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Original article

The effects of pre-planting treatment strategies on understory vegetation in an urban forest patch

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ABSTRACT

Urban forest patches experience a wide variety of anthropogenic and environmental stressors, including recurrent canopy gap-creating events, herbivory pressure, and invasive species. Forest restoration strategies to overcome these stressors frequently rely on enhancing tree regeneration, including tree-planting. Pre-planting treatment strategies are a crucial preparatory step in establishing appropriate site conditions to ensure successful long-term tree regeneration. However, many pre-planting treatments rely on synthetic herbicide, which can be associated with adverse environmental outcomes. Due to the negative perceptions and effects of synthetic herbicides, which are a common tool in forest restoration, many cities, towns, and parks have begun to ban the use of these chemicals. Our objective was to compare mechanical removal with synthetic and organic herbicide applications to determine which pre-planting strategy most effectively reduces non-native plants and enhances native plant cover. We conducted this study within a 16-hectare *Liriodendron-Quercus* forest located in Philadelphia, Pennsylvania, USA, over a two-year period. Organic herbicide demonstrated the lowest efficacy at reducing non-native plants (14.2 % reduction), followed by mechanical removal (-18.6 %). Synthetic herbicide application had the highest efficacy (-46.1 %). Although organic herbicide had the lowest efficacy, it did reduce non-native cover. Species-specific responses showed similar trends among pre-planting treatments. Additionally, we found that the timing and frequency of herbicide application may support higher efficacy in organic herbicide use. Our study supports species-specific management focused on above- and below-ground control mechanisms. This study provides best-management practices for pre-planting treatments and highlights the impacts these treatments have on diversity, composition, and restoration success.

1. Introduction

Urban forest patches are forested natural areas located in urban and suburban landscapes with forest vegetation capable of natural regeneration (Johnson et al. 2021; Doroski et al. 2022). These habitats are critical for maintaining urban biodiversity (Alvey, 2006; Aronson et al. 2017; Lepczyk et al. 2017), providing ecosystem services (Arcos-LeBert et al. 2021; Lovell and Taylor, 2013), and enhancing human health and wellbeing (Parven et al. 2024; Douglas, 2015; Robinson et al. 2024). Urban forest patches face multiple stressors similar to those in rural landscapes (e.g., climate change, disease, herbivory) but also face challenges unique to or amplified in cities (e.g., urban heat island effect, pollution, recreational over-use). These challenges hinder natural regeneration and drive recruitment failure (McDonald et al. 2023; Piana et al. 2019) necessitating restoration efforts by urban land managers (Pregitzer et al. 2021).

Many ecological restoration projects rely on active management because minimal intervention has frequently been shown to fall short of meeting restoration objectives (Aronson and Galatowitsch, 2008; Suding, 2011; Piana et al. 2019). Additionally, restoration activities that

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focus exclusively on alleviating major stressors, such as reducing herbivory or invasive plant competition, are often ineffective on their own, as restoration success typically requires complementary interventions (Aronson and Handel, 2011; Gorchov et al. 2021; Guo et al. 2018). Therefore, an active approach is commonly required, such as methods involving artificial regeneration (i.e., direct seeding or planting; Lof et al. 2021). In cities, afforestation or planting along edges or within canopy gaps are common practices (Collins and Pickett, 1988). However, identifying appropriate planting sites can be challenging due to multiple factors that influence the implementation and success of the restoration project (e.g., disturbance and land use history, access, stakeholder support).

Natural forest canopy gaps are often formed by senescing canopy trees, windthrow, and pest damage (Kern et al. 2013; Brokaw and Busing, 2000). Gaps are important for forest regeneration as they are sites with abundant sunlight and resources for growth (Xie et al. 2023). However, in urban and suburban areas, canopy gaps frequently lack tree seedlings and saplings because of premature mortality, resulting in limited regeneration and dominance by opportunistic, often non-native invasive species (Brokaw and Busing, 2000). This phenomenon is particularly found in urban and suburban forest patches where canopy gaps can support a dense understory of invasive vegetation (Senécal et al. 2018), compounded by consistent herbivory pressures (Aronson and Handel, 2011; Fisogni et al. 2022; Kern et al. 2013).

Understanding understory plant responses is critical in urban restoration ecology, particularly in cases when supporting regeneration of shade-intolerant trees, such as *Quercus rubra, Liriodendron tulipifera,* or *Carya cordiformis,* is necessary for forest succession and long-term success. Tree regeneration failure can occur for multiple reasons and competitive exclusion of the shade intolerant species by invasive shrubs, vines, and grasses (i.e., *Rosa multiflora, Lonicera japonica,* and *Microstegium vimineum*) is one common factor (Meiners, 2007; Aronson and Handel, 2011). Beyond invasive competition dynamics, gap restoration presents additional challenges due to their unique microenvironments. Increased heat and water stress, particularly drought in the growing season, can lead to high tree mortality in both natural and artificial regeneration scenarios (Anderegg et al. 2013). Due to the multiple stressors and high degree of invasion in canopy gaps within urban forest patches, land managers often must remediate site conditions prior to beginning an active restoration to ensure survival of planted trees. Remediating site conditions to ensure successful long-term natural and artificial tree regeneration is a crucial preparatory step (Lof et al. 2012; Preece et al. 2023), but best practices in cities that are successful and accepted by stakeholders are not well-known.

