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Efficacy of herbicides and application methods for management of midstory Callery pear (*Pyrus calleryana*)

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Abstract

Callery pear *(Pyrus calleyana* Decne.) is a problematic woody invasive plant in eastern North America that invades old fields, forests, and disturbed sites. While management guidance typically suggests foliar, basal bark, cut stump, and hack-and-squirt applications of herbicides for *P. calleryana*, there is a dearth of studies focusing on the efficacy of specific treatments. We evaluated seven herbicide treatments for control of midstory *P. calleryana*. Cut stump and hack and squirt applications of glyphosate, imazapyr, and triclopyr and a soil application of hexazinone were repeated at six sites within Georgia, Kansas, and South Carolina, and all study trees were monitored for approximately one year after herbicide application. Cut stump applications of glyphosate, imazapyr, and triclopyr provided the most consistent control with no resprouting and 100% mortality. Hack-and-squirt applications of glyphosate and triclopyr resulted in approximately 80% probability of mortality one year after treatment, while hack-and-squirt application of imazapyr and soil application of hexazinone averaged only 20 and 25% probability of mortality, respectively. Our results demonstrate the efficacy of seven treatment options for *P. calleryana* control in three geographic locations with varied habitat types, and our data suggest that cut stump applications of glyphosate, imazapyr, or triclopyr or hack-and-squirt application of glyphosate or triclopyr may be useful for reducing populations of *P. calleryana.* that have grown past the sapling stage.

Key Words: Bradford pear, cut stump, escaped ornamental, invasive species, woody invader

Management Implications

Land managers, homeowners, farmers, municipalities, and other resource professionals need reliable tools to efficiently manage *P. calleryana*. No herbicide manufacturers have specifically included *P. calleryana* in labeling. While the stem treatments in this study are well-established for woody species there are few comparative efficacy studies that managers and applicators can refer to for *P. calleryana m*anagement. Ongoing development of effective management strategies is imperative since the species continues to spread and ecological costs of invasion and economic costs of invasive species removal continue to rise. Results indicate that cut stump applications of glyphosate, imazapyr, and triclopyr yielded the most consistent and greatest efficacy, closely followed by hack-and-squirt applications of triclopyr and glyphosate. Hack-and-squirt application of imazapyr and soil application of hexazinone resulted in less consistent control with approximately 20 to 25% probability of mortality, respectively. Although cut stump applications can be labor intensive, thorny spur shoots on *P. calleryana* can limit access to the trunk and pose risk to applicators when using the hack-and-squirt technique, as well as pose a risk to tractor tires and other equipment which limit mechanical control. All of these control methods leave land managers standing dead or felled trees to deal with. These data contribute to existing recommendations of *P. calleryana* management and support the ongoing development of robust integrated pest management strategies to ultimately provide a greater number of efficient and applicable treatment options for land managers.

Introduction

Callery pear (*Pyrus calleryana* Decne.) was first introduced to the U.S. over a century ago from China to provide fire-blight resistance in European pear, *P. communis* (Creech 1973; Culley and Hardiman 2007; Cunningham 1984). After escaping cultivation, naturalized populations of *P. calleryana* were first documented in eastern Arkansas in 1964 (Vincent 2005), shortly after the first commercial cultivar (i.e., Bradford) was available. Many additional cultivars have been released since then, selected for desirable characteristics such as growth form and tolerance of a wide range of environmental conditions, and widely planted in urban areas. While self-crosses and within-cultivar crosses are not compatible, crosses between cultivars are, making areas with a diversity of cultivars within crossing distance a source of viable seed. Culley and Hardiman (2007) provide an excellent review of this and many other issues that have contributed to *P. calleryana's* success as a woody invasive. *Pyrus calleryana* is now widely distributed throughout the eastern half of North America, is expanding into several western states and Canadian provinces (Culley 2017; Culley and Hardiman 2007; EDDMapS 2024; iNaturalist 2024; Swearingen et al. 2014; Taylor et al. 1996; Vincent 2005) and is considered a legally noxious weed in Pennsylvania, Ohio, South Carolina, and Minnesota (Bradley 2021; Commonwealth of Pennsylvania 2025; Clemson University 2025; Minnesota Department of Agriculture 2025; Ohio Department of Natural Resources 2023).

Pyrus calleryana has several characteristics that make it highly invasive and difficult to manage. As such, concern has grown among landowners and land managers as *P. calleryana* has proven to be a troubling woody invasive in fields, roadsides, edge habitats, natural areas, and forest understories (Coyle et al. 2021; Swearingen et al. 2014; Woods et al. 2022). *Pyrus calleryana*

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can interfere with forest regeneration (Clabo and Clatterbuck 2020) and reforestation (Sundell et al. 1999; EM Poole and DR Coyle, pers. obs.), and its large, thorny spur shoots present a hazard to people, pets, livestock, and equipment (Coyle et al. 2021). Few herbivores feed on this species (Clem and Held 2015; Hartshorn et al. 2022), and the fruits are readily dispersed by wildlife (Clarke 2022; Reichard 2001). Additionally, the species and resulting leaf litter can alter soil ecology and nutrient cycling (Woods et al. 2021), which can aid in the species' ecological dominance in natural areas. *Pyrus calleryana* possesses high genetic diversity, suggesting high evolutionary potential in the invaded range (Sapkota et al. 2021; Sapkota et al. 2022); thus, its range is likely to continue to spread, threatening natural ecosystems (Fletcher et al. 2019) and potentially increasing costs (Pimentel et al. 2005; Pyšek et al. 2012) for land management, restoration efforts, and production forestry.

Despite the highly invasive nature of *P. calleryana*, few published management and control recommendations exist. Cutting down *P. calleryana* trees without treatment results in vigorous resprouting (Maloney et al. 2023). Prescribed fire, while a commonly used management tactic for unwanted vegetation, will top-kill the plant; however, *P. calleryana*'s vigorous resprouting makes this strategy ineffective in isolation (Maloney et al. 2023; Warrix and Marshall 2018). Recommendations frequently suggest foliar sprays, basal bark sprays, cut stump applications, and/or hack-and-squirt or frill applications depending primarily on the size of the target trees (Elmore 2019; Maloney et al. 2023; Miller et al. 2010; Quick 2021; Templeton et al. 2020; Vogt et al. 2020). However, little empirical data exists regarding management options by tree size for *P. calleryana.* Our objective was to build upon current knowledge surrounding *P. calleryana* chemical control strategies by examining the efficacy of seven herbicide treatments utilizing four commonly used active ingredients against a wide variety of midstory *P. calleryana* in several different habitat types.

