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Herbicide and Mulch Interactions: A Review of the Literature and Implications for the Landscape Maintenance Industry

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Use of organic mulch is one of the most common methods of weed control in landscape planting beds and provides other benefits, including improved soil characteristics, increased growth of ornamental plants, and enhanced property aesthetics. In the landscape maintenance industry, it is common to apply mulch and herbicides concurrently to landscape beds to provide long-term, broad-spectrum weed control. It is known that herbicides behave differently when applied to different soil types and organic materials; however, research is lacking concerning which herbicides are most effective with different mulch materials in the landscape. Determining the most effective herbicide–mulch combinations could potentially improve weed control, reduce labor costs from hand weeding, and mitigate negative environmental impacts resulting from off-site herbicide movement. The objective of this paper is to review the research that has been conducted pertaining to various mulch–herbicide combinations in the landscape and in other areas of agricultural production while also identifying key knowledge gaps that should be addressed in future research. Review of the literature suggests satisfactory weed control can be achieved with high mulch depths ($\geq$ 7 cm) regardless of herbicide use, and herbicide–mulch interactions become more pronounced as mulch depth decreases. Additionally, future research is needed to determine which herbicides are best suited for different mulch types to improve weed control and potentially reduce environmental impacts, including herbicide leaching and runoff into urban and suburban waterbodies.

Key words: Landscape planting bed, ornamentals, residential area.

El uso de coberturas orgánicas es uno de los métodos más comunes para el control de malezas en camas de siembra en paisajismo y brinda otros beneficios incluyendo el mejoramiento de las características del suelo, el aumento del crecimiento de plantas ornamentales, y mejores propiedades estéticas. En la industria de mantenimiento de paisajes, es común aplicar coberturas y herbicidas concurrentemente a camas de siembra para brindar un control de malezas más duradero y de amplio espectro. Es sabido que los herbicidas se comportan de forma diferente cuando se aplican a diferentes tipos de suelos y materiales orgánicos. Sin embargo, hay un faltante de información acerca de cuáles herbicidas son más efectivos dependiendo de los materiales para cobertura para paisajes. El determinar la combinación herbicida-cobertura más efectiva podría potencialmente mejorar el control de malezas, reducir los costos de deshierba manual, y mitigar los impactos negativos en el ambiente producto del movimiento no deseado de herbicidas. El objetivo de este artículo es revisar la investigación que se ha realizado relacionada a varias combinaciones cobertura-herbicida en paisajes y en otras áreas de producción agrícola, y a la vez identificar faltantes clave en información que podrían ser el tema de investigaciones futuras. La revisión de literatura sugiere que el control satisfactorio de malezas puede ser alcanzado con coberturas profundas ($\geq$ 7 cm) sin importar el uso de herbicidas, y que las interacciones herbicida-cobertura se vuelven más pronunciadas a medida que la profundidad de la cobertura disminuye. Adicionalmente, se necesitan investigaciones para determinar cuáles herbicidas son los más adecuados para diferentes tipos de coberturas, para así mejorar el control de malezas y potencialmente reducir impactos ambientales, los cuales incluyen lixiviación y escorrentía de herbicidas a cuerpos de agua en zonas urbanas y suburbanas.

Mulch is defined as any material that is applied to, or grows upon, the soil surface (Chalker-Scott 2007). Although multifunctional and often applied merely for aesthetic purposes, mulching is one of the most effective methods of weed control in landscape planting beds. In many cases, PRE-applied herbicides are used in combination with different mulch materials to provide longer durations of weed control and suppress a broader spectrum of weed species. This practice is often recommended to reduce labor costs associated with hand weeding, repeated application of POST-applied herbicides, or both (Wilen and Elmore 2007). There are many

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different PRE active ingredients labeled for use in residential and commercial landscapes, and most are available in different formulations or are commonly sold as combination products containing two or more active ingredients. Many different types of mulch are also available and vary widely in chemical and physical properties.