In urban forests, remediating site conditions for planting often relies on the use of synthetic herbicides to manage and control invasive plants. The use of synthetic herbicides in forest restoration has been a regular practice since the 1990s (Wagner et al. 2004; Miller 2013; Shepard et al. 2004). Many studies demonstrate the efficacy of synthetic herbicides, particularly when coupled with an integrative approach such as herbicide application in conjunction with mechanical removal (Ward and Mervosh, 2012; Lake et al. 2014; Evans, 1983). Despite their effectiveness, synthetic herbicides can be associated with adverse environmental outcomes, including negative impacts on biodiversity, water quality, and soil health (Sullivan and Sullivan, 2003; Michael, 2001; Busse et al., 2001). Therefore, when herbicides are used, careful planning, integration, and stakeholder support is vital (Wagner et al. 2004).

Because of the negative effects and perceptions of synthetic herbicides, many cities, towns, and parks have begun to ban the use of these chemicals (Zaller, 2020; White, 2019). For example, Baltimore, Maryland passed an ordinance in 2020 focused on pesticide control and regulation on public and private properties (City of Baltimore, 2020). In 2021, Chicago, Illinois announced the transition to organic management for a number of its city-owned parks (Cornall, 2021). New York City has made a commitment to have eight parks transitioned to fully organic maintenance by 2025 (Cornall, 2021). In particular, the city of Philadelphia, Pennsylvania passed a bill in January 2021, Bill No. 200425-A, potentially banning the use of synthetic herbicides on city lands. Philadelphia has over 4100 ha of city parkland including approximately 2200 ha of natural lands that falls under this legislation. Therefore, this ban will impact how the city manages invasive plant species for restoration projects in urban forest patches (Abraham, 2015). However, there has been little empirical research on the effectiveness of organic herbicide on invasive plant management. With a phased timeline and allowance of exemptions, this law, which is now in effect, has provided opportunities to evaluate alternative management strategies, including the efficacy of organic herbicides.

In this study, we compared the efficacy of synthetic and organic herbicide to mechanical removal as a pre-planting management strategy. In order to inform land managers responding to herbicide ordinances, our objective here was to determine which pre-planting strategy reduced non-native invasive and other dominant plant species that inhibit tree regeneration while enhancing native plant cover in canopy gaps in an urban forest. We evaluated the effectiveness of the treatments to improve site conditions for artificial regeneration success in tree canopy gaps in an urban *Liriodendron-Quercus* forest patch. Currently, all treatment types used at this site have advantages and drawbacks. Mechanical removal is often cost effective and highly efficient but is generally non-selective, depending on the method utilized. Synthetic herbicides are highly effective but can have negative environmental impacts. Lastly, organic herbicides often require direct application to the target plant and consistent reapplications which are expensive and time-consuming but traditionally are associated with lower negative perceptions and non-target effects compared to synthetic herbicides (Kraehmer 2014; Lanini, 2011). We hypothesized that organic herbicide application would have lower efficacy in comparison to other methods, but that responses would be species-specific. The results from this study can be used to determine the best approaches for reducing target invasive plants.

2. Methods

2.1. Study area and treatments

We conducted this study in the Pennypack Park forest (40.08017°N, 75.04717°W) located in northeast Philadelphia, Pennsylvania. Pennypack Park, approximately 700 ha, has multiple land uses, including active recreation areas of playgrounds and sports fields, along with forest, meadow, and wetland habitats. The study was located in a 9.8-hectare mature upland *Liriodendron-Quercus* stand protected by a deer exclosure fence (Fig. 1). Dominant canopy species at the site include *L. tulipifera, Q. rubra, Quercus alba,* and *Carya tomentosa* with *Lindera benzoin* being a dominant shrub layer species. Canopy gaps, created by natural tree falls from storms such as Hurricanes Irene (2011) and Sandy (2012) and tree senescence, have subsequently become heavily invaded by non-native invasive plant species and the native, L. *benzoin.* These non-native plants such as, *Alliaria petiolata, L. japonica, M. vimineum, Persicaria perfoliata, R. multiflora,* and *Rubus phoenicolasius* as well as the native species, *L. benzoin* have hindered natural regeneration of tree seedlings therefore necessitating restoration.

In 2021, we identified 15 naturally occurring canopy gaps that varied between 0.016 and 0.214 ha in size. Philadelphia Parks and Recreation cleared shrubs with a forestry mower (Bobcat compact skid-steer loader with a drum chopper/mulcher attachment) and seeded with ryegrass (*Lolium multiflorum*) for groundcover. *L. multiflorum* was used to provide rapid groundcover and erosion control, and thought to allow for subsequent vegetation regeneration. We established 36 plots (1–4 plots per gap) within these gaps, each of which was assigned a pre-planting treatment (mechanical removal (control) = 20; synthetic herbicide application = 8; organic herbicide application = 8 plots). This study was conducted within the framework of a larger restoration project thereby treatment allocation was determined by management objectives rather

Fig. 1. Thirty-six plots were established within a deer fence exclosure in Pennypack Park, Philadelphia, Pennsylvania, USA. There were three pre-planting treatments: mechanical removal (m-green), organic herbicide application (o-blue), and synthetic herbicide (s-yellow) application.

than equal replication.