Methods

In spring of 2021, six sites invaded by *P. calleryana* were identified in Georgia (2 sites), Kansas (3 sites), and South Carolina (1 site) (Table 1). Five blocks, each consisting of eight individual *P. calleryana* with a diameter at breast height (dbh) ≥ 5 cm, were established at each of the sites. Study trees were at least ten meters apart to reduce the chances of intraspecific root grafting. After spring leaf-out (April and May), crown fullness (using a visual estimate of green foliage

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present, 0-100%) and dbh were measured prior to treatment applications. All *P. calleryana* ranged from 5-36 cm dbh and appeared healthy. One tree per block was randomly assigned to each herbicide treatment, which included three cut stump applications, three hack-and-squirt applications, a soil application (Table 2) and a nontreated control. To ensure consistent application of herbicides, trees that received cut stump treatments were cut 10-15 cm from the ground with a chainsaw or heavy-duty folding saw. All herbicides used with the cut stump application were sprayed to thoroughly wet the cambium of all stems until the point of runoff immediately following cutting. Glyphosate (607.52 g L^{-1}), triclopyr (343.90 g L^{-1} acid), and imazapyr (22.47 g L^{-1} acid) were applied to cut stumps. Hack-and-squirt treatments were administered with a heavy machete by making downward angled evenly spaced cuts through the bark and into the cambium approximately 2.5 cm apart around the stem at breast height for glyphosate and imazapyr or slightly overlapping for triclopyr. Herbicide was then immediately sprayed into the cuts. Glyphosate (607.52 g L^{-1}) and triclopyr (343.90 g L^{-1} acid) were applied using 1 ml per 5.0 cm dbh and 0.5 ml in each cut, respectively. Imazapyr (22.47 g L^{-1} acid was applied at 1 ml per cut. We were interested in efficacy of the dilute solution for imazapyr application (22.47 g L^{-1} acid) over the concentrate solution (159.77 g acid equivalent L^{-1}) given the large difference between them. For the soil treatment, hexazinone (287.58 g L^{-1}) was applied within 0.9 m of the stem or root collar using an exact delivery handgun applicator (Simcro Velpar ® L VU Spotgun Applicator; https://www.cckoutfitters.com/products/datamars-syringe-simcro-velpar-applicator-15ml-spray-nozzle-large-draw-off-cap) or a syringe. All other herbicides were applied using a handheld plastic sprayer with a spray trigger at low pressure.

Data from nearby weather stations were used to estimate rainfall at sites in the 7 days before and 14 days after treatment (CoCoRaHs 2023; Georgia Forestry Commission Automated Weather Data 2024; Kansas Mesonet 2021). These data were of particular interest since hexazinone labels recommend applying product when soil is moist.

Following herbicide applications, the condition of each tree was assessed periodically, including an estimate of crown fullness and an assessment of mortality. Crown fullness was a visual estimate of expected live foliage based on branching minus dead foliage present, expressed as percent crown remaining. Two observations were made from two locations at a 90º angle and averaged. In addition, trees were considered alive if any green or subapical sprouting was present

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or if new growth was evident, and dead trees were confirmed with easily snapped twigs and scraping the bark to confirm brown, dead cambium where the bole was easily accessible. Measurement occasions, shown in Table 3, varied by site.

The experimental design was a randomized complete block design (RCBD) with repeated measures over time, replicated across six sites. As such, the design across all sites can be considered a RCBD with two blocking factors: site and block-within-site. Data were analyzed separately at two temporal endpoints: approximately 17 weeks after treatment (17WAT, corresponding to days 119, 119, 118, 124, 112, and 119 for sites Bartram1, Bartram2, JO KS, SC, SG KS, and SN KS, respectively) and at approximately one year after treatment (1YAT, corresponding to days 379, 379, 359, 377, 376, and 360 for sites Bartram1, Bartram2, JO KS, SC, SG KS, and SN KS respectively).

At each endpoint, crown percentage (crown%) was analyzed using a linear mixed effect model with a specification reflecting the experimental design. In particular, the models included fixed effects of site and treatment as well as random block-within-site effects. Because there was considerable variability in stem size among the trees used in this study, the model also included dbh and an interaction between treatment and dbh to consider the possibility of stem size-dependent treatment effectiveness. Assumptions of the model were standard; random effects for blocks and errors were assumed mutually independent with separate variance components. Models were fitted with restricted maximum likelihood, and Kenward-Roger approximate F and t tests were used for inference. In the presence of a significant treatment by dbh interaction, marginal treatment means were estimated and contrasted at low, medium and high values of dbh (specifically, at the quartiles of dbh). Contrasts included all pairwise comparisons using Tukey's Honest Significant Difference (HSD) approach to adjust for multiple comparisons.

At each endpoint, mortality was analyzed using logistic regression. However, because there were treatments with both 0% and 100% mortality, quasi-complete separation (Agresti 2013) was encountered when fitting the logistic model with standard maximum likelihood estimation, causing parameter estimates to diverge to plus or minus infinity and preventing valid model-based inference. Therefore, logistic regression models were fitted using penalized maximum likelihood estimation (aka Firth regression) (Firth 1993). This approach is a widely recommended alternative to standard logistic regression that provides finite parameter estimates and valid inference under QCS scenarios. The specification of the model was similar to the linear mixed effect models used for crown%. However, because random effects cannot be accommodated in Firth regression, site, block, treatment and dbh were modeled with fixed effects. A treatment by dbh interaction was dropped when non-significant. From the fitted model, marginal estimates of mortality probability were estimated for each treatment or, when the treatment by dbh interaction was significant, for each treatment at the quartiles of dbh. Pairwise contrasts between the treatments were tested yielding odds ratios comparing the odds of mortality across pairs of treatments. Tukey's HSD was used for inferences on pairwise odds ratios. Inferences from the Firth logistic regression model were based on penalized likelihood ratio statistics, which yield chi-square tests and intervals, and Wald Z tests.

All analyses were performed using R (R Core Team 2025). Models were fitted using the packages lme4 (Bates et al., 2015) and logistf (Heinze et al, 2025). Post-hoc inferences and plots were produced using the lmerTest (Kuznetsova et al., 2017), emmeans (Lenth, 2025) and ggplot2 (Wickham, 2016) packages. All hypothesis tests were conducted at significance level alpha=0.05 and confidence intervals were formed with a 95% confidence coefficient.