With multiple PRE-active herbicides and mulch materials readily available to homeowners and professional contractors, the most obvious question to ask is: Which herbicide is best suited for a specific mulch type? Another important factor to consider is how management practices and application procedures should potentially be altered depending on mulch type and herbicide used to achieve the best weed control. Currently, no application guidelines pertain specifically to different mulch types on PRE herbicide labels; the same general guidelines are used for all landscape or planting bed scenarios regardless of mulch type, particle size, or depth. There are several reasons for these omissions. First, herbicide labels are very expensive to develop and require long-term extensive testing, costing the registrant millions of dollars (Fishel 2008). Second, the landscape market would be considered niche in the specialty crop area, and as such, the incentive for the herbicide registrant to perform required testing is less because it is less lucrative and associated with higher liability compared with large-acreage (i.e., agronomic) crops (Fennimore and Doohan 2008). Additionally, a vast array of mulch materials are available, and their use and popularity often varies greatly by region (Chalker-Scott 2007), making it very difficult to test all combinations.

It has been well established that soil type and organic matter content can have a dramatic effect on herbicide behavior (Carter 2000; Weber 1990) and efficacy (Blumhorst et al. 1990). Therefore, it is important to determine which group(s) of herbicides or formulations are best suited for different mulches to achieve the best weed control and whether application procedures for different herbicide–mulch combinations need to be altered. The objective of this manuscript is to discuss the effects of different landscape mulch types with varying physical properties on PRE herbicide efficacy, with a focus toward implications for weed control in the landscape maintenance industry, as well as identify key knowledge gaps and offer suggestions for future research.

Overview and Economic Significance of Landscape Maintenance Sector

Weed control in landscape planting areas continues to be a challenge, partially due to a lack of research (and funding for research) in this area. Administrators and funding sources unfamiliar with the landscaping industry often dismiss this area as a small sector in a niche market, when, in fact, it is a multibillion dollar industry. In 2007, there were approximately 100,000 landscaping service companies in the United States which generated $54 billion in sales and employed more than 1 million people (Hodges et al. 2011). Although the economic impact represents all landscaping services, a large portion of these sales are derived from landscape maintenance contracts. One of the most costly and time-consuming aspects of landscape maintenance is weed control, specifically in perennial or woody ornamental planting beds and other nonturf areas. Currently numerous PRE and POST herbicides are labeled for use in turf that makes weed control in lawns more manageable and cost effective. In contrast, few herbicide options exist for weed control around desirable ornamentals, and the common use of multiple ornamental species in a planting bed make finding safe and effective herbicides difficult for landscape contractors. In many cases, landscape contractors must resort to hand weeding in planting beds, thus paying high labor costs that continue to increase (Martin and Calvin 2010). Small improvements in this area, such as finding the most effective mulch and herbicide combinations, could potentially represent significant labor savings for these companies and consequently higher profit margins.

Mulching as a Weed Control Method

Light Exclusion as a Physical Barrier. Mulch can consist of any material placed on the soil surface (Crutchfield et al. 1986), making the possibilities of different materials or combinations of materials infinite. Common mulch materials include crop or plant residues or yard trimmings, straw, leaves, paper, plastic films or geotextiles, gravel, bark, and other materials. An ongoing trend consists of using waste products as mulch materials, including pine and other barks, newsprint pellets, coconut coir, nut (peanut, pecan, etc.) hulls, wood shavings, and sea shells, among others (Sibley et al. 2004; Somireddy

2012). However, the availability of these waste or salvaged materials and popularity is likely to be variable by region. In most regions of the United States, the most popular materials include pine straw, pine bark (or other barks), cedar chips, shredded hardwood (and colored or dyed wood), and gravel or stone. Landscape fabric or weed barrier materials made of woven polypropylene are also commonly used but are unattractive in the landscape and thus are commonly overlaid with more aesthetically pleasing materials (Skroch et al. 1992). Rubber mulches made of shredded tires are a relatively new material but have not been evaluated extensively in landscape settings. However, some reports suggest that their application as a mulch around ornamentals in residential or commercial landscapes may be somewhat limited because of environmental concerns (zinc toxicity) and flammability (Kanematsu et al. 2009; Smolders and Degryse 2002; Steward et al. 2003).

