Mulch Type and Depth, Herbicide Formulation, and Postapplication Irrigation Volume Influence on Control of Common Landscape Weed Species

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Summary. Mulch is often applied in landscape planting beds for weed control, but little research has focused specifically on mulch and preemergence (PRE) herbicide combinations. The objectives of this research were to determine the efficacy of herbicide + mulch combinations and which factors significantly affected weed control, including herbicide formulation and posttreatment irrigation volumes. Additional objectives were to determine efficacy derived from mulch or herbicides used alone under herbicide + mulch combinations and to identify differences in the additive (herbicide + mulch combinations) or singular (herbicide or mulch) effects compared with the use of herbicides or mulch only. Large crabgrass (*Digitaria sanguinalis*), garden spurge (*Euphorbia hirta*), and eclipta (*Eclipta prostrata*) were used as bioassay species for prodiamine, dimethenamid-P + pendimethalin, and indaziflam efficacy, respectively. The experiment consisted of a factorial treatment arrangement of two herbicide formulations (granular or spray applied), three mulch types [hardwood chips (HWs), pine bark (PB), and pine straw (PS)], two mulch depths (1 and 2 inches), and three levels of one-time, posttreatment irrigation volumes (0.5, 1, and 2 inches). Three sets of controls were used: the first set included three mulch types applied at two depths receiving only 0.5-inch irrigation volume, the second set included only two herbicide formulations and three one-time irrigation volumes, whereas the last set received no treatment (no herbicide or mulch) and only 0.5-inch irrigation volume. High levels of large crabgrass and garden spurge control (88% to 100%) were observed with all herbicide + mulch combinations evaluated at mulch depths of 1 inch or greater. When comparing mulch types, the best eclipta control was achieved with hardwood at 2 inches depth. The spray formulation of indaziflam outperformed the granular formulation in most cases when used alone or in combination with mulch. Overall, the results showed that spray formulations of prodiamine and dimethenamid-P + pendimethalin were more effective than granular formulations when applied alone, whereas indaziflam was more effective as a spray formulation when used both alone and in combination with mulch. Increasing irrigation volume was not a significant factor for any of the herbicide + mulch combinations when evaluating overall weed control.

Mulch provides many benefits to landscape ornamentals, including soil temperature regulation (Fraedrich and Ham, 1982; Montague and Kjelgren, 2004), increased soil moisture (Fraedrich and Ham, 1982; Iles and Dosmann, 1999; Kraus, 1998; Litzow and Pellett, 1993; Watson, 1988; Watson and Kupkowski, 1991), and improved overall plant growth and survival (Green and Watson, 1989; Greenly and Rakow, 1995; Litzow and Pellett, 1993). Similarly, mulch increases the growth of container-grown ornamentals by providing the same benefits in a production (i.e., nursery) environment (Amoroso et al., 2010; Lohr, 2001).

Mulch is most often applied in landscape planting beds for aesthetic purposes and for weed management (Chalker-Scott, 2007). Mulch is less commonly used in container nursery production but may be used as a nonchemical weed management option for sensitive plant species (Case et al., 2005). Many different mulch materials have been evaluated for weed control in container plants. Richardson et al. (2008) reported up to 150 d of yellow woodsorrel (*Oxalis stricta*) and hairy bittercress (*Cardamine hirsuta*) control in large (3–7 gal) container-grown ornamentals with 3 inches of PB mini-nuggets. Similarly, Cochran et al. (2009) showed that 1 inch of PB mulch reduced garden spurge and eclipta fresh weights (FWs) and weed counts by more than 80% compared with a nonmulched control. Reviews of different mulch materials as a sole means for weed control have been summarized for landscape (Chalker-Scott, 2007) and nursery production (Case et al., 2005).

A review of earlier research focusing on the use of mulch in combination with, or in comparison with, PRE herbicides was recently published by Marble (2015). In many cases, research focused on evaluating different mulch or herbicide + mulch combinations to determine the most effective on target weed species, or evaluated the use of herbicide-treated mulches (Case and Mathers, 2006a, 2006b). For example, Bartley et al. (2017) evaluated three different mulch types applied at three depths (1, 2, and 4 inches) with and without addition of dimethenamid-P. The authors reported that 168 d after treatment (DAT), herbicide was no longer a significant factor as dimethenamid-P had lost all efficacy, and mulch depth was the only significant factor, with depths of 1–4 inches providing 90% to 100% spotted spurge (*Euphorbia maculata*) control for up to 90 d after seeding. All of these previous reports establish that different herbicide + mulch combinations can potentially provide a high

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
3.7854	gal	L	0.2642
9.3540	gal/acre	$L \cdot ha^{-1}$	0.1069
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
0.5933	$lb/yard^3$	$kg \cdot m^{-3}$	1.6856
1.6093	mph	$km \cdot h^{-1}$	0.6214
28.3495	oz	g	0.0353
6.8948	psi	kPa	0.1450
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

level of control of many different weed species.

Previous studies have shown that mulch can provide substantial weed control when applied alone at adequate depths (Cochran et al., 2009; Richardson et al., 2008; Wilen et al., 1999); however, it is unclear whether it is mulch or herbicide that contributed most to the observed weed control. Furthermore, a decrease in herbicide efficacy with certain herbicides such as dinitroanilines, which bind tightly to mulch, can occur with increased levels of organic matter on the soil surface. Consequently, the herbicide becomes unavailable for weed control (Buhler, 1992). Mulch depth is an important factor to consider as research conducted by Banks and Robinson (1986) and Chauhan and Abugho (2012) showed that application of thin mulch layers reduces PRE efficacy in several agronomic studies because of rapid degradation caused by increased microbial activity (Locke and Bryson, 1997). Alternatively, herbicide placement (i.e., application of herbicides under mulch) or making the application before mulch addition improves weed control compared with PRE application on top of mulch (Chen et al., 2013). However, in most landscape situations, this application could only be made initially, and subsequent applications would have to be applied on top of existing mulch layers.

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Increasing posttreatment irrigation levels to mulched areas could be a means of increasing herbicide concentrations in the soil as PRE herbicides must be incorporated into the soil by irrigation following application. In most cases, PRE herbicide labels recommend irrigation volumes of 0.2–0.5 inches soon after application. Banks and Robinson (1986) reported that reduced amounts of acetochlor, alachlor, or metolachlor were received on the soil surface as wheat (*Triticum aestivum*) straw mulch depth increased, resulting in the need for higher irrigation volumes for thicker mulch layers. However, wheat straw has very different physical properties compared with common landscape mulch materials, and the herbicides that were evaluated are not commonly applied in landscape situations. Additional research is required to determine the extent to which activation irrigation can improve the efficacy of different herbicide + mulch combinations commonly used in landscapes and container nurseries. This experiment was designed to accomplish three primary objectives. First, we wanted to determine the efficacy of multiple herbicide + mulch combinations and determine which factors significantly affected the control, specifically focusing on herbicide formulation and posttreatment irrigation volumes. Second, we wanted to determine the efficacy derived from mulch or herbicides used alone under the same conditions as the herbicide + mulch combinations. Third, our goal was to identify differences in the additive effects of the herbicide + mulch combinations compared with the use of only herbicides or only mulch.