Results and Discussion

At 1YAT, the analysis of crown% revealed a significant interaction between treatment and dbh ($F(4, 133.4) = 3.26$, P = 0.014), as well as a significant main effect of treatment ($F(4, 131.0) = 75.19$, P < 0.001), representing non-equality of mean crown% at the mean dbh. Estimated marginal treatment means at the quartiles of dbh are displayed in Figure 1. Pairwise contrasts in estimated marginal treatment means at the quartiles of dbh are shown in Table 4. At the median dbh, all pairs of treatments have significantly different marginal mean crown% except imazapyr hack and squirt vs hexazinone soil treatment and glyphosate hack and squirt vs triclopyr hack and squirt.

Results for crown% at 17WAT were similar: a significant interaction between treatment and dbh ($F(4, 133.2) = 3.93$, P = 0.005) as well as a significant main effect of treatment ($F(4, 131.0) = 65.54$, P < 0.001) were found. These data highlight differences in the speed of defoliation from our treatments. Estimated marginal treatment means and contrasts among those means were similar to those at 1YAT. These results are plotted and tabulated in Supplementary Figure S1 and Supplementary Table S1, respectively.

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At 1YAT, an initial model for mortality revealed a non-significant interaction between treatment and dbh ($\chi^2(7) = 6.12$, $P = 0.526$), which was dropped from the model before re-fitting. The resulting model yielded significant effects of dbh ($\chi^2(1) = 12.44$, $P < 0.001$) and treatment ($\chi^2(7) = 166.81$, $P < 0.001$). Estimated marginal mortality probabilities for each treatment are plotted in Figure 2. Pairwise odds ratios comparing the odds or mortality for each pair of treatments are tabulated in Table 5. The odds of mortality were not found to differ significantly among any of the stump treatments plus the triclopyr and glyphosate hack and squirt treatments, which were all quite effective. The odds of mortality were also not found to differ significantly among the imazapyr hack and squirt, hexazinone soil, and control treatments, which were not effective.

An initial model for mortality at 17WAT revealed a significant interaction between treatment and dbh ($\chi^2(7) = 14.21$, $P = 0.048$) as well as a significant main effect of treatment ($\chi^2(7) = 143.54$, $P < 0.001$), implying non-homogeneity of mortality probability across treatments at the mean dbh. Estimated marginal mortality probabilities for each treatment are plotted at the quartiles of dbh in Figure 3. Smaller plants succumbed to hack-and-squirt treatments with glyphosate and triclopyr more quickly than larger plants at 17WAT (Fig. 3), but these treatments ultimately resulted in roughly 80% mortality at 1YAT (Fig. 2). Pairwise odds ratios comparing the odds of mortality for each pair of treatments at 17WAT are tabulated separately at the quartiles of dbh in Table 6.

One year after treatment, cut stump treatments using glyphosate, imazapyr, and triclopyr were the most effective method for killing *P. calleryana*, as all trees that received these treatments did not resprout and died, regardless of active ingredient. Additional observations at Bartram1 and Bartram2 in May 2025 (approximately 4 years post-treatment) found no signs of stump resprouts (C. Crowe and E. Poole, pers. obs.), which suggests success for long-term control. Glyphosate and triclopyr applied with the hack-and-squirt technique provided intermediate control (approximately 80% mortality), while results were comparatively poor using imazapyr hack-and-squirt and the soil application of hexazinone (approximately 20 and 25% mortality, respectively). Overall, our findings indicate that all tested herbicide treatments can kill *P. calleryana*, and the efficacy of the different treatments vary widely (20-100% mortality).

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We experienced several hurdles with using hexazinone soil treatment. We speculate the negligible effect of hexazinone soil applications may have been a result of less than satisfactory soil moisture conditions. Rainfall estimates at sites in the 7 days prior to hexazinone application ranged from 2.0-4.7 cm, whereas the sites received approximately 0.01-1.8 cm of rainfall in the two-week period after application. Georgia and South Carolina received the least amount of rain post application, with 0.03 cm and 0.01 cm of rain in the two weeks following hexazinone soil treatments, respectively. Manufacturers recommend the soil be moist at the time of application as well as the following two weeks, and per label recommendations, best results are seen when the soil receives approximately 0.64-1.27 cm of water in the two weeks post application (Helena Agri-Enterprises, LLC 2024). Yet, excessive soil moisture following application may also hinder efficacy. The results from hexazinone soil treatments were not entirely unexpected, as Vogt et al. (2020) described similar hurdles when using hexazinone soil treatments against *P. calleryana* understory trees. Since there are specific moisture recommendations, soil applications of hexazinone are unlikely to generate consistent results without irrigation or optimal timing and may prove to be a challenging method to utilize when managing *P. calleryana* on a large scale. Additionally, there was noticeable non-target grass dieback around the base of *P. calleryana* treated with hexazinone soil treatments in Kansas (R Armbrust, pers. obs.). While the herbicide application method is attractive due to the reduced effort and speed of application, information is needed to determine if timing of application may increase efficacy of this active ingredient.

Herbicide applications have proven to be an effective, efficient, and relatively inexpensive IPM tool (Miller et al. 2010; Terry 2018) that has been widely utilized to combat many woody invasive species in North America (Pile Knapp et al. 2023). Treatments such as foliar, basal bark, and hack-and-squirt herbicide applications have been successful on *P. calleryana* trees (Quick 2021; Terry 2018; Vogt et al. 2020), but the thorny spur shoots often present on *P. callerayana* can pose a substantial impediment to herbicide applicators. Deep incisions into the bark and cambium are needed for effective hack-and-squirt treatments, and the spur shoots, which can be several inches long, may serve as a physical risk to applicators and make the stems inaccessible or difficult to cut. Using a cut stump method can be physically demanding based on land parcel size and level of invasion and may require trimming of lower branches for access to the bole. Since no cut trees showed signs of resprout after the one-year study period, cut stump interventions with glyphosate, imazapyr, or triclopyr appear to be promising options for long-term control of midstory individual trees, and this application method has been recommended for many other woody invasive species, such as camphortree [*Cinnamomum camphora* (L.) J. Presl], invasive olives (*Elaeagnus umbellata* Thunb *and Elaeagnus angustifolia* L.), tallowtree [*Triadica sebifera* (L.) Small], and Trifoliate orange [*Poncirus trifoliata* (L.) Raf.](Miller et al. 2010). Additionally, standing dead trees may not be desirable for some land managers' objectives, so this factor along with efficacy may incentivize land managers to utilize cut stump interventions. It is important to note that any treatment method for mid-sized *P. calleryana* will leave landowners with either standing dead or downed trees to leave or dispose of, highlighting the importance of targeting *P. calleryana* before it is large and well established. Glyphosate and triclopyr applications resulted in faster mortality of smaller diameter trees, which would allow further remediation (mulching, pile and burn) sooner than larger diameter trees, with less risk of sprouting. Furthermore, research on other woody species suggests cut-stump treatments may be performed in a wide application window (Ballard and Nowack 2006, Enloe et al. 2018). Studies are needed to determine efficacy of cut stump treatments for *P. calleryana* during each season to potentially provide flexibility for treatment plans.

