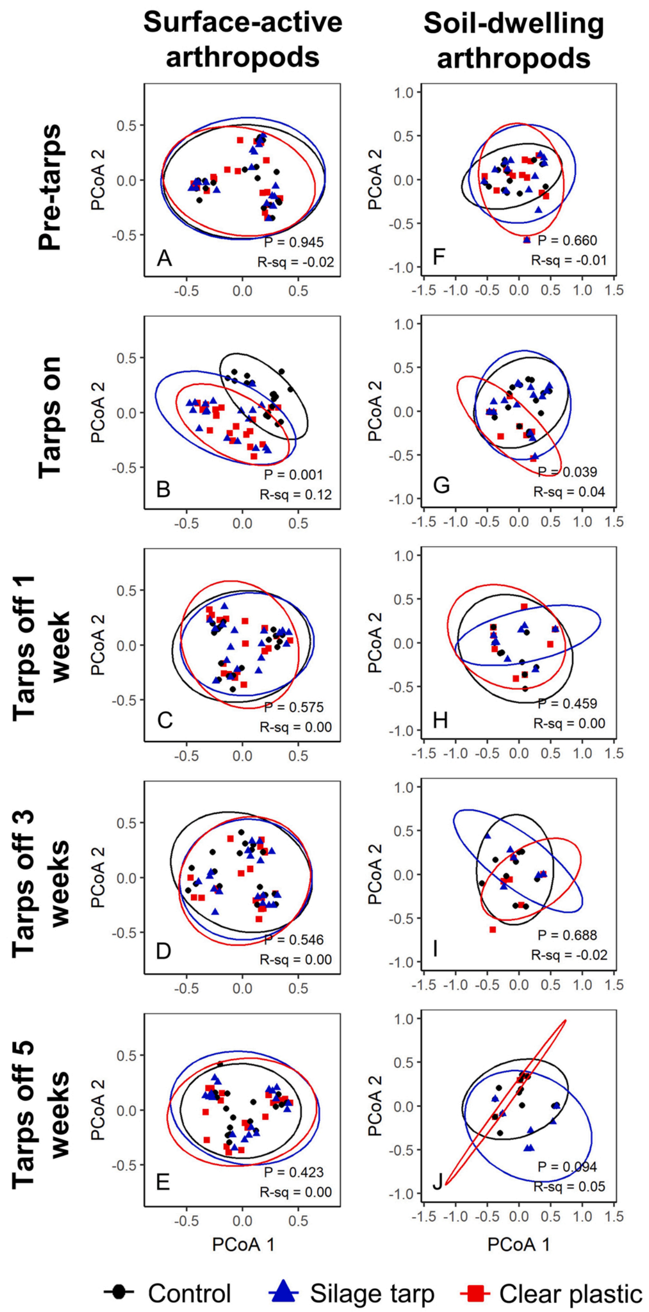

Fig. 3. Principal coordinates analysis (PCoA) showing the separation of surface-active (A-E) and soil-dwelling (F-J) arthropod morphospecies composition in each treatment. Trends are shown for each sampling period. R^2 and P values in each plot correspond to the fit and significance of treatment.

or soil-dwelling arthropods, and there were additionally no significant differences before tarps were applied (Fig. 3).

3.5. Importance of experimental and environmental variables

When tarps were on the fields, environmental and experimental variables explained over 75% of the variation in surface-active arthropod richness and around 43% of the variation in surface-active arthropod composition (Table 2). Treatment had the greatest variable importance score, and both treatment and the interaction between treatment and farm significantly explained both surface-active arthropod richness and composition (Fig. A3, Tables A4 and A5). Farm additionally significantly explained surface-active arthropod composition.

For soil-dwelling arthropods, our models explained around 44% of the variation in richness and 28% of the variation in composition during tarp cover (Table 2). Treatment again had the greatest variable importance score and significantly explained soil-dwelling arthropod richness, though no other variables were significant.

When tarps were removed, our models explained around 20% and 30% of the variability in surface-active arthropod richness and composition, respectively (Table 2). Farm site had the highest variable importance score and was significant in both models. While no other variables significantly explained surface-active arthropod richness, composition was significantly explained by sampling period, soil moisture, and treatment.