The 20 mechanical treatment (control) plots were cleared three times during the study period using brush saw and string trimmers on August 20, 23, 2021, June 23, 27, 2022, and August 29, 2022. Synthetic and organic herbicides were applied on July 14, 15, 2021, August 24, 2021, June 28, 2022, and August 30, 2022. Treatment timing reflected contractor availability and established Philadelphia Parks and Recreation management practices. The synthetic herbicide was Rodeo® (Corteva, Indianapolis, IN), which contained 53.8 % glyphosate as the formulated product, applied at a 2 % working solution. The organic herbicide was Scythe® (Corteva, Indianapolis, IN), which contained 57 % pelargonic acid as the formulated product, applied at a 7 % working solution. Spray volume for Rodeo® ranged from 6 to 17 gallons per treatment event (total applied across all relevant plots), and spray volume for Scythe® ranged from 15 to 24 gallons per event. In all cases, reported total volumes reflect the amount of diluted herbicide solution applied across the study plots during each application.

Both herbicides were selectively applied directly onto individual invasive plants, with a particular emphasis on the target invasive species: *A. petiolata, L. japonica, M. vimineum, P. perfoliata, R. phoenicolasius,* and *R. multiflora,* but also *Berberis thunbergii, Celastrus orbiculatus, Euonymus alatus, Reynoutria japonica,* and *Lonicera maackii*.

To monitor plant understory response to pre-planting treatments, we established 5-m diameter subplots at the center of each of the 36 control and treatment plots. Initial vegetation surveys were conducted on July 7,8, 2021, prior to treatments, and again on September 13,14, 2021, June 7,8, 2022, and September 21,22, 2022. Within each subplot, we identified all plant species and measured percent cover of each species using cover classes. Cover classes employed were 0–1 % (0.5 %), 1–5 % (3 %), 5.01–10 % (7.5 %), 10.01–25 % (17.5 %), 25.01–50 % (37.5 %), 50.01–75 % (62.5 %), and 75.01–100 % (87.5 %) with median values for data entry listed in parenthesis (Tiner, 2017; Mueller-Dombois and Ellenberg, 1974; Daubenmire, 1959). All cover values were relativized by total plot cover. Mechanical and herbicide treatments were implemented between the plant surveys. Plants were classified as native, non-native, or invasive based on USDA and NISIC definitions (USDA Plant Database 2023; NISIC, 2023). In this study, plants were categorized as invasive if they were widely established and are considered to cause economic and/or ecological harm (NISIC, 2023).

2.2. Data analyses

All statistical analyses were completed using R version 4.3.1 (2023 The R Foundation for Statistical Computing Platform. Negative vegetation cover change values indicate a decrease in cover in response to treatment. We also assessed which species were more prevalent in the plots. Prevalence was defined as species comprising greater than 1 % relative total abundance across all plots throughout the duration of the study. This threshold was chosen because over 90 % of species had a total relative abundance of < 1 %.

We used a linear mixed model (LMM) to evaluate the effect of treatment on non-native plant cover, with gap included as a random effect to account for non-independence among plots. The model was fit using the lmer function from the lme4 package in R. Post-hoc comparisons were performed with Tukey-adjusted pairwise tests of estimated marginal means using the emmeans package. Model assumptions of normality and homogeneity of variance were assessed with Q–Q plots, residual versus fitted plots, and a Shapiro–Wilk test ($W = 0.98166$, $p = 0.7999$), which indicated no departure from normality. The same LMM framework was applied to species-specific responses, with treatment as a fixed effect and gap as a random effect, followed by Tukey-adjusted pairwise comparisons of estimated marginal means for each species and normality and homogeneity of variance were assessed as well and showed no departure from normality ($W = 0.969$, $p = 0.4$ for *L. japonica*; $W = 0.980$, $p = 0.754$ for *M. vimineum*). The significance level was 0.05 for all tests.

We used non-metric multidimensional scaling (NMDS) based on Bray-Curtis dissimilarity to compare understory plant species composition patterns prior to and after pre-planting treatments of mechanical removal, synthetic herbicide application, and organic herbicide application. The metaMDS function of the vegan package, k = 2 was used (Muche et al., 2024; Oksanen et al., 2022; Legendre and Legendre, 1998). We then used the ENVFIT function within the vegan package to calculate species correlations with NMDS axes 1 and 2 (Sievers et al. 2024; Dixon, 2003). We used PERMANOVA (pairwiseAdonis2) to test for community composition differences among treatments, time, and the interaction between treatment and time. Centroid groups were identified for mechanical removal, organic herbicide application, and synthetic herbicide application for both pre- and post-treatments. We conducted pairwise comparisons to determine which specific treatments differ from each other in their effects over time. This resulted in 15 pairwise comparisons to evaluate. We used adjusted p-values provided by the PERMANOVA to determine pairwise interaction significance to account for making multiple comparisons.