Due to the persistent and pervasive nature of *P. calleryana*, integrated pest management is needed to effectively target this invasive species. Herbicides are and will continue to be a critical component of IPM programs. Efforts are increasing to educate the public in hopes of reducing existing and future plantings of *P. calleryana* (Clarke et al. 2019), which will help reduce the seed source on the landscape. However, nurseries and retailers are still selling Bradford pear and other *P. calleryana* cultivars (EM Poole and DR Coyle, personal observation). Reducing and eliminating new plantings of *P. calleryana* is essential to a successful IPM program, especially since prior studies have found that its seeds are easily dispersed and can persist in the seed bank for many years (Serota and Culley 2019). Warrix and Marshall (2018) have delineated the application of prescribed fire alone to fruits, seeds, and one year old seedlings in prairie ecosystems in the Midwest region of the US. Efforts are ongoing to understand seed viability, germination rates and potential use of prescribed fire for managing seedlings and saplings in the southeastern US. However, even with other cultural interventions, we speculate that careful use of herbicides will still play a large role in IPM approach for established *P. calleryana* (Flynn et al. 2015, Warrix and Marshall 2018), as seen with management of other woody invasive species like Chinese privet (*Ligustrum sinense* Loureiro) (Hanula et al. 2009), invasive honeysuckles

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(*Lonicera* sp.), Chinaberry *(Melia azedarach* L.*),* and Tallowtree [*Triadica sebifera* (L.) Small] (Miller at al. 2010). Altogether, our study tested the effectiveness of seven herbicide treatments against *P. calleryana* in common habitats such as fields, pine stands, mixed stands, and flood plains. Although the study herein encompasses sites in the southeast and midwest, instead of the entire range of *P. calleryana* in the eastern half of the US, we anticipate that results would be comparable in the northern extent of *P. calleryana's* range. For a comprehensive IPM plan additional research is needed to confirm long-lasting effects of these treatments in the full range of *P. calleryana* in the US and to identify any potential synergistic effects when existing treatments are combined with other management strategies.

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Conflicts of Interest

No conflicts of interest have been declared.

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Table 1. Site descriptions for a midstory *Pyrus calleryana* management study. Climate data for county-level mean annual temperature and precipitation were obtained from National Oceanographic and Atmospheric Administration, National Centers for Environmental Information (2023), and soil types were obtained from United States Department of Agriculture, Natural Resources Conservation Service (2020).

Site name	State	County	Coordinates	Site Description	Common Woody Vegetation Present	Soil Types	Mean annual temperature (°C)	Mean annual precipitation (m)
Bartram Forest Wildlife Management Area (1)	Georgia	Baldwin	33° 00’ 01” N, -83° 12’ 48” W	Managed pine stand thinned to approx. 24-28 trees ha. $^{-1}$ with a 3-year controlled burn rotation	Loblolly and slash pine (*Pinus taeda* L. and *Pinus elliottii* Engelm.) with average dbh 25-30 cm. Understory was mostly Callery pear (*Pyrus calleryana* Decne.) with some sweetgum (*Liquidambar styraciflua* L.), winged sumac (*Rhus copallinum* L.), black cherry (*Prunus serotina* Ehrh.), winged elm (*Ulmus alata* Michx.), and American beautyberry (*Callicarpa americana* L.).	Well-drained Norfolk loamy sand	17.2	1.08
Bartram Forest Wildlife Management Area (2)	Georgia	Baldwin	33° 00’ 01” N, -83° 12’ 48” W	Rolling floodplain below earthen dam	Callery pear; other vegetation included red maple (*Acer rubrum* L.), loblolly pine, and water oak (*Quercus nigra* L.).	Highly disturbed well-drained Norfolk loamy sand	17.2	1.08

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Chisholm Creek Park	Kansas	Sedgwick	37° 44’ 21” N, -97° 15’ 49” W	Mostly flat natural area bisected with a small creek	Predominantly woody, with Callery pear, eastern red cedar (*Juniperus virginiana* L.), ash (*Fraxinus* sp.), bush honeysuckle (*Lonicera* sp.), tree-of-heaven [*Ailanthus altissima* (Mill.) Swingle], elm (*Ulmus* sp.), Chinese pistache (*Pistacia chinensis* Bunge), osage-orange (*Maclura pomifera* Raf.), and dogwood (*Cornus* sp.).	Tabler silty clay loam with a small portion in Farnum loam	13.3	0.87
Shawnee Mission Park	Kansas	Johnson	38° 58’ 22” N, -94° 48’ 10” W	Rolling hillside slope above a small pond. Prior use was as a cool-season brome pasture	Callery pear, scattered honeylocust (*Gleditsia triacanthos* L.), osage-orange, and dogwood.	Martin silty clay loam and Chillicoth silt loam	13.06	1.02
Warren Nature Area	Kansas	Shawnee	39° 1’ 17” N, -95° 43’ 02” W	Flat field of warm season grass with trails; Mowed about 3 years prior to study	Callery pear, scattered ash, elm, oak (*Quercus* sp.), American sycamore (*Platanus occidentalis* L.), and other hardwoods.	Ladysmith and Reading silty clay loams	12.78	0.93
Manchester State Forest	South Carolina	Sumter	33° 53' 51" N, -80° 30' 55" W	20-year-old pine forest that was thinned to approx. 300 stems ha. $^{-1}$ 15 years before the study.	Loblolly pine, Callery pear, water oak, and Chinese privet (*Ligustrum sinense* Loureiro) in the understory.	Faceville sandy loam and Orangeburg loamy sand	16.67	1.19

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Table 2. Trade names, active ingredients, and treatment application methods used to evaluate *Pyrus calleryana* control at sites in Georgia, Kansas, and South Carolina, U.S.