Materials and methods

Greenhouse experiments were conducted at the Mid-Florida Research and Education Center in Apopka, FL, in 2016 and 2017. Square black plastic nursery containers [4 inches (width) × 4 inches (length) × 5 inches (height) dimensions] were filled with PB:peat mix (Fafard®52 Growing Mix; Sun Gro Horticulture, Agawam, MA) amended with 8 lb/yard^3 controlled-release fertilizer [15N–3.9P–9.9K (Osmocote® Plus; Everris, Geldermalsen, The Netherlands)] based on the manufacturer's recommended medium rate for incorporation. About 35 seeds of large crabgrass, garden spurge, or eclipta were then surface-sown to the filled containers. All emerged weeds were allowed to grow for the duration of the experiment. Large crabgrass seeds were supplied by Azlin Seed Services (Leland, MS), whereas eclipta and garden spurge seeds were collected from the natural population present at the Mid-Florida Research and Education Center. Following seeding, three different mulch types, including PS (Pine Straw of Central Florida, Winter Garden, FL), PB mini-nuggets (Timberline; Old Castle Lawn & Garden, Atlanta, GA), or HWs (Florida Select Natural Eucalyptus Mulch; Scotts®, Marysville, OH), were applied to containers at depths of 0, 1, or 2 inches. Particle size distribution for each mulch type was determined. Particle size was determined for each mulch material using established methodology (Bilderback et al., 2005). Four samples of mulch material were collected randomly from different bags (HW and PB) or bales (PS) and air-dried in the laboratory for 7 d at 22 °C at which time a constant weight was achieved. From each sample, four 100-g samples were measured out for each mulch type and hand-shaken through a series of soil sieves (W.S. Tyler, Mentor, OH) ranging from 1 to 25 mm for 3 min. Mulch that was retained in each sieve was weighed and the percentage of the total mulch mass was calculated for each screen size and the pan [<1 mm (Fig. 1)]. More than 50% of PB and PS particles were retained in the 25-mm sieve. Only 11% of HW particles were retained in the largest screen, indicating that it had a higher percentage of smaller particles, which would be expected from a shredded-wood mulch. Shallow mulch depths of 1 and 2 inches were chosen as deeper mulch depths (e.g., 4 inches or greater) have been associated with increased exposure to pathogens, decreased ornamental plant growth, or both (Bartley et al., 2017; Chalker-Scott, 2007; Koski and Jacobi, 2004). In addition to negative impacts associated with high mulch depths, lower mulch depths were chosen to more closely evaluate herbicide + mulch combinations. Mulch applied alone (without the addition of a herbicide) at depths of 3–4 inches is often sufficient for season-long weed control

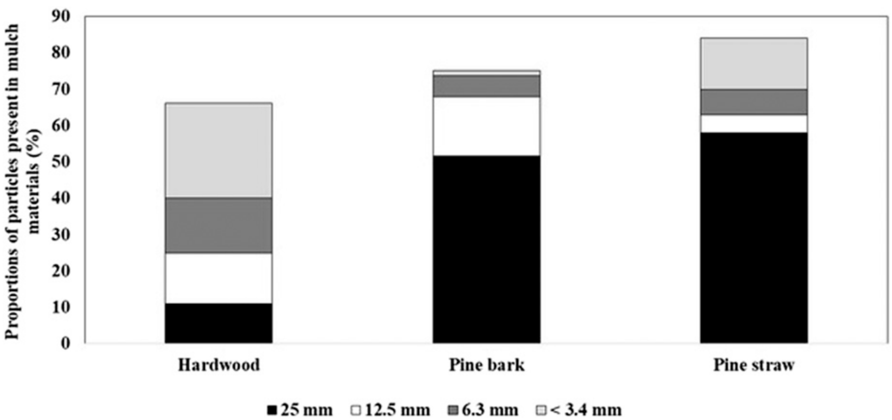

Fig. 1. Different particle sizes present in hardwood, pine bark, and pine straw mulch materials after screening through soil sieves; 1 mm = 0.0394 inch.

(Bartley et al., 2017; Richardson et al., 2008), which could potentially reduce the ability to determine what effects herbicides may have when used in combination with mulch. Mulch applied at 2 inches is also often used as standard mulch depth in the landscape industry. In the nursery industry, mulch may be applied at depths up to 2 inches but is rarely applied at a higher depth because greater mulch depths would require more space in a container and thus limit the potential root area in a pot. Depths of 1–2 inches were chosen to closely evaluate herbicide and mulch effects and also chose depths that would be used in both the landscape and nursery and landscape industries.

Liquid or granular formulations of indaziflam (Marengo® 0.622 SC and Marengo® 0.0224 G; Bayer Crop Science, Research Triangle Park, NC), prodiamine [Barricade® 4 FL (Syngenta Crop Protection, Greensboro, NC) and RegalKade® 0.5 G (Regal Chemical Co., Alpharetta, GA)], and dimethenamid-P + pendimethalin (Tower® 6 EC + Pendulum® 3.3 EC and Freehand® 1.75 G; BASF Corp., Research Triangle Park, NC) were applied on 17 Aug. 2016 [first experimental run (application time 10:30 AM, temperature 28 °C, humidity 69%, wind speed 6 mph, and sunny condition)] and 2 Apr. 2017 [second experimental run (application time 10:40 AM, temperature 27.7 °C, humidity 65%, wind speed 5 mph, and sunny condition)] at their labeled rates to pots seeded with eclipta, large crabgrass, or garden spurge, respectively. These herbicides/weed combinations were selected because these are the common weed species that are found in landscapes and container nurseries, and these herbicides are the most widely and commonly used in ornamental crop production. Liquid formulations were applied with a carbon dioxide (CO_2) backpack sprayer (custom-built sprayer from Bellspray R&D Sprayer, Opelousas, LA) calibrated to deliver 20 gal/acre using an 8004 flat-fan nozzle (TeeJet Technologies, Wheaton, IL) at a pressure of 30 psi. Granular formulations were applied to each container using a hand shaker. Following treatment, the pots were placed inside a full-light greenhouse. Each container received 0.5, 1, or 2 inches of irrigation by hand using an irrigation wand (Titanium Series Front-Trigger 7-Pattern Aqua Gun®; Melnor®, Winchester, VA) that was previously calibrated to determine the flow rate. The three irrigation volumes were applied 1 d after herbicides were applied. Following the initial hand watering, used as one-time herbicide activation irrigation, the pots were kept dry for 3 d. After 3 d, all containers were irrigated using overhead sprinklers and received 0.2 inch total per day via two irrigation cycles throughout the remainder of the trial. Air temperature was maintained between 21 and 35 °C inside the greenhouse throughout the trial.

The experiment consisted of a factorial treatment arrangement of the two herbicide formulations (granular or spray applied), three mulch types (HW, PB, and PS), two mulch depths (1 and 2 inches), and three levels of one-time, posttreatment irrigation volumes (0.5, 1, and 2 inches). Three sets of controls were included in the study to accomplish the objectives noted previously. The first set of controls included only the three mulch types applied at the two depths and received only the 0.5-inch irrigation volume. The second set of controls included only the two herbicide formulations and the three one-time irrigation volumes, whereas the last set of control pots received no treatment (no herbicide or mulch) and received only the 0.5-inch irrigation volume. This design yielded 49 individual treatments per weed species (36 formulation × mulch depth × mulch type × irrigation combinations, six formulation × irrigation combinations, six mulch type × mulch depth combinations, and one no herbicide, no mulch control) with eight single-pot replications per treatment, per weed species. The pots were grouped by weed species in a completely randomized block design, and each weed species was treated as a separate experiment.