Although the mechanism responsible for weed control is not well understood for all mulch types (Chalker-Scott 2007), for most weed species, control can be attributed predominately to light exclusion (Teasdale and Mohler 2000). Many weed species, specifically annual species with small seeds, require light to germinate (Wesson and Wareing 1967) and germinate at the soil surface or at very shallow depths (Popay and Roberts 1970). Agronomic studies have shown that light can only penetrate a few millimeters of soil (Pons 1991; Wesson and Wareing 1967); therefore, mulch applied evenly at depths of 5 cm or more, as is commonly recommended, would eliminate light from the soil surface and consequently reduce weed seed germination or prolong dormancy (Fitter and Hay 1987). Mulches can also act as a physical barrier to weed germination and growth. Weeds that germinate near the soil surface may be weakened by even thin layers of mulch that reduce the weeds ability to photosynthesize (Crutchfield et al. 1986; Facelli and Pickett 1991). Landscape fabrics in particular can be very effective as a physical barrier (Skroch et al. 1992); however, this physical effect is temporary, and the benefits of mulch as a physical barrier decrease over time as mulch materials degrade. Additionally, many mulch materials such as pine bark nuggets have hydrophobic properties and quickly dry following rainfall or irrigation, which reduces water availability to germinating weeds (Richardson et al. 2008).

Allelopathic Effects. Certain mulch materials may also control weeds by leaching allelopathic chemicals (Chalker-Scott 2007). Previous studies have shown that winter rye (*Secale cereale* L.) residues, which contain strong allelopathic chemicals, significantly inhibited weed growth in no-tillage cropping systems and were particularly effective on annual broadleaf weed species (Barnes and Putnam 1983). A report by Schumann et al. (1995) suggested that mulches derived from *Pinus patula* Schldl. et Cham., *Eucalyptus grandis* W. Hill ex Maiden, and *Acacia mearnsii* De Wild. contained allelopathic chemicals that suppressed growth of weed species, including *Conyza sumatrensis* (Retz.) E. Walker, *Trifolium* spp., *Echinochloa utilis* Ohwi et. Yabuno, and *Lactuca sativa* L. Numerous other reports suggest strong allelopathic properties from various agronomic crop residues (Einhellig and Leather 1988; Weston 1996), but most of these materials would not be suitable in a landscape setting because of a lack of commercial availability, the tendency of these materials to degrade quickly (which is not a concern in a continual agronomic cropping system), and, most notably, poor aesthetic appeal. Several studies have investigated allelopathic properties of common landscape mulches. Duryea et al. (1999) evaluated six common landscape mulches, including materials made of cypress, eucalyptus, pine bark, pine straw, *Melaleuca*, and a utility trimming mulch. Results showed that extracts from all materials contained hydroxylated aromatic compounds and exhibited allelopathic effects on lettuce seed germination. Lettuce seed germination was inhibited to the greatest degree by extracts from pine straw and utility trimming mulch; however, in field studies, weed seed germination after one year was not different, indicating a decreasing allelopathic effect over time. In a study by Rathinasabapathis et al. (2005), exudates of wood chips from red maple (*Acer rubrum* L.), swamp chestnut oak (*Quercus michauxii* Nutt.), red cedar (*Juniperus silicicola* L.H. Bailey), neem (*Azadirachta indica* A. Juss), and magnolia (*Magnolia grandiflora* L.) were also shown to be highly inhibitory on lettuce seed germination. Additionally, red cedar exudates significantly reduced germination and growth of Florida beggarweed (*Desmodium tortuosum* DC.).

Table 1. Partial list of soil-applied, PRE active herbicides currently registered for use in landscape planting beds, with their mode of action and pertinent physical properties. Information in this table was derived from Senseman (2007).

Common name	WSSA herbicide group[a]	Mode of action	Vapor pressure[b]	K_{oc}[c]	Water solubility[d]
			mPa	mL g^{-1}	mg L^{-1}
Dithiopyr	3	Microtubule assembly inhibition	0.53	1,638	1.38
Oryzalin	3		0.00133	600	2.6
Pendimethalin	3		1.25	17,200	0.275
Prodiamine	3		0.00334	13,000	0.013
Trifluralin	3		14.7	7,000	0.3
Flumioxazin	14	Inhibition of protoporphyrinogen oxidase	0.321	191	1.79
Oxadiazon	14		0.103	3,200	0.7
Oxyfluorfen	14		0.267	100,000	0.1
Dimethenamid-P	15	Inhibition of very long chain fatty acids	36.8	125	1174
S-metolachlor	15		3.73	200	488
Dichlobenil	20	Inhibition of cell wall (cellulose) synthesis	133	400	21.2
Isoxaben	21		0.052	380	1
Indaziflam	29	Inhibition of cellulose biosynthesis	0.000068	496	2.8

[a] WSSA, Weed Science Society of America. Herbicide groups according to primary sites of action (Mallory-Smith and Retzinger, 2003).