Application Method	Active Ingredient	Trade name	Manufacturer, City, State, Website	Grams active ingredient L^{-1} finished solution	Dilution (%v/v)
Cut stump	Glyphosate	Accord® XRT II	Corteva Agriscience, Indianapolis, IN https://www.corteva.us	607.52	100
Cut stump	Imazapyr	Arsenal®	BASF Corp., Research Triangle Park, NC, https://bettervm.basf.us	22.47 (acid equivalent)	9.38
Cut stump	Triclopyr	Trycera®	Helena Chemical Co., Collierville, TN, https://www.helenaagri.com/	343.90 (acid equivalent)	100
Hack-and-squirt	Glyphosate	Accord® XRT II	Corteva Agriscience, Indianapolis, IN, https://www.corteva.us	607.52	100
Hack-and-squirt	Imazapyr	Arsenal®	BASF Corp., Research Triangle Park, NC, https://bettervm.basf.us	22.47 (acid equivalent)	9.38
Hack-and-squirt	Triclopyr	Trycera®	Helena Chemical Co., Collierville, TN, https://www.helenaagri.com/	343.90 (acid equivalent)	100
Soil application	Hexazinone	Velossa®	Helena Chemical Co., Collierville, TN, https://www.helenaagri.com/	287.58	100
Nontreated control	---	---	---	---	---

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Table 3. Measurement occasions for *Pyrus calleryana* assessments following herbicide treatments at six sites.

Site	Treatment date	DAT[a]							
Bartram1	04/07/2021	0	91	119	154	195	379	---	---
Bartram2	04/07/2021	0	91	119	154	195	379	---	---
JO KS	07/13/2021	0	23	62	90	118	359	---	---
SC	05/13/2021	0	20	54	90	124	148	191	357
SG KS	06/24/2021	0	32	50	89	112	145	376	---
SN KS	07/12/2021	0	24	63	91	119	360	---	---

[a]DAT, days after treatment

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Table 4. Results for crown%[1] at 1YAT[2] for *Pyrus calleryana* following application of four herbicidal treatments plus nontreated control at sites in GA, SC, and KS. Pairwise contrasts among estimated marginal treatment means at the quartiles of dbh[3]. P-values are adjusted for multiplicity with Tukey's HSD method.

dbh	Contrast	Estimate	df	t-ratio	p
7.6	imazapyrHS - glyphosateHS	29.85	131	4.21	0.001
7.6	imazapyrHS - triclopyrHS	30.56	132	4.20	0.001
7.6	imazapyrHS - hexazinone	6.00	132	0.82	0.923
7.6	imazapyrHS - control	-61.15	133	-8.19	<.0001
7.6	glyphosateHS - triclopyrHS	0.71	132	0.10	1.000
7.6	glyphosateHS - hexazinone	-23.84	131	-3.36	0.009
7.6	glyphosateHS - control	-90.99	132	-12.39	<.0001
7.6	triclopyrHS - hexazinone	-24.56	132	-3.37	0.009
7.6	triclopyrHS - control	-91.71	132	-12.23	<.0001
7.6	hexazinone - control	-67.15	132	-8.92	<.0001
10.2	imazapyrHS - glyphosateHS	31.28	131	5.05	<.0001
10.2	imazapyrHS - triclopyrHS	32.19	131	5.23	<.0001
10.2	imazapyrHS - hexazinone	0.48	131	0.08	1.000
10.2	imazapyrHS - control	-58.88	131	-9.50	<.0001
10.2	glyphosateHS - triclopyrHS	0.90	131	0.15	1.000
10.2	glyphosateHS - hexazinone	-30.81	131	-4.95	<.0001
10.2	glyphosateHS - control	-90.16	131	-14.45	<.0001
10.2	triclopyrHS - hexazinone	-31.71	131	-5.12	<.0001
10.2	triclopyrHS - control	-91.07	131	-14.69	<.0001
10.2	hexazinone - control	-59.36	131	-9.50	<.0001
13.8	imazapyrHS - glyphosateHS	33.28	131	5.30	<.0001
13.8	imazapyrHS - triclopyrHS	34.44	132	5.29	<.0001
13.8	imazapyrHS - hexazinone	-7.18	131	-1.13	0.792
13.8	imazapyrHS - control	-55.74	132	-8.58	<.0001
13.8	glyphosateHS - triclopyrHS	1.17	132	0.18	1.000
13.8	glyphosateHS - hexazinone	-40.45	131	-6.56	<.0001
13.8	glyphosateHS - control	-89.01	132	-14.10	<.0001
13.8	triclopyrHS - hexazinone	-41.62	131	-6.51	<.0001
13.8	triclopyrHS - control	-90.18	132	-13.80	<.0001
13.8	hexazinone - control	-48.56	131	-7.59	<.0001

[1]crown%; percent crown fullness

[2]1YAT; approximately one year after treatment.

[3]dbh; diameter at breast height in cm.

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Table 5. Estimated marginal mortality probabilities at 1YAT[1] for *Pyrus calleryana* following application of four herbicidal treatments plus a nontreated control at sites in GA, SC, and KS. Tests correspond to the null hypothesis that the odds ratio is 1. P-values are adjusted for multiplicity with Tukey's HSD method.

Contrast	Odds ratio	z	P
glyphosateStump - imazapyrStump	1.44	0.26	1.000
glyphosateStump - triclopyrStump	0.76	-0.19	1.000
glyphosateStump - imazapyrHS	263.00	4.73	0.000
glyphosateStump - glyphosateHS	14.80	2.41	0.242
glyphosateStump - triclopyrHS	18.70	2.63	0.153
glyphosateStump - hexazinone	184.00	4.55	0.000
glyphosateStump - control	10000.00	5.62	<.0001
imazapyrStump - triclopyrStump	0.53	-0.44	1.000
imazapyrStump - imazapyrHS	183.00	4.60	0.000
imazapyrStump - glyphosateHS	10.20	2.14	0.395
imazapyrStump - triclopyrHS	13.00	2.38	0.259
imazapyrStump - hexazinone	127.00	4.38	0.001
imazapyrStump - control	6960.00	5.57	<.0001
triclopyrStump - imazapyrHS	346.00	4.78	0.000
triclopyrStump - glyphosateHS	19.40	2.57	0.174
triclopyrStump - triclopyrHT	24.50	2.77	0.110
triclopyrStump - hexazinone	241.00	4.61	0.000
triclopyrStump - control	13200.00	5.63	<.0001
imazapyrHS - glyphosateHS	0.06	-4.26	0.001
imazapyrHS - triclopyrHS	0.07	-4.06	0.002
imazapyrHS - hexazinone	0.70	-0.59	0.999
imazapyrHS - control	38.00	3.02	0.056
glyphosateHS - triclopyrHS	1.26	0.39	1.000
glyphosateHS - hexazinone	12.40	3.98	0.002
glyphosateHS - control	679.00	5.03	<.0001
triclopyrHS - hexazinone	9.83	3.75	0.006
triclopyrHS - control	537.00	4.92	<.0001
hexazinone - control	54.60	3.25	0.029