3. Results

3.1. Overall non-native plant responses

Across all 36 plots, initial non-native vegetation cover did not differ significantly among treatments ($F = 1.896$, $p = 0.1670$), confirming comparable baseline conditions prior to treatment application. The synthetic herbicide treatment resulted in the greatest reduction in non-native plant cover at −46.1 % ±17.2 sd; compared to mechanical treatment (control) at −18.6 % ±21.6 sd, and organic herbicide treatment at −14.2 % ±20.3 sd over the duration of the study (Fig. 2). There was a significant reduction in non-native cover under the synthetic herbicide treatment compared to mechanical removal (t-ratio = 3.484, $p = 0.0055$), while no significant difference was detected between mechanical removal and organic herbicide. The difference between synthetic and organic herbicide was just outside of the significance level of $\alpha = 0.05$ (t-ratio = 2.289, $p = 0.0763$). However, this comparison does approach significance, suggesting a potential difference between the synthetic and organic treatments, but limited sample sizes, variability among canopy gaps, and the conservative nature of Tukey-adjusted tests likely contributed to the marginal result (Day and Quinn, 1989; Ruxtona and Beauchampb, 2008). For the organic herbicide treatment, there was a minimum value of −59.3 % that was an identified outlier. This outlier was driven by the high abundance of the seeded cover crop, *L. multiflorum*, and its subsequent reduction after treatment. While we recognize that this decline partly reflects the species' annual life history, we retained it in our analyses because ryegrass establishment was part of the standard site preparation protocol. Excluding *L. multiflorum* would remove the role and interaction effects of the cover crop, which are important for evaluating restoration outcomes under current management practices.

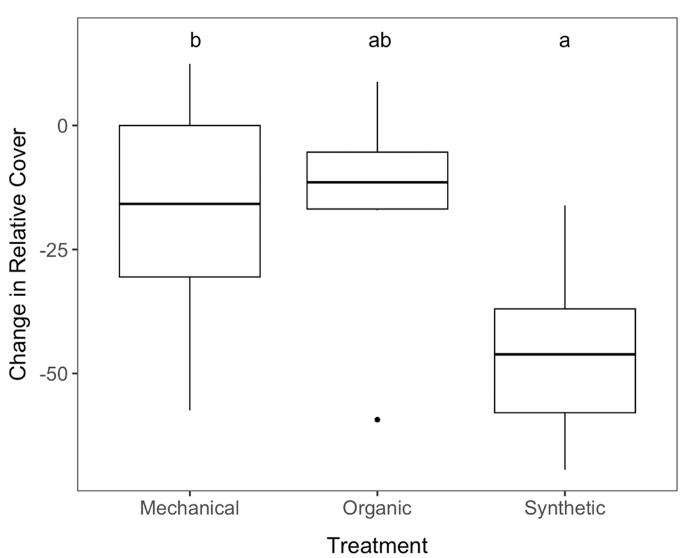

Fig. 2. Change in relative cover in non-native species in response to three pre-planting treatments: mechanical removal (control), organic herbicide application, and synthetic herbicide application, at Pennypack Park, Philadelphia, Pennsylvania, USA. Lowercase letters are used to show significant differences among treatments.

3.2. Species-specific responses

Two target species, *L. japonica* and *M. vimineum* showed treatment differences, while *A. petiolata*, *P. perfoliata*, *R. multiflora, R. phoenicolasius*, and *L. benzoin* did not differ significantly among treatments (Fig. 3). For *L. japonica*, pairwise comparisons detected statistical differences between mechanical removal and both organic (t-ratio = 2.591, $p = 0.0385$) and synthetic herbicide application (t-ratio = 3.56, $p = 0.0038$). However, the actual changes in cover were minimal across all treatments, with synthetic herbicide showing a slight decrease (–0.13 % ± 0.23 SD) and the other treatments showing similarly small increases (Fig. 3). For *M. vimineum*, there was a significant difference in cover between synthetic and organic herbicide treatments (t-ratio= 3.2933; $p = 0.007$) but not between the other treatments. Both mechanical removal (0.675 % ± 41.0 sd) and organic herbicide application (29.3 % ± 36.0 sd) led to increases in M. *vimineum* cover, compared to a nearly 30 % decrease in cover in response to synthetic herbicide application (-28.5 % ± 34.4 sd) (Fig. 3).

3.3. Understory community response

A total of 176 species were recorded across 36 plots within the 15 canopy gaps. Of those 176 species, 46 (26.1 %) were non-native. Prevalent native species were *L. benzoin* (5.93 % ± 0.08 sd)*, Sassafras albidum* (2.04 % ± 0.08 sd), *L. tulipifera* (2.00 % ± 0.05 sd), *Acer rubrum* (1.55 % ± 0.07 sd)*, Ageratina altissima* (1.46 % ± 0.05 sd) (Supplementary Table 1). Prevalent non-natives species were *M. vimineum* (25.60 % ± 0.23 sd average relative cover)*, L. multiflorum* (11.71 % ± 0.23 sd)*, Polygonum persicaria* (3.43 % ± 0.07 sd)*, P. perfoliata* (3.15 % ± 0.07 sd)*, R. phoenicolasius* (3.07 % ± 0.06 sd).