Our model for soil-dwelling arthropod richness and composition showed similar results (with total model R^2s of 23% and 24%, respectively). While treatment again had the largest variable importance score and was significant, farm site was additionally a significant predictor for both models. No other variables were significant predictors of soil-dwelling arthropods after tarp removal, and the interaction between treatment and sampling was not significant in any models (Fig. A3). Summaries of how environmental variables differed among treatments can be found in the Appendix (Table A6).

4. Discussion

Tarps had immediate detrimental impacts on the diversity of both surface-active and soil-dwelling arthropods and changed arthropod community composition, supporting other studies in tarping and plastic mulch research (Seman-Varner, 2005; Tuovinen et al., 2006; Addison et al., 2013). While surface-active arthropod diversity recovered 1–3 weeks after tarps were removed, soil-dwelling arthropods showed a less clear recovery — five weeks after tarps were removed, soil-dwelling arthropod richness and Shannon's diversity were significantly lower in plots that had been tarped than control plots. These results suggest that tarps' impacts may be temporary for surface-active arthropods but could be longer lasting for soil-dwelling arthropods.

4.1. Impacts during tarp application

While tarps affect the soil ecosystem in a variety of ways, including soil sealing and being impermeable, a large factor likely determining arthropod responses to tarping is heat tolerance. As ectotherms with no (or little) internal control over their body temperature, arthropods are susceptible to external temperature fluctuations. Their ability to withstand heat is highly interspecific and poorly understood, relating to body size, exoskeleton color and thickness, life stage, and trophic level, among other factors (Franken et al., 2018; González-Tokman et al., 2020).

For larger and more mobile arthropods, tarping may trigger a "stay" or "go" response. For instance, low abundance of many surface-active arthropod orders under tarps likely represents migration out of the tarped area. However, other arthropods may be more resilient or unbothered by tarps' effects, such as detected for Coleoptera (Fig. 1B). Coleoptera have a relatively thick cuticle, which may make them more heat tolerant and resistant of desiccation compared to other invertebrates (Wikars and Schimmel, 2001). High mobility of many Coleoptera taxa may also allow them to pass through tarps quickly without succumbing to heat effects. Mobile arthropods may also take cover under tarps as a means to warm up during cooler temperatures or as a shelter from predators.

In contrast, soil-dwelling arthropods have generally low mobility, with some taxa moving as little as only a few centimeters per day (Ojala and Huhta, 2001). Therefore, with low dispersal ability, soil-dwelling arthropod composition under tarps may reflect a "live" or "die" response. We found that soil-dwelling arthropods were affected by clear plastic tarps but not silage tarps during tarp application, suggesting that

Table 2
Results from models predicting arthropod morphospecies richness (multiple linear regression) and composition (RDA) with environmental and experimental variables. We include F statistics and P-values from all models and variable importance (standardized regression coefficients, totaling 1) for the richness models. Models were run separately for surface-active and soil-dwelling arthropods and for two sampling periods: when tarps were on the fields ("tarps on"), and 1, 3, and 5 weeks after tarp removal ("tarps off").

	Surface-active arthropods					Soil-dwelling arthropods				
	Richness			Composition		Richness			Composition	
	Variable import- ance	F	P	F	P	Variable import- ance	F	P	F	P
Tarps on										
Treatment	**0.84**	**7.40**	**0.002**	**3.21**	**0.001**	**0.63**	**7.31**	**0.002**	1.48	0.131
Farm	0.05	3.06	0.057	**4.03**	**0.001**	0.03	0.14	0.874	1.55	0.082
Soil moisture	0.02	2.76	0.104	1.54	0.098	0.10	1.06	0.308	0.53	0.809
Treatment:Farm	**0.09**	**3.00**	**0.029**	**2.21**	**0.001**	0.24	1.97	0.116	1.18	0.248
Total model fit (R^2)	76.6%			42.6%		43.7%			27.9%	
Tarps off										
Treatment	0.10	1.34	0.265	**1.39**	**0.044**	**0.40**	**6.01**	**0.003**	1.20	0.233
Farm	**0.35**	**6.21**	**0.003**	**3.23**	**0.001**	**0.31**	**6.56**	**0.002**	**4.59**	**0.002**
Sampling	0.28	2.05	0.132	**13.9**	**0.001**	0.08	0.45	0.454	1.57	0.143
Soil moisture	0.06	0.70	0.405	**3.11**	**0.001**	0.01	0.48	0.489	0.62	0.641
Weed coverage	0.09	0.57	0.452	0.74	0.738	0.11	0.01	0.918	2.26	0.076
Treatment: Sampling	0.12	0.80	0.525	0.99	0.479	0.09	0.91	0.462	1.11	0.336
Total model fit (R^2)	20.3%			31.3%		22.9%			23.6%	