Weed emergence (i.e., counts) were recorded at 30 and 60 DAT and shoot FWs were recorded at 60 DAT. Weed emergence data followed the same trend as shoot FW data, so only shoot FW data are discussed and presented for brevity. Shoot FW data were collected by clipping weeds at the soil line and weighing on a portable scale. Data collected in nontreated pots (no mulch and no herbicide) and pots receiving either a herbicide or a mulch treatment were used to calculate percent control and the percent increase in control achieved with the herbicide + mulch combination compared with either herbicide or mulch applied alone. First, percent control (shoot FW reduction) of all treated pots (herbicide + mulch, herbicide-only, or mulch-only) was calculated based on the FW of the nontreated pots (no mulch or herbicide) using the formula [(FW nontreated − FW treated) ÷ FW nontreated] × 100. The percent increase in control was then calculated for the herbicide + mulch combination based on 1) mulch treatments receiving no herbicide (herbicide caused increase in control or "herbicide effect") [(percent control combination − percent control mulch) ÷ percent control mulch] × 100 and 2) herbicide treatments receiving no mulch (mulch caused increase in control or "mulch effect") [(percent control combination

– percent control herbicide) ÷ percent control herbicide] × 100. This resulted in three different data points for each weed species on each evaluation date: 1) percent control; 2) herbicide-caused increase (herbicide effect); and 3) mulch-caused increase (mulch effect). This methodology allowed us to determine which herbicide + mulch combination was most efficacious (Bartley et al., 2017) and additionally the significance of experimental variables (herbicide formulation, mulch type, depth, and irrigation volume) when used in combination at different levels.

STATISTICAL ANALYSIS. All data were subjected to mixed model analysis of variance using SAS (version 9.4; SAS Institute, Cary, NC), reflecting the factorial treatment arrangement, and pooled over trial runs as there were no treatment × trial run interactions. Herbicide-only treatments were analyzed to determine significant effects of formulation and irrigation volume when no mulch was included. Replication was considered random, whereas all other experimental variables and interactions between these variables were considered fixed factors. Herbicide-only treatments were analyzed to determine significant effects of formulation and irrigation volume when no mulch was included. Mulch-only treatments were analyzed to determine significant effects of mulch type and depth when no herbicide was included. Data from mulch-only treatments were also compared with herbicide-only treatments after pooling data over all irrigation volumes to compare efficacy. Data from herbicide + mulch combinations (percent control, herbicide effect, and mulch effect) were then analyzed as three (mulch types) × two (mulch depths) × three (irrigation levels) × two (herbicide formulations) × three (weed species) factorial. In all cases, linear or quadratic trends over irrigation rate were determined with orthogonal contrasts and least significance difference values were calculated when main effects or interactions for other parameters were significant ($P \leq 0.05$). Visual percent control data and seedling counts collected at 30 and 60 DAT are reflected in data derived from shoot FW; therefore, only percent control data derived from shoot FW are discussed for brevity. Data with no variance were not analyzed but are discussed, and treatment least squares means are presented.

Results and discussion

HERBICIDE-ONLY TREATMENTS. Percent control data from herbicide-treated pots (no mulch) showed that formulation was significant for all three herbicides as dimethenamid-P + pendimethalin, indaziflam, and prodiamine were all more effective when applied as a spray-applied formulation compared with the granular formulation (Table 1). The use of spray-applied formulations of indaziflam, prodiamine, or dimethenamid-P + pendimethalin resulted in an increase in control of 42%, 17%, and 13% for eclipta, large crabgrass, and garden spurge, respectively, in comparison with the granular formulation. These findings are consistent with earlier reports evaluating flumioxazin in which greater control was consistently achieved with spray-applied formulations compared with a granular formulation (Wehtje et al., 2015).

Irrigation volume was not significant for large crabgrass, nor were there any formulation × irrigation interactions. Prodiamine is widely recommended for PRE control of large crabgrass and other grassy weeds (Neal et al., 2017). As prodiamine is highly efficacious for large crabgrass, irrigation likely plays little role in efficacy as long as a sufficient amount is applied to properly incorporate the herbicide. In pots seeded with garden spurge, irrigation volume was significant for dimethenamid-P + pendimethalin as there was a linear decrease in garden spurge control as irrigation volume increased from 0.5 to 2 inches. Although the decrease was significant, commercially acceptable control (≈80%) was achieved at all three irrigation levels averaged over both formulations. Similar to the results with large crabgrass, there were no formulation × irrigation interactions with garden spurge, again likely due to the high efficacy of this combination on spurge (*Euphorbia*) species (Neal et al., 2017).

Irrigation was not a significant main effect for eclipta, but there was a significant formulation × irrigation interaction. For the granular formulation of indaziflam, control decreased as irrigation volume increased, ranging from 59% control at 0.5 inches to 41% control at 2 inches. The spray formulation was more effective than the granular formulation, and no irrigation effect was observed. It is unclear why these differences occurred. However, higher variability in eclipta control could be because while indaziflam is effective for eclipta control, it is typically slightly less efficacious on eclipta than prodiamine is on large crabgrass or dimethenamid-P + pendimethalin is on garden spurge (Neal et al., 2017), and this variability may have led to greater variability in results. Granular herbicides are often less effective than spray-applied herbicides because granules need to be uniformly dispersed on the soil surface and in adequate quantities so that the herbicidal active ingredient is in close proximity to germinating seedlings (Wehtje et al., 2015). Although it was not recorded, it is possible that the higher irrigation volume of 2 inches may have slightly dispersed granules inside the pots, resulting in less weed control. This is not likely as all pots were irrigated carefully and uniformly. The influence of posttreatment irrigation on granular herbicide formulations likely depends on the weed species and herbicide. Wehtje et al. (2015) reported that higher posttreatment irrigation levels had no influence on the efficacy of a granular flumioxazin application for spotted spurge (*Euphorbia maculata*) but did for bittercress (*C. hirsuta*) (Yang et al., 2013). Although posttreatment irrigation may play a role in granular efficacy, it appears that any effects would be minimal if the required amount of irrigation that is needed to activate the herbicide were applied.

Based on these results across all three species, herbicide formulation will have a greater influence on weed control than irrigation, similar to previous reports (Saha et al., 2016; Wehtje et al., 2015; Yang et al., 2013). Although some irrigation effects were noted in garden spurge treated with dimethenamid-P + pendimethalin, all irrigation levels resulted in commercially acceptable weed control and would have little practical importance. Irrigation and formulation interactions were significant for eclipta as difference results were observed over the three irrigation levels within the granular formulation but not the more effective spray formulation. Although indaziflam is effective for eclipta, eclipta is often difficult to control with PRE herbicides (S.C. Marble, unpublished data). Irrigation levels and other environmental variables could have a greater influence on weed control when troublesome weeds or less efficacious herbicides are evaluated.

Mulch-only treatments. Mulch type was not significant for large crabgrass or garden spurge but was for eclipta as HW provided greater control of eclipta (64%) than PB (44%) or PS (46%) (Table 2). Eclipta seeds have been shown to be strongly photoblastic with 0% germination observed in darkness (Altom and Murray, 1996). Albeit less than in high light levels, large crabgrass can germinate in darkness (Chauhan and Johnson, 2008). Similar to eclipta, garden spurge is also photoblastic with only 1% germination occurring in darkness (Rooden et al., 1970). Although light levels underneath mulch were not evaluated, greater eclipta control with HW may be related to the higher percentage of smaller particle sizes in HW (Fig. 1). The HW mulch may have reduced light more effectively than PB or PS applied at similar depths and reduced eclipta emergence but did not block out enough light to affect garden spurge or large crabgrass. It is unknown how the physical properties of mulch influence light levels on the soil surface, and additional research is needed in this area. It is also important to note that although the small particle size of HW mulch may have reduced light levels and prevented growth, germination of eclipta, or both in this study, all seeds were placed on the soil surface. When seeds are placed on the surface of a mulch, as would be expected to occur over time in a production or landscape environment, smaller particle size materials can be prone to encourage greater weed growth (Chalker-Scott, 2007) because of greater water holding capacity.