Mean species richness increased from 28.3 ± 4.64 sd pre-treatment to 29.3 ± 6.04 sd post-treatment across all mechanical removal plots. For organic herbicide, mean species richness was 30.4 ± 6.3 sd before and 28.1 ± 7.4 sd after treatment. Synthetic herbicide richness decreased from 28.8 ± 5.75 sd to 24.8 ± 7.34 sd post-treatment. However, there were no significant differences in species richness among treatment, time, or the treatment-time interaction.

Mechanical removal and organic herbicide treated plots displayed similar patterns in NMDS space in comparison to synthetic herbicide treated plots (Fig. 4). NMDS1 (axis 1) showed separation by treatment particularly between the synthetic herbicide and the two other treatments (mechanical removal and organic herbicide). NMDS2 (axis 2) was associated with time, showing that the pre-treatment communities (circles) and post-treatment communities (triangles) were found in separate clusters along this axis. All three treatments resulted in communities moving in a similar direction (represented by arrows) after treatment, with the synthetic herbicide treatment having the greatest divergence from pre-treatment communities (Fig. 4).

For community composition, PERMANOVA found no significant differences among treatments (F= 1.5565, 0.1030) alone, but time was a significant driver of community composition change across all treatment types (F= 20.2703, $p = 0.001$), indicating significant changes in the treatment communities by the end of the study. We also found significant differences in community composition when examining the interaction between treatment and time (F= 2.1057; $p = 0.0260$). This interaction was further investigated as pairwise comparisons. We found

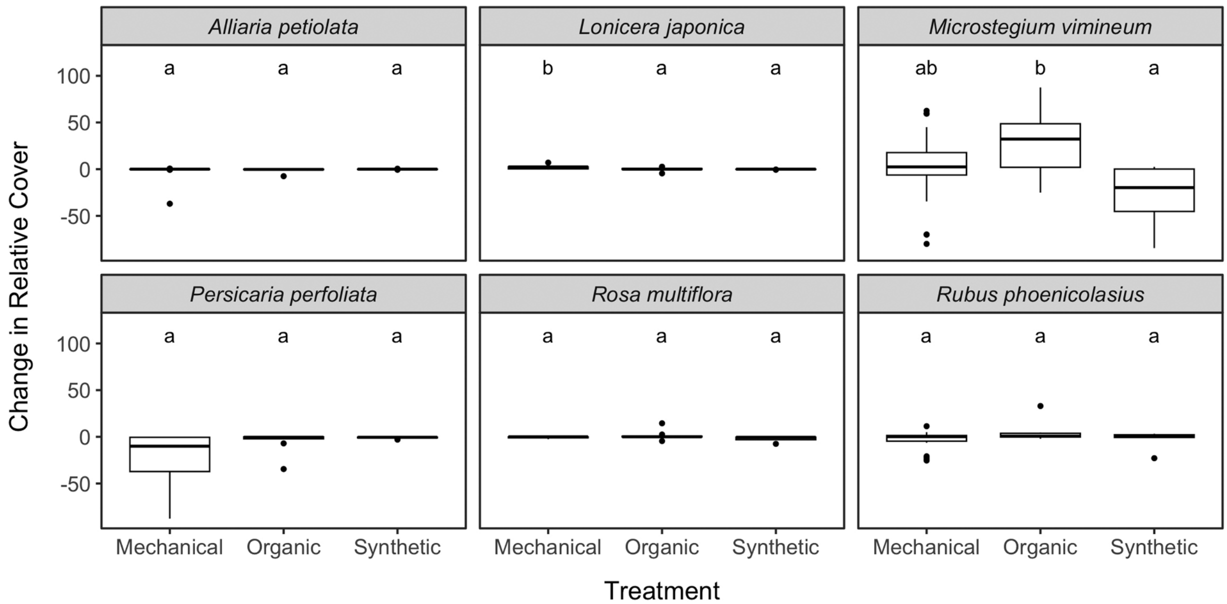

Fig. 3. Species-specific responses of non-native target species to three pre-planting treatments: mechanical removal (control), organic herbicide application, and synthetic herbicide application, at Pennypack Park, Philadelphia, Pennsylvania, USA. Lowercase letters are used to show significant differences among treatments.

no significant compositional differences in community composition before treatments were applied (pre-treatment) among mechanical removal, organic herbicide, and synthetic herbicide treatments (Fig. 4A, Supplementary Table 2). However, pre- and post-mechanical treatment communities were significantly different in composition ($p = 0.015$), as were pre- and post-organic herbicide application communities ($p = 0.03$), and pre- and post-synthetic herbicide application communities ($p = 0.015$). Post-treatment communities also differed from each other. Post-mechanical treatment communities and post-organic herbicide treated communities were significantly different from post-synthetic community composition ($p = 0.03$, $p = 0.045$, respectively). There were no differences in community composition between post-mechanical and post-organic treatments.