higher soil temperatures under clear plastic tarps (8 °C warmer than silage tarps) were inhospitable (Table A6, Fig. A2). The impact of silage tarps on surface-active arthropods but not soil-dwelling arthropods during tarp application may support the theory that small-bodied organisms have higher heat tolerances than larger organisms (Smith et al., 2009; Sheridan and Bickford, 2011), or may simply reflect the decreasing temperature effects of tarps with soil depth (Oz et al., 2017).

4.2. Recovery of arthropods after tarp removal

In response to disturbances, like tarping, biological communities can have very different trajectories, with some engaging in recovery (Moretti et al., 2006; Pryke and Samways, 2012) – as seen for surface-active arthropods – while others experience diversity declines (Birthisel et al., 2019) – as seen for soil-dwelling arthropods. Recovery (or recolonization) of arthropods after tarps reflects either the dispersal of organisms back into the disturbed space or the regeneration of populations and communities (Bengtsson, 2002). Because our farm sites were adjacent to forested areas, there was likely high dispersal of larger and more mobile arthropods back into our experimental plots after tarping. Conversely, the dispersal of less mobile soil-dwelling arthropods may have been limited during our relatively short study, though it is possible that these arthropods engaged in vertical dispersal (Moradi et al., 2020). To better understand the role of dispersal, a study specifically looking at arthropods' movement patterns would be useful (Perry et al., 2021).

To support population regeneration, certain requirements need to be met, including having sufficient numbers of mates (for sexually reproducing organisms), food availability, lack of competition and predation, and abiotic suitability (Menge and Sutherland, 1987). For tarps, the spatial scale of effects may be felt differently for surface-active and soil-dwelling communities. For larger arthropods, tarps may create heterogeneity within their habitat, but not have a large enough impact to prohibit them from finding resources or mates. Conversely, smaller and less mobile arthropods, especially those living belowground, depend more on local conditions, especially because some are restricted to movement within existing soil pore networks (Vreeken-Buijs et al., 1998), and thus the impact of tarps may encompass their entire range. Tarps may also have fundamental impacts on the food resources, community and population dynamics, and habitat conditions for soil-dwelling organisms, creating complex and even cascading effects (Bengtsson, 2002). All these effects may explain why we see a fast recovery of surface-active arthropods and a less clear recovery of soil-dwelling arthropods.

4.3. Importance of environmental and experimental variables

The importance of environmental and experimental variables differed when tarps were on the field and after they were removed. During tarping, treatment was extremely predictive of soil arthropods but after tarp removal, while it remained significant in some models, its relative importance declined (Table 2). Conversely, farm was not as predictive as treatment in most models during tarping but became one of the most predictive variables after tarps were removed. The strength of farm at predicting arthropod richness and composition is not surprising, as our three farm sites had considerable differences, including for soil texture, soil nutrient profiles, and weed composition (Table 1), and such biophysical differences can lead to unique arthropod communities (Schaffers et al., 2008; Philpott et al., 2014; Ghiglieno et al., 2021). The result that farm site was relatively not as important during tarping demonstrates the strong impact of tarping at driving trends. However, we did interestingly find a significant interaction between treatment and farm during tarping, showing that tarps' effects may differ depending on the site. Specifically, we found that tarps had less effect on surface-active arthropod richness at Catamount Farm (Fig. A3; farm-separated data summaries listed in Tables A4 and A5). An explanation for this is that Catamount had ambiently higher soil temperatures than the other farms (by 1–2 °C) due to sandy soil, and thus arthropods there may have been more thermally adapted (Brans et al., 2017).