In addition to the light requirement for seed germination, the seed burial depth (or mulch depth) is an important factor to consider. Mulch depth was significant for all three weed species, with the 2-inch depth resulting in a 71%, 147%, and 57% increase in control compared with the 1-inch depth for eclipta, large crabgrass, and garden spurge, respectively. Seedling emergence through 2 inches of mulch depth requires more resources than emergence through lower mulch depths (0 or 1 inch). Greater depths will require more time for emergence and generally use more of the seed energy reserve (Black, 1956). Smaller seeds, such as those used in these experiments, often cannot emerge from deeper depths as they do not have the ability to store the required resources to emerge from greater depths. No mulch type × depth interactions were observed for any weed species, indicating that for most weed species, mulch depth will be a more critical factor for control than mulch type as has been previously reported (Marble et al., 2015).

Table 1. Effect of herbicide formulation and posttreatment irrigation volume on control of three landscape/container nursery weed species.

		Control (%)[x]		
Formulation[z]	Irrigation vol (inches)[y]	Eclipta	Large crabgrass	Garden spurge
Granular	0.5	59	82	89
	1.0	50	78	84
	2.0	41	71	77
		L*[w]	NS[w]	NS
	Mean granular	50 b[v]	78 b	84 b
Spray	0.5	71	92	99
	1.0	65	98	98
	2.0	77	91	94
		NS	NS	NS
	Mean spray	71 a	94 a	97 a
Irrigation[u]		NS	NS	L*
ANOVA[t]				
Formulation (F)		0.001	0.001	0.001
Irrigation volume (I)		0.152	0.211	0.034
F × I		0.004	0.344	0.590

[z]Granular and spray-applied formulations of indaziflam, prodiamine, and dimethenamid-P + pendimethalin were evaluated with eclipta, large crabgrass, and garden spurge, respectively.
[y]1 inch = 2.54 cm.
[x]Calculated as percent decrease based on shoot fresh weights (FWs) in nontreated, nonmulched control pots by using the formula: [(FW nontreated − FW treated) ÷ FW nontreated] × 100; means are shown for pots treated with herbicide only.
[w]L* represents a significant linear response ($P \le 0.05$) with respect to irrigation volume based on orthogonal contrasts; NS = not significant linear or quadratic response with respect to irrigation volume based on orthogonal contrasts.
[v]Means within species followed by the same letter are not significant different ($P \le 0.05$) based on analysis of variance (ANOVA).
[u]L* and NS = linear ($P \le 0.05$) or no significant response with respect to irrigation volume over both formulations. L* or NS shows linear or not significant responses within each formulation where interactions are significant.
[t]ANOVA was performed using a mixed model analysis in SAS (version 9.4; SAS Institute); effects are considered significant at $P \le 0.05$.

Table 2. Effect of mulch type and depth on control of three container nursery weed species.

	Control (%)[z]		
	Eclipta	Large crabgrass	Garden spurge
Mulch type			
Hardwood	64 a[y]	29	69
Pine bark	44 b	33	62
Pine straw	46 b	36	73
Mulch depth (inches)[x]			
1.0	38 b	19 b	53 b
2.0	65 a	47 a	83 a
ANOVA[w]			
Mulch type (T)	0.002	0.545	0.267
Mulch depth (D)	0.001	0.001	0.001
T × D	0.301	0.879	0.782

[z]Calculated as percent decrease based on shoot fresh weights (FWs) in nontreated, nonmulched control pots by using the formula: [(FW nontreated − FW treated) ÷ FW nontreated] × 100; means are shown for pots treated with mulch only.
[y]Means within a column and factor (type or depth) followed by the same letter or no letters are not significantly different based on Fisher's protected least significant difference ($P < 0.05$).
[x]1 inch = 2.54 cm.
[w]Analysis of variance (ANOVA) was performed using mixed model analysis in SAS (version 9.4; SAS Institute); effects are considered significant at $P \le 0.05$.

HERBICIDE VS. MULCH-ONLY TREATMENTS. The best eclipta control was observed in pots mulched with HW at 2 inches (83%) and pots treated with the spray formulation of indaziflam (71%), which were similar (Table 3). The spray formulation of indaziflam provided efficacy similar to that of PB and PS applied at the 2-inch depth and outperformed all three mulch types applied at the 1-inch depth. The spray formulation of prodiamine provided the highest large crabgrass control of any treatment (94%) followed by the granular formulation (78%) (Table 3). Both formulations provided greater control than any mulch material, which ranged from 15% to 45% control. As large crabgrass has the ability to germinate in darkness (Chauhan and Johnson, 2008; Holm et al., 1977), mulch was less effective in reducing emergence of this species. Dimethenamid-P + pendimethalin provided 97% control of garden spurge when applied as spray formulation, and this treatment provided better control than any of the mulch treatments applied at the 1-inch depth. Hardwood (87%) and PS (87%) at the 2-inch depth provided control similar to that observed with the spray formulation. For all three weed species, the spray formulation provided greater or similar control to that observed with any of the mulch types applied at the 2-inch depth and greater control than the 1-inch depth. The granular formulation was generally less effective than the spray, as discussed previously, but still provided greater control than a 1-inch mulch layer in all cases except eclipta mulched with HW at 1 inch, which was similar. This suggests that over the short term (≈3 months), herbicides will generally outperform mulch materials. However, mulch materials will be slow to degrade (Duryea et al., 1999), whereas herbicides will require reapplication every 2–3 months (Neal et al., 2017). As proposed and discussed by Bartley et al. (2017), mulching for weed control will become more beneficial and cost-effective over the long term as mulch has been shown to provide weed control for several seasons without the need for reapplication.

HERBICIDE + MULCH TREATMENTS. Eclipta control with indaziflam was influenced by formulation, mulch type, mulch depth, and the interactions of formulation × mulch type, formulation × mulch depth, and mulch type × irrigation volume (Table 4). Within the granular formulation, HW (84%) provided greater control than PB (66%) or PS (67%), but there was no difference in mulch type within the spray-applied treatments as the spray formulation generally provided better eclipta control throughout the experiment (Table 5). In all cases, a higher level of control was achieved with the 2-inch mulch depth compared with the 1-inch depth. Similarly, the spray formulation outperformed the granular formulation at all mulch depths. Irrigation volume had no influence on eclipta control in HW or PS; however, greater eclipta control was observed in PB at the 0.5-inch irrigation volume compared with the 2-inch volume (Table 6) as there was a linear decrease in control with increasing irrigation volume. In herbicide-only pots, we also observed a decrease in eclipta control at the 2-inch irrigation volume compared with the 0.5-inch volume (Table 1). In this case, herbicides were applied to the pots mulched with PB. As we speculated previously, the higher irrigation volume may have dispersed the herbicide, especially the granular formulation, and the herbicide was not uniform on the soil surface, and the control decreased. However, there was no formulation × mulch type × irrigation interaction, so this does not seem likely. It is unknown why this difference occurred, but the difference was of little practical importance as ≈70% to 80% control was achieved at all irrigation levels.