Forty-seven species were significantly correlated with NMDS axes 1 and 2 (Supplemental Table 3). However, only 8 species had an R^2 of greater than 0.25, indicating moderate correlations with the axes (Fig. 4B). These included, *Ampelopsis brevipedunculata* ($R^2 = 0.3065$, $p < 0.01$), *L. tulipifera* ($R^2 = 0.3132$, $p < 0.01$), *L. multiflorum* ($R^2 = 0.6279$, $p < 0.01$), *M. vimineum* ($R^2 = 0.4716$, $p < 0.01$), *P. perfoliata* ($R^2 = 0.2503$, $p < 0.01$), *Prunus serotina* ($R^2 = 0.3331$, $p < 0.01$), *Taraxacum officinale* ($R^2 = 0.2828$, $p < 0.01$), and *Toxicodendron radicans* ($R^2 = 0.4365$, $p < 0.01$). Some species were strongly correlated to the positive ends of Axis 2 (e.g., *L. multiflorum*) or Axis 1 (e.g., *P. perfoliata*), thus more closely associated with pre-treatment communities. In comparison, species correlated with the negative ends of Axis 2 (e.g., *A. brevipedunculata*) or Axis 1 (e.g., *L. tulipifera*), were closely associated with post-treatment communities. Synthetic herbicide treated post-treatment communities were characterized primarily by native species, including *L. tulipifera*, *P. serotina*, and *T. radicans*, as these species were significantly correlated with the negative end of Axis 1. Post-treatment communities treated with mechanical removal or organic herbicide were more closely associated with non-native species, *T. officinale* and *A. brevipedunculata*.

4. Discussion

The success of ecological restoration projects often depends on pre-planting site preparation (Lof et al. 2012; Preece et al. 2023). Particularly in urban forest patches, where tree regeneration is limited and site treatments are necessary for tree planting survival and growth, identifying the best practices for site treatments is critical. Land managers often rely on mechanical removal and synthetic herbicide but growing concerns on the ecological and human health impacts of synthetic herbicides has caused some cities to ban the use of these chemicals. However, this often leads to land managers in need of alternative methods to control site conditions, particularly for invasive species. Here we found that although organic herbicide may be partially effective in some systems, such as agricultural (Loddo et al. 2023), it may not be effective on alone as a viable control mechanism in forest systems. We found here that organic herbicide and mechanical removal had lower efficacy in reducing non-native invasive plants compared to synthetic herbicide. However, it is important to note that our experiment tested only a single organic herbicide product, at one concentration, and with one application method; therefore, our findings should not be generalized to all potential organic herbicide options or practices in forest management.

Similar results have been reported by others (Judge et al. 2005; DeNux et al. 2024) where synthetic herbicide was found to have a higher efficacy compared to other treatment options for invasive plant control. Although while synthetic herbicide had a greater ability to reduce invasive plants, the organic herbicide, pelargonic acid, does show promise. We found that pelargonic acid reduced plant cover at lower rates than synthetic herbicides. This reduction may indicate that repeated herbicide applications are necessary over time, or that native species now require a greater level of invasive suppression to successfully regenerate. Carreiro et al. (2020) compared the use of synthetic herbicide (glyphosate) and organic herbicide (pelargonic acid and cinnamon plus clove oils) on suppressing growth of non-native woody vines (*Akebia quinata, Euonymus fortunei, Hedera helix,* and *Vinca minor*). They found that two application cycles of organic herbicide application were needed to kill the vines in year 1, but that a third application was needed to prevent year 2 growth. While synthetic herbicide application may be more effective short-term, organic herbicides may be just as effective if we are we able to identify optimal treatment amounts and/or application timing that would yield higher efficacy.

Additionally, the treatments utilized in this study focused on control of above ground biomass. However, studies have shown that effective invasive plant management also targets root systems (Jackson and Finley, 2007). Organic herbicides are generally more effective on above-ground biomass than below-ground biomass, as they act