[1] 1YAT; approximately one year after treatment

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Table 6. Estimated marginal mortality probabilities at 17WAT[1] for *Pyrus calleryana* following application of four herbicidal treatments plus a nontreated control at sites in GA, SC, and KS. Pairwise contrasts among estimated marginal mortality probabilities for each treatment at the quartiles of dbh[2]. Tests correspond to the null hypothesis that the odds ratio is 1. P-values are adjusted for multiplicity with Tukey's HSD method.

dbh	Contrast	Odds ratio	z	P
7.6	glyphosateStump - imazapyrStump	1.19	0.12	1.000
7.6	glyphosateStump - triclopyrStump	1.01	0.01	1.000
7.6	glyphosateStump - imazapyrHS	5140.00	5.27	<.0001
7.6	glyphosateStump - glyphosateHS	120.00	3.41	0.017
7.6	glyphosateStump - triclopyrHS	24.60	2.35	0.274
7.6	glyphosateStump - hexazinone	1900.00	4.89	0.000
7.6	glyphosateStump - control	30000.00	5.66	<.0001
7.6	imazapyrStump - triclopyrStump	0.85	-0.11	1.000
7.6	imazapyrStump - imazapyrHS	4310.00	5.28	<.0001
7.6	imazapyrStump - glyphosateHS	100.00	3.36	0.021
7.6	imazapyrStump - triclopyrHS	20.60	2.29	0.306
7.6	imazapyrStump - hexazinone	1590.00	4.87	0.000
7.6	imazapyrStump - control	25100.00	5.69	<.0001
7.6	triclopyrStump - imazapyrHS	5070.00	5.29	<.0001
7.6	triclopyrStump - glyphosateHS	118.00	3.42	0.017
7.6	triclopyrStump - triclopyrHT	24.30	2.36	0.267
7.6	triclopyrStump - hexazinone	1880.00	4.90	0.000
7.6	triclopyrStump - control	29600.00	5.67	<.0001
7.6	imazapyrHS - glyphosateHS	0.02	-3.80	0.005
7.6	imazapyrHS - triclopyrHS	0.01	-4.50	0.000
7.6	imazapyrHS - hexazinone	0.37	-1.13	0.950
7.6	imazapyrHS - control	5.82	1.49	0.814
7.6	glyphosateHS - triclopyrHS	0.21	-1.75	0.658
7.6	glyphosateHS - hexazinone	15.90	3.13	0.042
7.6	glyphosateHS - control	251.00	4.32	0.001
7.6	triclopyrHS - hexazinone	77.20	3.98	0.002

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7.6	triclopyrHS - control	1220.00	4.93	<.0001
7.6	hexazinone - control	15.70	2.32	0.291
10.2	glyphosateStump - imazapyrStump	1.52	0.33	1.000
10.2	glyphosateStump - triclopyrStump	0.98	-0.01	1.000
10.2	glyphosateStump - imazapyrHS	2350.00	5.64	<.0001
10.2	glyphosateStump - glyphosateHS	132.00	4.02	0.002
10.2	glyphosateStump - triclopyrHS	78.10	3.72	0.006
10.2	glyphosateStump - hexazinone	1180.00	5.30	<.0001
10.2	glyphosateStump - control	8290.00	5.92	<.0001
10.2	imazapyrStump - triclopyrStump	0.65	-0.35	1.000
10.2	imazapyrStump - imazapyrHS	1540.00	5.84	<.0001
10.2	imazapyrStump - glyphosateHS	86.90	4.05	0.002
10.2	imazapyrStump - triclopyrHS	51.30	3.73	0.006
10.2	imazapyrStump - hexazinone	773.00	5.46	<.0001
10.2	imazapyrStump - control	5450.00	6.07	<.0001
10.2	triclopyrStump - imazapyrHS	2390.00	5.66	<.0001
10.2	triclopyrStump - glyphosateHS	135.00	4.03	0.002
10.2	triclopyrStump - triclopyrHT	79.50	3.75	0.006
10.2	triclopyrStump - hexazinone	1200.00	5.32	<.0001
10.2	triclopyrStump - control	8440.00	5.94	<.0001
10.2	imazapyrHS - glyphosateHS	0.06	-3.57	0.011
10.2	imazapyrHS - triclopyrHS	0.03	-3.91	0.003
10.2	imazapyrHS - hexazinone	0.50	-0.94	0.982
10.2	imazapyrHS - control	3.53	1.28	0.904
10.2	glyphosateHS - triclopyrHS	0.59	-0.75	0.995
10.2	glyphosateHS - hexazinone	8.90	2.90	0.077
10.2	glyphosateHS - control	62.70	3.96	0.003
10.2	triclopyrHS - hexazinone	15.10	3.30	0.025
10.2	triclopyrHS - control	106.00	4.27	0.001
10.2	hexazinone - control	7.05	1.98	0.501
13.8	glyphosateStump - imazapyrStump	2.13	0.62	0.999
13.8	glyphosateStump - triclopyrStump	0.94	-0.05	1.000
13.8	glyphosateStump - imazapyrHS	794.00	5.77	<.0001