The herbicide effect, calculated by determining the percent increase in control achieved with the herbicide + mulch combination in comparison with mulch-only pots, showed that formulation and mulch depth were significant main effects but were influenced by interactions of formulation × mulch type, formulation × depth, and mulch type × mulch depth. The granular formulation of indaziflam contributed to a higher herbicide effect in pots mulched with HW (74%) compared with pots mulched with PS (34%), whereas the spray formulation resulted in an increase of 108% to 130% control across all three mulch types, and there was no difference in the herbicide effect across the mulch types (Table 5). In all but one case, the herbicide effect from both formulations of indaziflam was less at the 2-inch mulch depth, indicating that application of indaziflam would have a higher influence on weed control when mulch was at the lower 1-inch depth. The one exception was the granular formulation applied to PB, which caused a 59% increase in control at the 1-inch depth and a 51% increase in control at the 2-inch depth and was similar. Similar to results observed in nonmulched pots, addition of the spray formulation resulted in higher control (118%) compared with the granular formulation (54%) (Table 5). As the spray formulation was more efficacious in all instances, it would be expected that the spray formulation provide a greater herbicide effect. In addition, as mulch depth was found to be significant for all three weed species and all mulch types when evaluating mulch alone (Table 2), a greater herbicide

Table 3. Control of three common landscape weed species with the use of herbicide or mulch at two different depths.

Treatment		Control (%)[z]		
		Eclipta	Large crabgrass	Garden spurge
Herbicide	Granular	50 c[y]	78 b	84 b
	Spray	71 ab	94 a	97 a
Mulch	Hardwood, 1 inch[x]	45 cd	15 d	51 d
	2 inches	83 a	43 c	87 ab
	Pine bark, 1 inch	34 d	21 d	49 d
	2 inches	59 bc	45 c	75 bc
	Pine straw, 1 inch	34 d	21 d	59 cd
	2 inches	59 bc	45 c	87 ab

[z]Calculated as percent decrease based on shoot fresh weights (FWs) in nontreated, nonmulched control pots by using the formula: [(FW nontreated – FW treated) ÷ FW nontreated] × 100; indaziflam, prodiamine, and dimethenamid-P + pendimethalin were evaluated as granular and spray-applied formulations for eclipta, large crabgrass, and garden spurge, respectively.
[y]Means within a column followed by the same letter are not significantly different based on Fisher's protected least significant difference ($P \le 0.05$).
[x]1 inch = 2.54 cm.

Table 4. Response of eclipta, large crabgrass, and garden spurge to the main effects of herbicide formulation, mulch type and depth, and irrigation volume and all three-way interactions.

	Eclipta			Large crabgrass			Garden spurge		
Main effects[z]	Control (%)[y]	Herbicide effect[x]	Mulch effect[w]	Control (%)	Herbicide effect	Mulch effect	Control (%)	Herbicide effect	Mulch effect
Formulation (F)	<0.001	<0.001	<0.001	NA[v]	NA	NA	0.081	0.646	<0.001
Mulch type (T)	<0.001	0.660	<0.001	0.655	0.002	0.017	0.137	<0.001	0.781
Mulch depth (D)	<0.001	<0.001	<0.001	0.001	<0.001	0.257	0.043	<0.001	0.483
Irrigation volume (I)	0.731	0.480	<0.001	0.606	0.943	<0.001	0.591	0.956	<0.001
Interactions									
F × T	0.002	0.008	<0.001	NA	NA	NA	0.090	0.848	0.749
F × D	<0.001	<0.001	<0.001	NA	NA	NA	0.099	0.657	0.555
T × D	0.203	<0.001	0.001	0.099	0.048	0.843	0.128	<0.001	0.773
F × I	0.888	0.813	<0.001	NA	NA	NA	0.576	0.955	<0.001
T × I	0.007	0.281	0.382	0.762	0.698	0.313	0.656	0.995	0.989
D × I	0.487	0.241	0.003	0.704	0.923	0.409	0.604	0.958	0.939
F × T × D	0.144	0.077	0.001	NA	NA	NA	0.087	0.847	0.743
F × T × I	0.451	0.594	0.299	NA	NA	NA	0.645	0.995	0.988
F × D × I	0.280	0.818	0.007	NA	NA	NA	0.607	0.957	0.939
T × D × I	0.183	0.543	0.710	0.280	0.578	0.800	0.658	0.995	0.989

Data relating to herbicide formulation, mulch type, and mulch depth and interactions are included in Table 5 and Fig. 2. Irrigation and interactions involving irrigation are included in Tables 6–8.

[z]Formulation refers to granular or spray-applied formulations of indaziflam, prodiamine, or dimethenamid-P + pendimethalin, which were evaluated with eclipta, large crabgrass, and garden spurge, respectively. Mulch types evaluated included hardwood, pine bark, and pine straw. Mulch depths included 1 or 2 inches (1 inch = 2.54 cm). Irrigation volumes included 0.5, 1, and 2 inches. Analysis of variance was performed using a mixed model in SAS (version 9.4; SAS Institute). Main effects and interactions are significant at $P \le 0.05$.

[y]Calculated as percent decrease in shoot fresh weights (FWs) in pots that received the herbicide + mulch combination in comparison with pots receiving no herbicide or mulch treatment by using the formula: [(FW nontreated – FW treated) ÷ nontreated] × 100.

[x]Calculated as percent increase in control with the herbicide + mulch combination in comparison with mulch-only treatments by using the formula: [(percent control combination – percent control mulch) ÷ percent control mulch] × 100.

[w]Calculated as percent increase in control with the herbicide + mulch combination in comparison with herbicide-only treatments by using the formula: [(percent control combination – percent control herbicide) ÷ percent control herbicide] × 100.

[v]NA = not analyzed. Data from spray-applied treatments in large crabgrass were not analyzed because of zero variance (all 100% control).

effect would be expected at the lower mulch depths.

Mulch effects, calculated by comparing control of the herbicide + mulch combination with pots treated with herbicide only, were influenced by all main effects, but significant interactions occurred, including formulation × mulch type, formulation × mulch depth, mulch type × mulch depth, formulation × irrigation volume, and the three-way interactions of formulation × mulch type × mulch depth and formulation × mulch depth × irrigation volume. Hardwood resulted in the highest increase in control (121%) within the granular formulation of indaziflam, followed by PB (63% increase) and PS (16% increase) (Table 5). In all cases, a greater mulch effect was observed at the 2-inch depth compared with 1 inch within the granular formulation (Table 5). A decrease in control (–105%) was observed in PS applied at the 1-inch depth, indicating that the granular formulation was less effective when used in combination with PS compared with its use alone (Table 5). There was no difference in mulch types or mulch depth within the spray formulation, indicating that mulch type and depth would not be as significant of a factor in eclipta control when using the more effective spray formulation. This suggests that at least in the short term, control would be adequate with the use of spray formulation alone.

The granular indaziflam + mulch combination also resulted in less control than the granular formulation applied alone when examining the formulation × depth × irrigation interaction evidenced by negative values at the 0.5- and 1-inch irrigation volumes (Table 7). Across all three mulch types, addition of mulch at the 1-inch depth resulted in 17% and 31% decrease in control when receiving a 0.5- or 1-inch irrigation volume, respectively, compared with the granular formulation applied alone and irrigated similarly. This suggests that the herbicide + mulch combination was less effective than the herbicide applied alone at similar irrigation volumes, indicating that binding occurred tying up the herbicide and making it unavailable for weed control. There were, however, no irrigation effects within the granular formulation applied to the 1-inch mulch depths. Mulch applied at the 2-inch depth provided a 62% to 226% increase when used in combination with the granular formulation compared with the granular herbicide applied alone and increased linearly from the lowest irrigation volume to the highest irrigation volume. This linear increase was a result of the granular herbicide providing less control at the higher irrigation volume, as discussed in Table 1. When the spray formulation of indaziflam was applied, there was no difference in the mulch additive effect between the different irrigation volumes when mulch was applied at the 1-inch depth. At the 2-inch depth, the mulch caused a greater percentage increase in control at the 1-inch irrigation volume than the 2-inch volume, again coinciding with the control observed in the herbicide-only treatments as shown in Table 1. Mulch effect had a quadratic response at both mulch depths in the spray formulation. The mulch effect for the spray formulation ranged from 6% to 40% at the 1-inch mulch depth and 36% to 78% at the 2-inch mulch depth. The higher mulch level contributed

Table 5. Effect of herbicide formulation, mulch type, and mulch depth on control of three landscape/container nursery weed species.