Other factors within our system, including soil moisture, weed coverage, and the sampling period, less consistently explained arthropod dynamics. Both weed coverage and soil moisture can be important drivers of soil arthropod communities (Norris and Kogan, 2000; Grear and Schmitz, 2005; Tsiafouli et al., 2005), and we had particularly expected weed coverage to relate to soil arthropod communities, as a possible food source and habitat. Lack of relationships for weed coverage and soil moisture may be due to relationships with other variables, for example between soil moisture and farm or weed coverage and sampling (though collinearity was not detected for these variable pairs). Similarly, we likely did not detect a strong effect of sampling because of the quick recovery of arthropods following tarping and because, while arthropod richness patterns can change inter-annually (Liu et al., 2016; Kirse et al., 2021), sampling for five weeks after tarping may not have been enough time to see significant changes.

Finally, while soil temperature was removed from the models due to high collinearity with treatment (Table A6), we found a significant negative relationship between soil temperature and arthropod richness (Fig. A2), though it is difficult to decouple the effects here attributable only to soil temperature. Tested models for surface-active arthropod richness including soil temperature but not treatment performed relatively poor (yielding $R^2 = 0.40$, compared to the current $R^2 = 0.77$), demonstrating that tarps' effects stretch beyond temperature effects and losses in soil arthropod richness are driven by other factors as well (such as light-availability or soil sealing).

4.4. Experimental limitations

A major limitation in our study is that our tarped treatment plots are much smaller than tarps used in practice — our tarps were 2 by 4.5 m, while tarps in practice are often 10 by 15 m or larger. Furthermore, while we sealed the edges of tarps with soil, some farmers use sandbags to hold tarp edges down (especially for silage tarps), which may allow for more airflow. Larger tarp sizes may make it more difficult for mobile organisms to migrate out of the tarped area, potentially causing more negative effects. Conversely, increased airflow and ultimately lower temperatures under tarps may lead to less negative temperature-related diversity declines. While we decided to use small tarp pieces to maximize the replication of treatments on our limited land area, repeating this experiment with larger tarp sizes might provide more insights.

The long-term impacts of tarps also remain unclear. Our study was limited to 5 weeks after tarp removal, but effects may continue long after this period — in studies on fire, soil arthropod communities took decades to recover (Pressler et al., 2019). As well, while we saw recovery of surface-active arthropods during our experimental time frame, recovery patterns are complex and not always linear; thus, sampling for longer periods of time may reveal different dynamics than we observed. Additionally, many farmers use tarps twice or even three times a summer for quick growing crops. The continuous use of tarps could expound effects by not allowing communities to fully recover. Another possible outcome of frequent tarp use is adaptation. In fact, studies on urbanization suggest that arthropods can adapt to warm temperatures (Diamond et al., 2017; Yilmaz et al., 2021). It is important to consider these potential long-term changes to species, community structure, and biological function.

4.5. Conclusions and implications for agricultural management

Tarps are an exciting new practice which may help farmers transition away from intensive practices like tillage and herbicide use, but we are only starting to understand the impacts of tarps on biodiversity. This study has unveiled important information on the short-term effects of tarps on arthropods but, going forward, more research will be necessary to contextualize our results. For example, it will be valuable to compare the effects of tarps and other weed management techniques, or to conduct tarp research over multiple years and in different geographic regions, seasons, and soil types. Additionally, while we did not specifically look at tarps' impacts on pests, this has been one major application of tarps (Stapleton and DeVay, 1986) and remains a topic of interest among farmers (Kinnebrew et al., 2022). We encourage future research on tarps' effects on pests, though suggest consideration of concurrent impacts on beneficial arthropods, including on natural enemies of pests. In conclusion, we hope this study helps inform agricultural management that can be effective for both crop production and biodiversity conservation (Díaz et al., 2015).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data are available at https://doi.org/10.6084/m9.figshare.c.6620806.v1.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2023.108542.

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