13.8	glyphosateStump - glyphosateHS	152.00	4.42	0.000
13.8	glyphosateStump - triclopyrHS	386.00	4.68	0.000
13.8	glyphosateStump - hexazinone	605.00	5.60	<.0001
13.8	glyphosateStump - control	1400.00	5.87	<.0001
13.8	imazapyrStump - triclopyrStump	0.44	-0.68	0.997
13.8	imazapyrStump - imazapyrHS	372.00	5.14	<.0001
13.8	imazapyrStump - glyphosateHS	71.40	3.71	0.007
13.8	imazapyrStump - triclopyrHS	181.00	4.10	0.002
13.8	imazapyrStump - hexazinone	284.00	4.98	<.0001
13.8	imazapyrStump - control	657.00	5.45	<.0001
13.8	triclopyrStump - imazapyrHS	844.00	5.81	<.0001
13.8	triclopyrStump - glyphosateHS	162.00	4.50	0.000
13.8	triclopyrStump - triclopyrHT	410.00	4.74	0.000
13.8	triclopyrStump - hexazinone	643.00	5.69	<.0001
13.8	triclopyrStump - control	1490.00	5.96	<.0001
13.8	imazapyrHS - glyphosateHS	0.19	-1.92	0.542
13.8	imazapyrHS - triclopyrHS	0.49	-0.73	0.996
13.8	imazapyrHS - hexazinone	0.76	-0.36	1.000
13.8	imazapyrHS - control	1.76	0.64	0.998
13.8	glyphosateHS - triclopyrHS	2.53	0.92	0.984
13.8	glyphosateHS - hexazinone	3.98	1.73	0.669
13.8	glyphosateHS - control	9.20	2.29	0.302
13.8	triclopyrHS - hexazinone	1.57	0.47	1.000
13.8	triclopyrHS - control	3.63	1.19	0.934
13.8	hexazinone - control	2.31	0.96	0.979

[1]17WAT; approximately 17 weeks after treatment.[2]dbh; diameter at breast height (cm).

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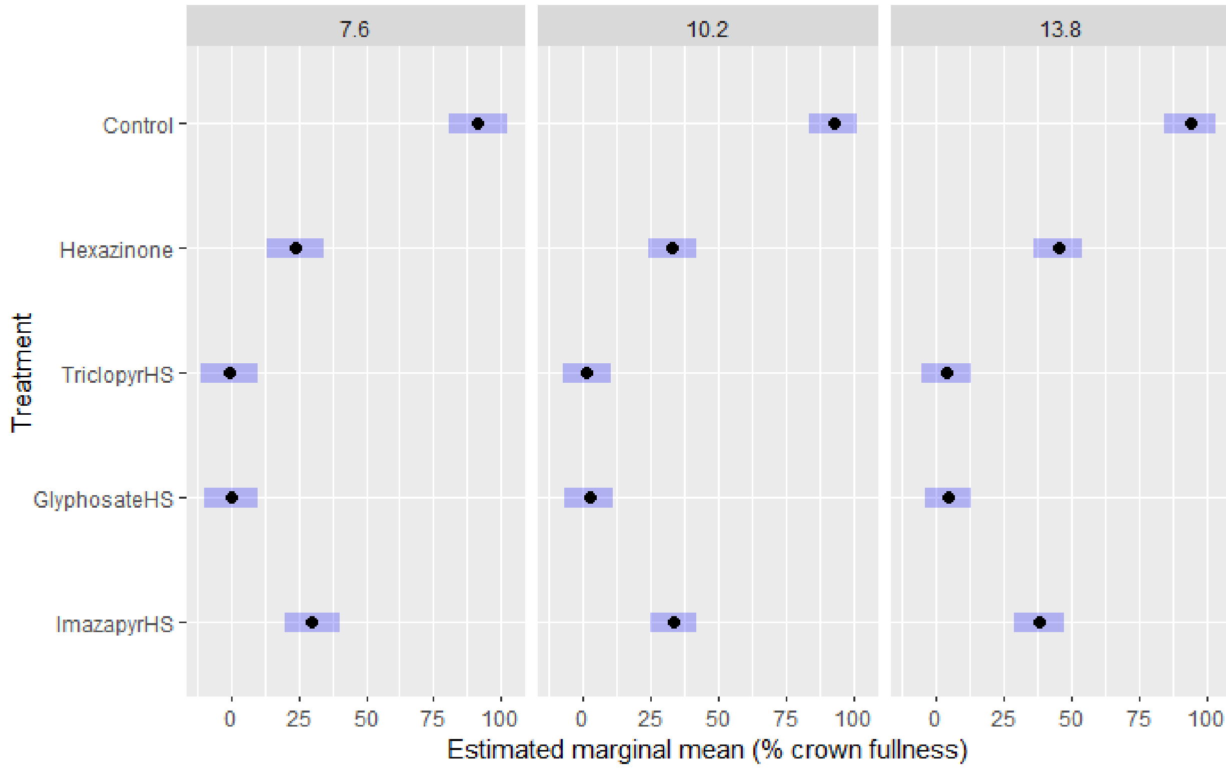

Figure 1. Estimated marginal means and 95% confidence intervals for percent crown fullness of *Pyrus calleryana* at approximately one year after application of four herbicide treatments; imazapyr, glyphosate, and triclopyr hack-and-squirt applications (appended with -HS), a hexazinone soil treatment, and a nontreated control. Means are estimated across quartiles of diameter at breast height (dbh; 7.6, 10.2, and 13.8 cm).