			Eclipta			Large crabgrass			Garden spurge		
Formulation[z]	Mulch type	Depth (inches)[y]	Control (%)[x]	Herbicide effect[w]	Mulch effect[v]	Control (%)	Herbicide effect	Mulch effect	Control (%)	Herbicide effect	Mulch effect
Granular	Hardwood	1	70 b[u]	128 a	67 b	100[t]	763[t]	32[t]	99	134	25
		2	98 a	20 b	175 a	100[t]	140[t]	31[t]	99	16	25
		Mean	84 A	74 A	121 A	100[t]	452[t]	32[t]	99	75	25
	Pine bark	1	53 b	59 a	7 b	93	442 a	24	96	105	21
		2	79 a	51 a	118 a	97	131 b	27	99	39	26
		Mean	66 B	55 AB	63 B	95	269 A	26 A	98	72	23
	Pine straw	1	46 b	4 b	–105 b	88	388 a	17	99	73	25
		2	88 a	64 a	136 a	99	110 b	19	99	17	26
		Mean	67 B	34 B	16 C	94	219 B	18 B	99	45	25
	Mean granular		73 B	54 B	67 A	96	313	27	99	64	25 A
Spray	Hardwood	1	79 b	196 a	20 a	100[t]	763[t]	8[t]	99	134	3
		2	98 a	20 b	57 a	100[t]	140[t]	8[t]	98	16	4
		Mean	88 A	108 A	39 A	100[t]	452[t]	8[t]	99	76	3
	Pine bark	1	76 b	159 a	18 a	100[t]	412[t]	8[t]	98	113	4
		2	92 a	78 b	46 a	100[t]	125[t]	8[t]	100	39	4
		Mean	84 A	118 A	32 A	100[t]	286[t]	8[t]	99	76	4
	Pine straw	1	79 b	174 a	25 a	100[t]	331[t]	8[t]	99	74	4
		2	96 a	86 b	54 a	100[t]	106[t]	8[t]	100	16	4
		Mean	87 A	130 A	40 A	100[t]	249[t]	8[t]	100	45	4
	Mean spray		86 A	118 A	37 B	100[t]	329[t]	8[t]	100	66	4 B

[z]Formulation refers to granular or spray-applied formulations of indaziflam, prodiamine, or dimethenamid-P + pendimethalin, which were evaluated with eclipta, large crabgrass, and garden spurge, respectively.
[y]1 inch = 2.54 cm.
[x]Calculated as percent decrease in shoot fresh weights (FWs) in pots that received the herbicide + mulch combination in comparison with pots receiving no herbicide or mulch treatment by using the formula: [(FW nontreated – FW treated) ÷ nontreated)] × 100.
[w]Calculated as percent increase in control with the herbicide + mulch combination in comparison with mulch-only treatments by using the formula: [(percent control combination – percent control mulch) ÷ percent control mulch] × 100.
[v]Calculated as percent increase in control with the herbicide + mulch combination in comparison with herbicide-only treatments by using the formula: [(percent control combination – percent control herbicide) ÷ percent control herbicide] × 100.
[u]Means within columns followed by different lowercase letters show differences in depth within each mulch type and formulation, whereas different uppercase letters show differences in formulation or mulch type based on Fisher's protected least significant difference ($P \leq 0.05$). Means followed by no letters are not significantly different. Significant mulch type × mulch depth interactions across both formulations in large crabgrass and garden spurge are shown in Fig. 2.
[t]Shows data that were not analyzed because of zero variance.

Table 6. Effects of mulch type and irrigation volume on eclipta control[z] with indaziflam + mulch combinations.

	Mulch type		
Irrigation vol (inches)[y]	Hardwood	Pine bark	Pine straw
0.5	84	82	75
1.0	86	75	75
2.0	89	69	81
	NS[x]	L**[x]	NS

[z]Calculated as percent decrease in shoot fresh weights (FWs) in pots that received the indaziflam + mulch treatment in comparison with pots receiving no herbicide or mulch treatment by using the formula: [(FW nontreated – FW treated) ÷ nontreated] × 100.
[y]1 inch = 2.54 cm.
[x]NS represents no significant response, whereas L** indicates a significant ($P \leq 0.01$) linear response based on orthogonal contrast statements.

more significantly to overall eclipta control than the granular formulation, and the mulch effect increased at the higher mulch depth as would be expected.

The spray formulation of prodiamine resulted in 100% large crabgrass control when combined with any mulch treatment, whereas the granular formulation resulted in 100% control when combined with HW; therefore, these data were excluded from the analysis and only data from the granular formulation used in combination with PB and PS were analyzed (Tables 4 and 5). The spray formulation resulted in a herbicide effect of 331% to 763% increase in large crabgrass control compared with mulch alone applied at the 1-inch depth and over a 100% increase in control compared with mulch applied at the 2-inch depth (Table 5; Fig. 2). The mulch additive effect was 8% across all mulch types and depths, indicating that the use of spray-applied prodiamine will likely contribute to large crabgrass control to a much greater degree than would mulch.

Mulch depth was the only significant effect for large crabgrass control within the granular prodiamine, with the 2-inch depth resulting in greater control than the 1-inch depth. The herbicide effect was influenced by mulch type, mulch depth, and the interaction of these terms (Table 4). In all three mulch types, the granular prodiamine had a higher herbicide effect at the lower mulch depth, similar to results observed with eclipta (Table 5; Fig. 2). Again, this indicates that similar to results with indaziflam, prodiamine will have more of an influence on weed control when lower mulch depths are used. Addition of granular prodiamine resulted in increases of 763%, 388%, and 442% in control for HW, PB, or PS, respectively, compared with these mulch materials applied alone at the 1-inch depth (Table 5). There was a greater mulch effect in PB (427%) than in PS (359%). Although not included in the analysis, granular prodiamine resulted in a 763% increase in control compared with the HW used alone (Fig. 2). At the 2-inch depth, there was no difference in herbicide effect among mulch types, with prodiamine resulting in a 110% to 140% increase in control for all three mulch materials. Again, these results indicate that similar to results with indaziflam, prodiamine will have more of an influence on weed control when lower mulch depths are used, and as mulch depth increases, the use of herbicides becomes less significant.

The mulch effect for prodiamine-treated pots was influenced by the main effects of mulch type and irrigation volume. Pine bark had a greater mulch effect (26%) than PS (18%), whereas HW resulted in a 32% increase in control compared with granular prodiamine applied alone (Table 5). A greater mulch effect was observed following the 2-inch irrigation volume (39%) compared with the 1-inch (22%) or 0.5-inch (18%) irrigation volumes as there was a linear increase in mulch effect

Table 7. Influence of indaziflam formulation, mulch depth, and irrigation volume on mulch effect[z] in eclipta.

		Mulch depth	
Formulation	Irrigation vol (inches)[y]	1 inch	2 inches
Granular	0.5	–17	62
	1.0	–31	141
	2.0	18	226
		NS[x]	L***[x]
Spray	0.5	16	43
	1.0	40	78
	2.0	6	36
		Q**[x]	Q***

[z]Calculated as percent increase in control with the indaziflam + mulch combination in comparison with herbicide-only treatments by using the formula: [(percent control combination – percent control herbicide) ÷ percent control herbicide] × 100.

[y]1 inch = 2.54 cm.