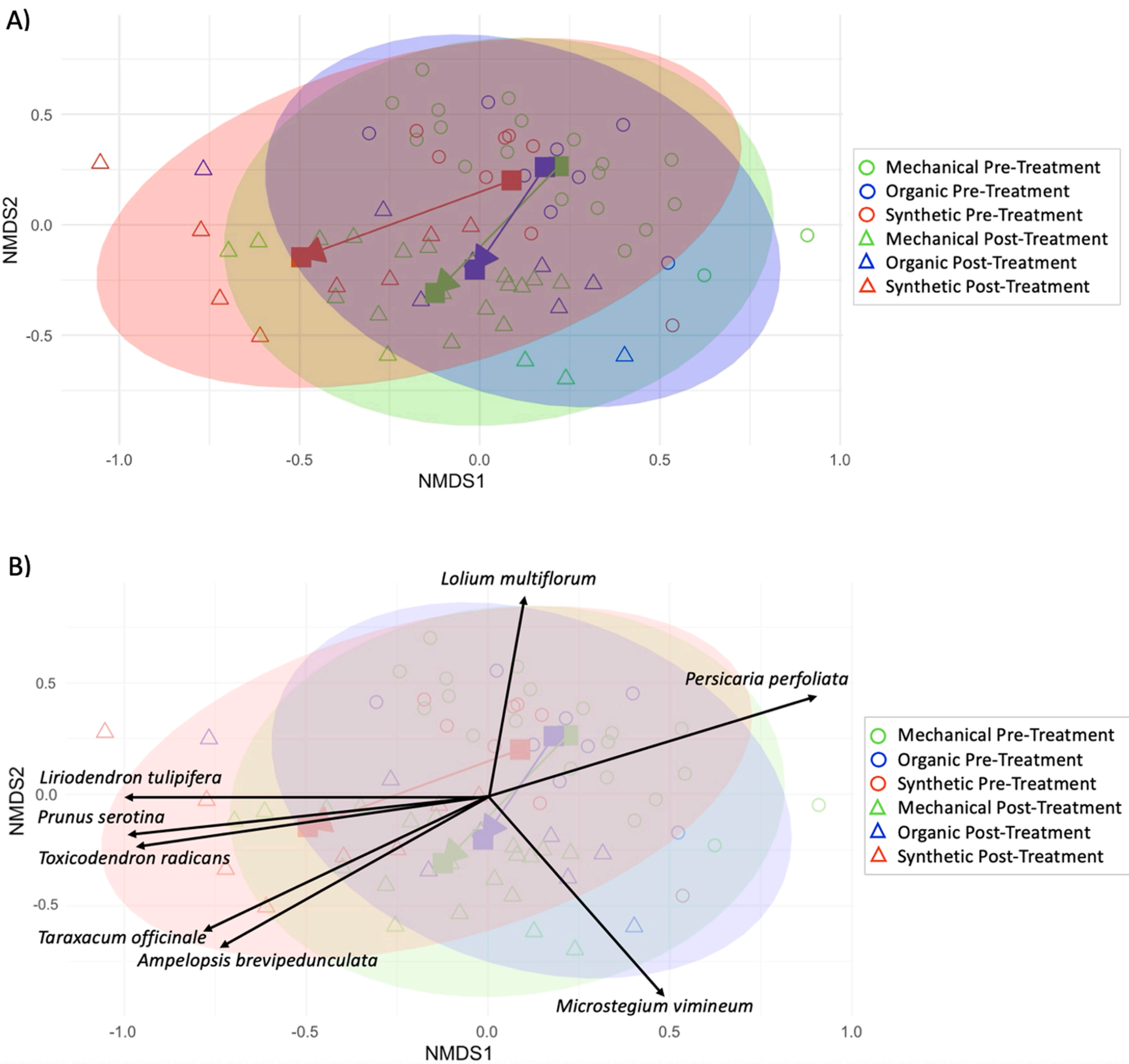

Fig. 4. A) Non-metric multidimensional scaling of community composition before and after pre-planting treatments (mechanical removal, organic herbicide application, and synthetic herbicide application) at our study site in Pennypack Park, Philadelphia, USA. Centroids are denoted as boxes and arrows between before and after centroids indicate movement of community composition. The stress value was 0.2439 and 94.2 % (R^2 = 0.942) of the variation in the dissimilarities is captured by the represented NMDS (Supplemental Figure 1). B) Species correlations overlaid onto the community ordination. Species shown had a p-value of less than 0.05 and a R^2 value of greater than 0.25 when correlated with NMDS 1 or 2.

primarily through contact rather than systemic movement within the plant (Abouziena et al. 2009; Wiley 2012). Organic herbicides, like pelargonic acid, break down the plant cuticle causing cellular leakage and death (Wilen, 2012). However, this does not always reduce below-ground biomass, necessitating the need for continuous application (Carreiro et al. 2020; Manning and Miller, 2011). This may explain why organic herbicide application and mechanical removal resulted in lower efficacy in our study for reducing older and established *L. japonica* and *M. vimineum* populations.

We found here that two of the target invasive species responded differently to the three treatments. Understanding species-specific responses can lead to the development of more effective management plans to support the control of invasive plants. Adaptive control approaches can be more effective when based on individual species life history (Buhle et al. 2005; Ni et al., 2024), demographic processes (Ramula et al. 2008), and responses to different types of treatments. Reduction of *L. japonica* and *M. vimineum* was highest with synthetic herbicide applications. Mechanical removal of *L. japonica* resulted in a 1.82 % ± 1.86 sd increase in cover. Mechanical removal for *L. japonica* is ineffective especially in cases where managers are only focused on above-ground vegetation (mowing) which was the practice for our study site (Wang et al. 2012; MDC, 2012). Mowing *L. japonica* patches slows growth temporarily and limits the stem length but increases the number of stems (MDC, 2012) particularly for sites with established invasion. Organic herbicide application led to no change in cover, indicating that organic herbicide may be successful in reducing the prevalence of *L. japonica*, but not at reducing it. To decrease the use of synthetic herbicides, managers could test combinations of applications in localized and widely established sites of *L. japonica* invasion. For example, combining mechanical and organic herbicide application in younger non-established populations may yield reduction success whereas in more mature and established sites, managers could focus on testing synthetic and organic herbicide applications.