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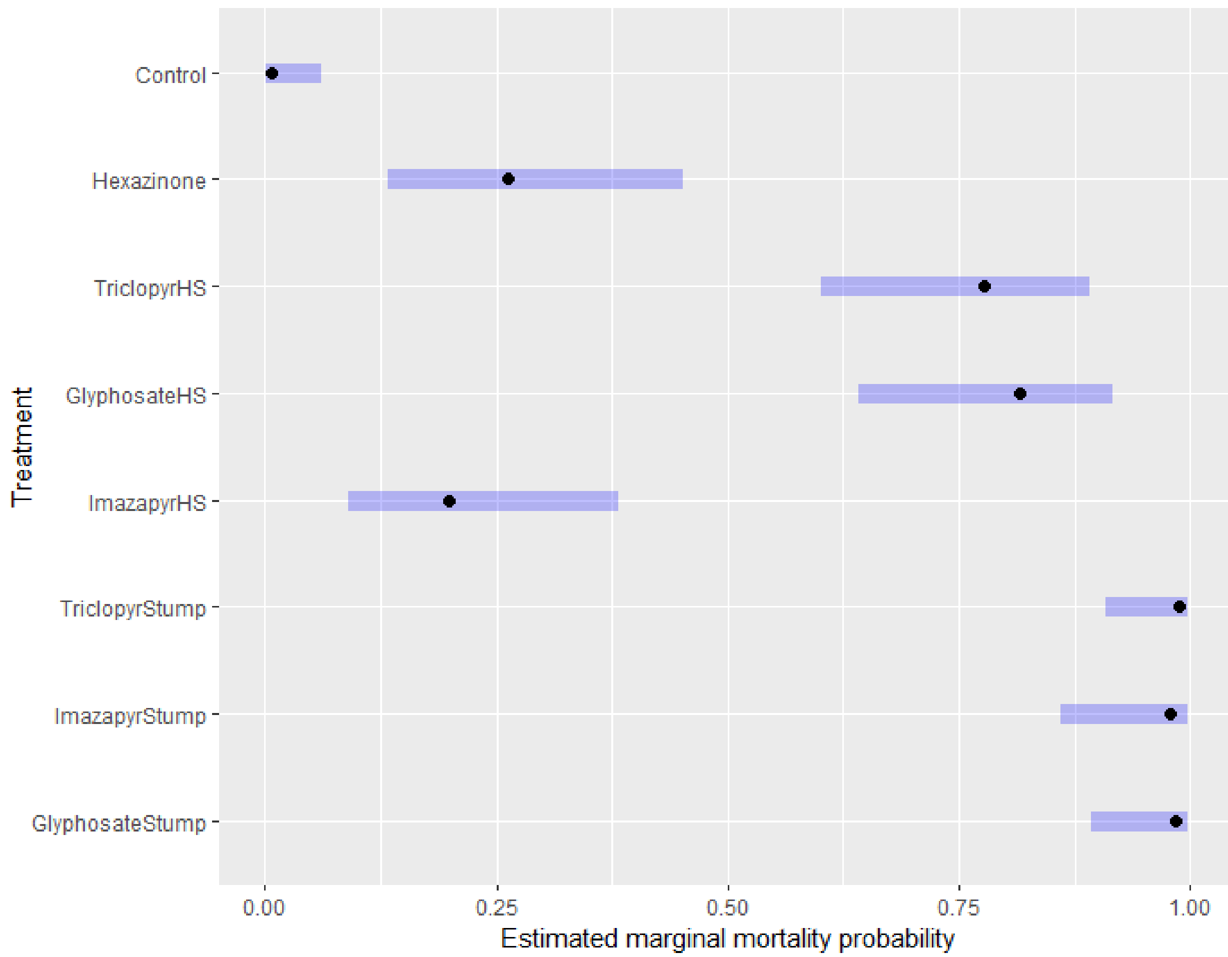

Figure 2. Estimated marginal means and 95% confidence intervals for probability of mortality in *Pyrus calleryana* at approximately one year after application of seven herbicide treatments; a hexazinone soil treatment, triclopyr, glyphosate, and imazapyr hack-and-squirt applications (appended with -HS), triclopyr, imazapyr, and glyphosate cut-stump applications (appended with -Stump), and a nontreated control.

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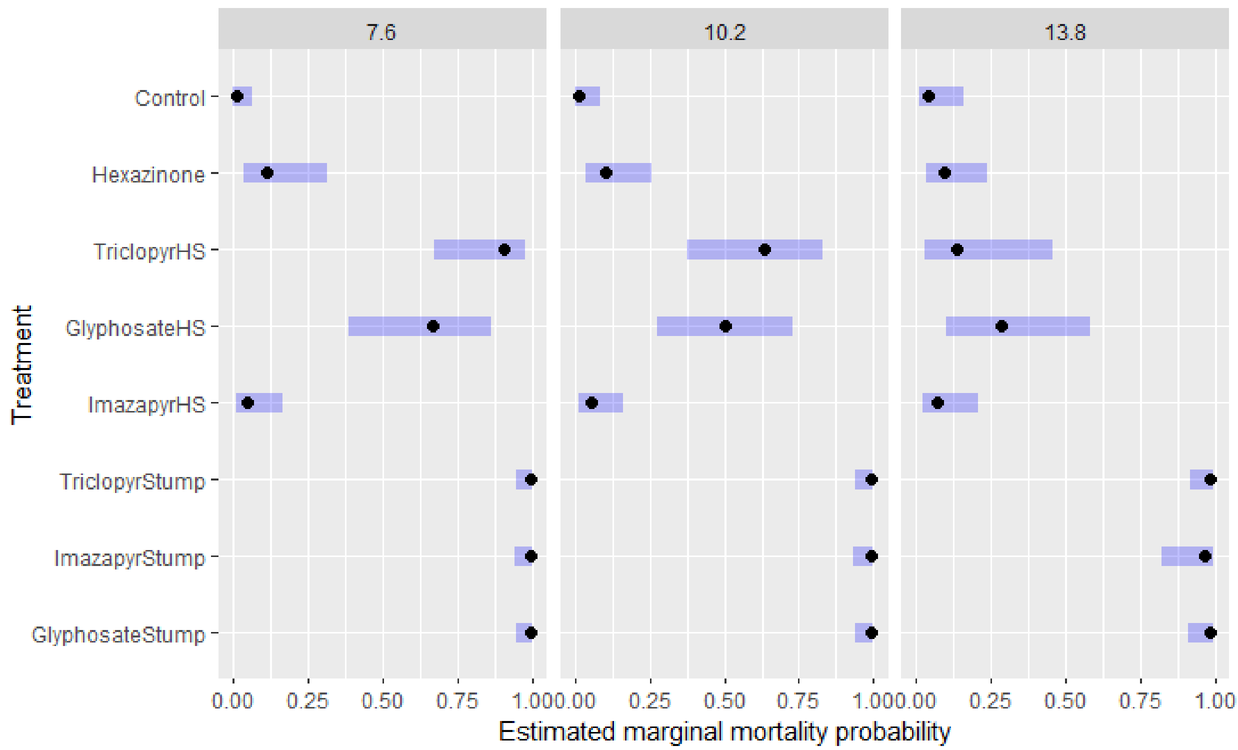

Figure 3. Estimated marginal means and 95% confidence intervals for probability of mortality in *Pyrus calleryana* at approximately 17 weeks after application of seven herbicide treatments; a hexazinone soil treatment, triclopyr, glyphosate, and imazapyr hack-and-squirt applications (appended with -HS), triclopyr, imazapyr, and glyphosate cut-stump applications (appended with -Stump), and a nontreated control. Means are estimated across quartiles of diameter at breast height (dbh; 7.6, 10.2, and 13.8 cm).