[x]NS, L, and Q represent no, linear, or quadratic response in mulch effect with respect to irrigation volume, respectively, based on orthogonal contrasts; ** and *** represent significant effects when $P \leq 0.01$ and 0.001, respectively.

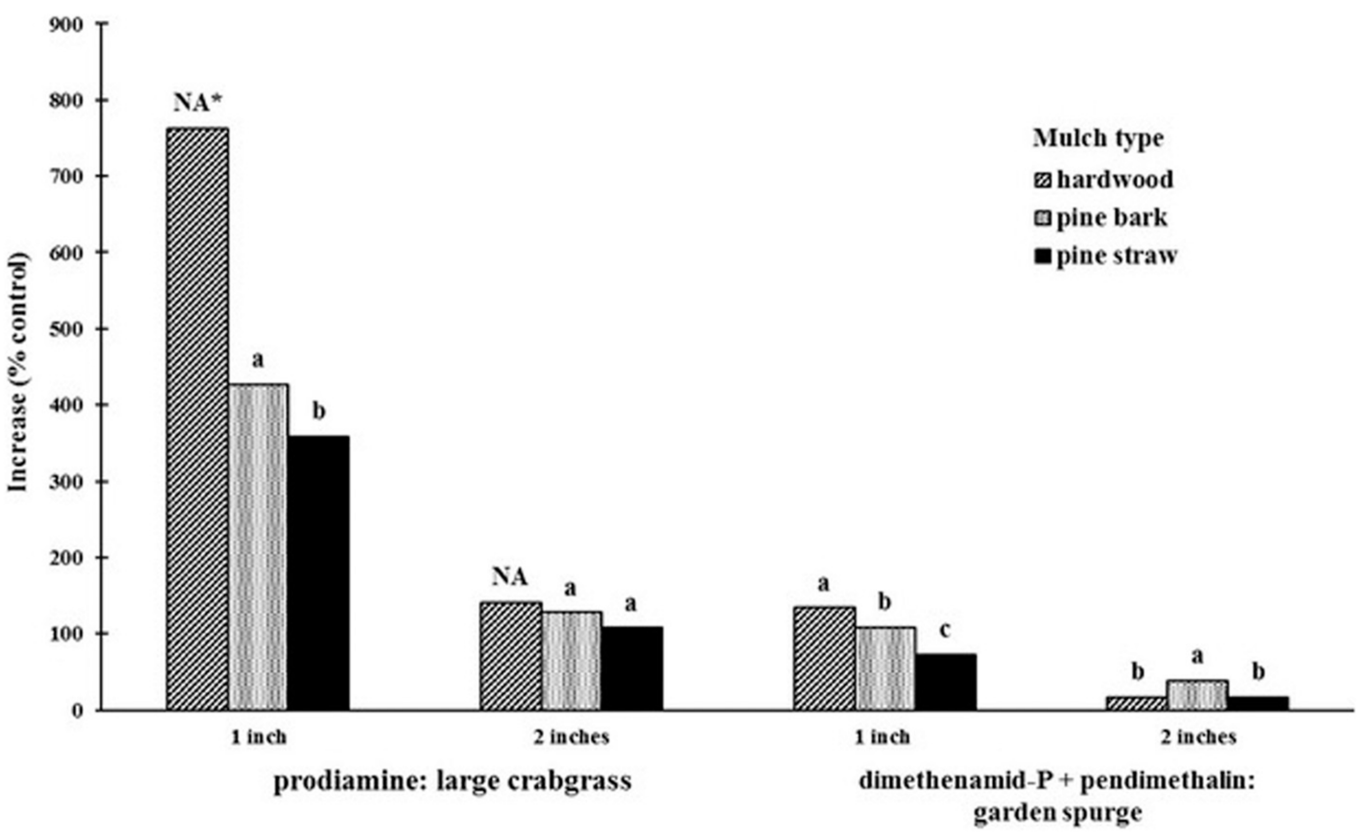

Fig. 2. Influence of mulch type and mulch depth on the herbicide effect observed in large crabgrass (treated with prodiamine) and garden spurge (treated with dimethenamid-P + pendimethalin). Herbicide effect is the percent increase in control with the herbicide + mulch combination in comparison with control achieved with mulch-only treatments and is calculated by using the formula: [(percent control combination − percent control mulch) ÷ percent control mulch] × 100. Means followed by the same letter within each species and mulch depth are not significantly different based on Fisher's protected least significant difference ($P \leq 0.05$); NA* = not analyzed because of zero variance; 1 inch = 2.54 cm.

with increasing irrigation volume (Table 8). As control with herbicide-only treatments generally was reduced with higher irrigation volumes, the mulch effect would consequently increase and account for a greater percentage of the weed control observed.

Similar to large crabgrass data, there was a high level of spurge control in all pots that were mulched and treated with dimethenamid-P + pendimethalin and all combinations resulted in ≥96% control (Table 5). Mulch depth was the only significant effect for spurge control, with the 2-inch depth (100%) providing 2% greater control than the 1-inch mulch depth (98%) (Tables 4 and 5) across both formulations and all three mulch types.

Herbicide effect was influenced by mulch type, mulch depth, and the interaction of these terms (Table 4). At the 1-inch mulch depth, a greater herbicide effect was observed in HW (134% increase), followed by PB (109% increase) and PS (73% increase). At the 2-inch depth, there was a greater herbicide effect for PB (39% increase) compared with either HW or PS (both 17% increase) (Fig. 2). Less herbicide effect would be expected at the 2-inch depth as spurge control was greater at 2 inches; thus, the herbicide would have less influence. The increase in herbicide effect was related to the ability of the mulch materials to control spurge on their own. That is, there was a greater herbicide effect in less efficacious mulch materials and greater herbicide effect at lower mulch depths.

Mulch effect was influenced by formulation, irrigation, and the interaction of formulation and irrigation (Table 4). In pots treated with the granular formulation of dimethenamid-P + pendimethalin, the mulch effect increased with increasing irrigation volume (11%, 22%, and 41% mulch effect at the 0.5-, 1-, and 2-inch irrigation volumes, respectively). In the spray formulation, there was again a linear increase in mulch effect with increasing irrigation volume (Table 8). As the spray formulation was more effective, the mulch effect was lower (4%) than the mulch effect of the less effective granular formulation (25%). This shows that similar to eclipta and large crabgrass, mulch contributes more to overall weed control in cases where herbicides are not as effective. Regardless of any herbicide or mulch effect, all mulch and herbicide combinations resulted in commercially acceptable weed control of spotted spurge.

Overall, these results suggest that for the weed species evaluated, PRE herbicides will likely provide similar or greater control than common mulch materials applied at a 1- or 2-inch depth, especially when considering spray formulations that consistently outperformed granular formulations. Mulch applied at adequate depths, generally 1 inch or greater, has provided better control of common nursery and landscape weed species when compared with PRE herbicides (Bartley et al., 2017; Burrows, 2017; Marble et al., 2017). However, short-term studies often suggest that PRE herbicides are, or more, effective than mulch (Ferguson et al., 2008; Smith et al., 1998), similar to our results over a 60-d evaluation period.

High levels of large crabgrass and garden spurge control (88% to 100%) were observed with all herbicide + mulch combinations evaluated. With these species, herbicides provided more effective control than mulch in most cases, but control increased with the combination. The highest eclipta control was achieved with the spray formulation and with higher mulch depths. Although mulch type was not a significant factor in control when the more effective spray formulation was applied, the best eclipta control was observed with the HW mulch when the granular formulation was used. In almost all cases, herbicide additive effects were greater at the lower mulch depths, and mulch additive effects were greater at the higher mulch depth. Similar to findings by Somireddy (2012), the use of herbicides in combination with mulch become more meaningful in terms of weed control when lower mulch depths are used. By examining weed control achieved with the use of herbicides alone (Tables 1 and 3), mulch depth also becomes a more important factor when troublesome weed species are evaluated, as was the case with indaziflam applied for eclipta control.