For *M. vimineum*, mechanical removal resulted in a slight increase (~1 %) in cover, while organic herbicide led to a 30 % increase in *M. vimineum* cover. Similar results were seen in a study evaluating pre-planting treatments on *M. vimineum* along the Connecticut River, USA; where a variety of synthetic herbicides showed the greatest reduction in *M. vimineum* compared to hand-pulling, mowing, heating, pelargonic acid, or vinegar (Ward and Mervosh, 2012; Brooke et al. 2015). Management of *M. vimineum* likely will be dependent upon site conditions (i.e., soil moisture, shade amount, etc.). Synthetic herbicides are highly effective, but managers looking for alternative approaches may want to try consistent hand weeding in confined invasions, repeated trimming/mowing followed by densely re-seeding bare areas with native plants, or repeated trimming/mowing with organic herbicide application in more established populations (DiTommaso, 2024; Pomp et al. 2010).

We found here that pre-planting treatments influence entire communities. While species richness of our study site at Pennypack Park was 75 % native, non-native invasive plants continue to be prevalent. The community resulting after synthetic treatment had the greatest reduction in species abundance compared to the other two communities. These results are similar to other studies that show broad spectrum herbicides, such as glyphosate, reduce species diversity (Gibson et al. 2019; Schmitz et al. 2014; Rook et al. 2011; Schutte et al., 2017). Plant community composition also responded differently to the different treatments. When evaluating how these communities changed over time, noticeable shifts in composition occurred between pre- and post-treatment communities for each management strategy. The post-treatment communities treated mechanically and with organic herbicide were similar to each other, but communities treated with synthetic herbicide diverged significantly. This is in line with other research that has shown that herbicides influence composition and can drive community changes (Sullivan and Sullivan, 2003; Ristau et al. 2011). In a 2023 study in Canada, researchers found that composition varied between non-herbicide and herbicide-treated sites a decade after application in a mixed forest (within a temperate-boreal transition zone) containing similar dominant tree species as our study (Xiao et al. 2024). However, some communities can be resilient to the impacts of herbicides (Ristau et al. 2011; Bataineh et al. 2014), so continued treatment is necessary. Our study focuses on short term compositional changes, so we may expect future compositional changes with further management.

Our data suggests that eight species significantly drove differences in community composition among time-periods and treatments: *A. brevipedunculata*, *L. tulipifera*, *L. multiflorum*, *M. vimineum*, *P. perfoliata, P. serotina*, *T. officinale*, and *T. radicans. L. multiflorum* had a strong relationship with time and a close association to pre-treatment communities as canopy gaps were seeded with *L. multiflorum* for ground cover before treatments commenced. *P. perfoliata,* a relatively common invasive plant at this site, increased in abundance in some plots, particularly under organic herbicide treatment, but overall was associated with pre-treatment communities. Post-treatment communities were associated with the following native species: *L. tulipifera*, *P. serotina* and *T. radicans*, indicating that all treatments may drive community composition towards native prevalence (Smith et al., 2022). However, *A. brevipedunculata,* a common invasive plant, was also found it to be associated with post-treatment communities, indicating that some species may not show a strong preference for treatment type (Stalter et al. 2009; Emerine and Richardson, 2011) and to manage these species, more comprehensive treatment strategies are needed.

In urban forest patches, species-specific management that focuses on above and below ground control mechanisms may be necessary. We suggest that land managers use adaptive approaches to pre-planting treatments based on specific species of concern and site conditions. From our work, we identified the need for research on how treatment timing and frequency influence the reduction of invasive plant biomass (i.e., ensuring appropriate intervals, repetitions, and seasonal applications). Further work is also needed to establish thresholds of invasive species suppression that allow for native plant regeneration. We believe that long-term control is necessary for invasive plant suppression, and multiple restoration studies have shown a need for extended efforts, particularly with herbicide use (Kettenring and Reinhardt Adams, 2011). Future research should also evaluate a broader range of organic herbicide formulations, concentrations, and application strategies to better assess their potential role in forest restoration. Determining best practices for restoration of northeastern forests remains a priority for land managers in both urban and rural landscapes. Particularly in urban settings, identifying effective restoration techniques is critical to ensure the longevity of these systems that provide ecological resources and services.

Author Statement

We, the authors would like to confirm that this manuscript presents original ecological research that has not been published previously and is not currently under consideration for publication elsewhere. All authors have contributed significantly to the design, data collection and analysis, and the interpretation of the data. All authors have reviewed and approved the manuscript.

The corresponding author has provided a declaration of interest on behalf of the authors and agrees to keep the authors informed on the process of this manuscript.

The authors would lastly like to thank the editorial team and reviewers for the dedication and consideration of our manuscript.

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.

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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.ufug.2025.129174.

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