Irrigation volume was not a significant factor for any of the herbicide + mulch combinations when evaluating overall weed control but was significant when accounting for the mulch additive effect, i.e., comparing the herbicide + mulch combination to herbicide-only treatments. However, interactions that occurred are more likely related to the lower control observed in herbicide-only treatments at higher irrigation levels (Table 1) and not specifically to any effect irrigation volume had on control.

For eclipta, the indaziflam + mulch combination provided less control than when granular indaziflam was applied alone. Similarly, PS mulch applied at 1 inch + granular indaziflam resulted in a 105% reduction in eclipta control (an increase in eclipta growth) compared with use of granular indaziflam alone. As all weed seeds were placed on the soil surface, underneath mulch, this reduction in control indicates that low PS mulch levels may impede indaziflam

Table 8. Influence of herbicide formulation and irrigation volume on mulch effect in garden spurge and large crabgrass.

		Mulch effect[y]	
Formulation	Irrigation vol (inches)[z]	Large crabgrass	Garden spurge
Granular	0.5	18	11
	1.0	22	22
	2.0	39	41
		L***[x]	L***
Spray	0.5	12	1
	1.0	2	3
	2.0	1	7
		NA[x]	L***

[z]1 inch = 2.54 cm.
[y]Calculated as percent increase in control with the herbicide + mulch combination in comparison with herbicide-only treatment by using the formula: [(percent control combination − percent control herbicide) ÷ percent control herbicide] × 100. Prodiamine was evaluated with large crabgrass, and dimethenamid-P + pendimethalin was evaluated with garden spurge.
[x]L*** indicates a significant ($P \le 0.001$) linear response based on orthogonal contrast statements; NA = not analyzed because of zero variance.

movement to the soil surface and reduce weed control. Indaziflam is a relatively new active ingredient for use in landscapes and nurseries, and little research has focused on its use in combination with common mulch materials. Burrows (2017) evaluated indaziflam when used in combination with 2 inches of PB mini-nuggets but reported a high level of control and no difference when indaziflam was applied either above or below the mulch layer. However, a high level of control was also reported with mulch-only treatments in that experiment; therefore, it is not clear whether mulch caused any antagonistic effects.

Overall, results from these experiments show that spray formulations of prodiamine and dimethenamid-P + pendimethalin are more effective than granular formulations when applied alone, whereas indaziflam was more effective as a spray formulation when used both alone and in combination with mulch. Increasing irrigation volume lead to statistically lower levels of weed control in the case of indaziflam and dimethenamid-P + pendimethalin in some cases, but considering the overall level of weed control observed, these differences would likely have little practical significance. Furthermore, as control was generally greatest at the lower irrigation volumes, increasing irrigation volume to "move herbicide through the mulch" would likely provide little improvement in weed control, given that label directions are followed. Addition of PRE herbicides becomes more important to overall weed control when lower mulch depths are used, and similarly, addition of mulch becomes more critical when the PRE herbicide is not as effective or troublesome weed species are present. Because of some negative effects observed with the combination, specifically with application of indaziflam to a 1-inch layer of PS, additional research is needed to determine herbicide sorption to various mulch materials. If mulch was applied at an adequate depth, this potential sorption would become less important as the mulch would be able to provide adequate weed control in many cases. Additional studies should also investigate efficacy of these and other combinations when seeds are placed on top of the mulch. If some weed species can germinate and grow within a mulch layer, herbicide binding to these materials could potentially offer greater control of weed seeds that are introduced over the course of a growing season.

In the landscape industry, mulch is usually used in landscape beds for both aesthetic purposes and weed control and typically applied at 2–3 inches (Marble et al., 2015). Mulch is less commonly used in the nursery industry because of the increased cost and difficulty of application but may be used in longer term crops or for crops that are sensitive to PRE herbicide applications (Case et al., 2005). In larger pots or pot-in-pot production systems, herbicide and mulch combinations may be used to extend the length of weed control (Mathers, 2003). Results from these studies indicate that in both the landscape and nursery industries, the use of PRE herbicides, specifically spray-applied formulations, will outperform common mulch materials over the short term (≈9 weeks). Although long-term weed control was not evaluated in these studies, mulch usually provides effective weed control for a greater period of time compared with a single herbicide application; thus, the benefits of using mulch from both a weed management and cost perspective increase over time (Bartley et al., 2017). As seeds were placed on the soil surface before mulching in our study, additional research is needed to determine if there are any synergistic or antagonistic effects of herbicide + mulch combinations over time. Over time, weed seeds would be continually introduced on top of the mulch layer. If certain weed species had the ability to germinate within a layer of mulch, the use of herbicides could provide additional benefits not captured in these experiments. Our data also suggest that weed control will likely not improve with additional overhead irrigation when herbicides and mulch are used concurrently. There does not seem to be any benefit to additional irrigation once the recommended irrigation volume is applied for each herbicide. However, more research is needed on additional herbicides with differing solubility characteristics and more mulch materials.

As would be expected, the use of herbicides became more advantageous when lower mulch levels were used as the lower mulch depth consistently provided less control than the higher depth. Similarly, the use of higher mulch depths became more important when granular herbicides were used (which were less effective) or when eclipta was evaluated as it is difficult to control with PRE herbicides alone. For eclipta and large crabgrass, acceptable weed control was rarely achieved with the use of mulch alone, but with garden spurge, more than 85% control was achieved with HW and PS at 2 inches. For the herbicide + mulch combinations, acceptable weed control was achieved for all three weed species at the 2-inch depth when herbicides were used. Based on these findings, there is an advantage for using PRE herbicides when mulch is applied at depths of 2 inches or less. As mulch depths of 3 inches or even 4 inches are sometimes used in the landscape and provide long-term weed control when used alone (Chalker-Scott, 2007), it is unlikely that PRE herbicides would provide a meaningful benefit until the mulch began to decompose. In "real-world" scenarios, it is also important to consider that it is difficult to uniformly apply mulch at a certain level throughout a landscape bed or within a nursery container. Mulch materials will settle, move off target during rain or wind events, or may be displaced by countless other means. Use of PRE herbicides either soon before or after mulch application could provide additional assurance that a high level of weed control would be achieved in cases where mulch was applied nonuniformly. A topic that has not been studied adequately is the effects of mulch particle size on weed growth and determining what weed species have the ability to germinate and grow within mulch layers. For weed species that can grow within mulch layers, a PRE herbicide application would be beneficial regardless of mulch depth.

Overall, it is likely that PRE herbicides will provide a significant improvement in weed control when mulch depths of 2 inches or less are used. In landscapes where mulch is applied at depths greater than 2 inches, PRE herbicide applications could possibly be delayed until mulch materials began to degrade or weed control began to fail. In the nursery industry, mulch depths of 2 inches or less are most often used as it would be difficult and expensive to apply significantly higher depths inside a nursery container. At these lower mulch depths, growers could use PRE herbicides in combination with mulch in tolerant crops to increase weed control. In crops where herbicides could not be used, mulch would still provide a benefit and would likely be much more cost-effective than hand weeding (Case et al., 2005). In all cases, spray-applied herbicides will likely provide additional benefits over granular herbicides and additional irrigation is likely not warranted when using mulch in combination with herbicides. Additional research is needed to determine how mulch physical properties affect weed germination and growth and to determine how various herbicide + mulch combinations interact so that herbicides could be selected for use with specific mulch materials.

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