[b] Vapor pressure at 25 C; potential volatility decreases as millipascal (mPa) value decreases.

[c] K_{oc} is the ratio of the mass of pesticide absorbed per unit mass of soil to the mass of the pesticide remaining in a solution at equilibrium. In general, solubility decreases as K_{oc} increases.

[d] Water solubility at 20 to 25 C. In general, as solubility increases, binding to soil particles and organic matter decreases.

It should be noted that to realize the benefits of allelopathic effects for weed control, most mulch materials must be applied fresh (without composting) (Duryea et al. 1999), which can have a negative effect on ornamental plant health, primary by limiting available N (Mary et al. 1996).

Common landscape mulch materials that are coarse textured and applied at adequate depths have been shown to provide satisfactory weed control and outperform chemical methods of weed control in certain situations (Cahill et al. 2005; Froment et al. 2000). However, many weed species, specifically perennials, still have the ability to germinate and grow through thick layers of mulch and even landscape fabric materials (Appleton and Derr 1989; Martin et al. 1987). To obtain adequate weed control, specifically for perennial weed species, certain types of mulch need to be applied very deeply (10 to 15 cm), which might not be conducive to ornamental plant growth (Billeaud and Zajicek 1989; Chalker-Scott 2007). Annual weed species can also begin to germinate on top of mulch as it degrades or thins. Therefore, use of PRE herbicides in combination with mulch is an inexpensive method to provide a broader spectrum, longer lasting weed control (Chen et al. 2013).

Herbicide–Mulch Interactions

Current Herbicides and Practices. PRE herbicides labeled for landscape use are predominately members of group 3 based on the mode of action classification of the Weed Science Society of America (Mallory-Smith and Retzinger 2003). This includes the dinitroanilines such as oryzalin, pendimethalin, prodiamine, and trifluralin and pyridines such as dithiopyr. Other common herbicides include *S*-metolachlor, dichlobenil, dimethenamid-P, oxadiazon, isoxaben, indaziflam, and flumioxazin. Many different combination herbicides containing two or more active ingredients are also popular because they eliminate the need for mixing herbicides and provide broader spectrum control. A partial list of commonly used PRE herbicides in commercial or residential landscapes is included in Table 1. Most products marketed toward this industry are in dry granular form, because granular materials are thought to be safer for use on most ornamentals (Hart 2001). These herbicides are applied to landscape planting beds either below (at the time of landscape installation) or on top of mulch materials and watered in (0.6 to 1.3 cm) soon after application. Both the solubility and volatility of these herbicides play an important role in herbicide–mulch interac-

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tions. For example, more volatile herbicides such as dichlobenil (133 mPa; Table 1) would likely be more effective when applied under mulch unless irrigation could be applied soon after application. When greater weed control was achieved with dichlobenil incorporated into mulch, Lanphear (1968) concluded that improved efficacy may have been a result of decreased losses via volatility. Solubility will influence how much herbicide leaves the mulch layer and reaches the soil below. Oxyfluorfen, a common component of many granular combination herbicides, is tightly bound to soil organic matter and may not readily escape the mulch layer and reach the soil surface.

Herbicide Placement. The value of soil-applied herbicides is dependent on its soil activity (Banks and Robinson 1984). It is known that different mulch materials will interact differently with various herbicides. For example, Knight et al. (2001) evaluated movement of isoxaben, metolachlor, and pendimethalin when applied to mulches composed of pine straw, pine bark, or recycled newspaper pellets. Results showed that newspaper pellets absorbed more herbicide (57 to 82% retention) than did pine straw (34 to 88% retention) or pine bark (37 to 83% retention) with metolachlor being absorbed less than any other herbicide in all mulch materials.

Herbicide efficacy has been shown to be inhibited by increasing levels of plant residue on the soil surface in conservation tillage systems (Buhler 1992). These residue materials, or mulch, usually decrease efficacy by intercepting and binding the herbicide and inhibiting it from reaching the soil surface (Banks and Robinson 1986; Chauhan and Abugho 2012) or by increasing microbial activity, which can increase the speed of degradation (Locke and Bryson 1997).

Most of the research pertaining to herbicide–mulch interactions has focused on agronomic cropping systems and conservation tillage in which crop stubble and residue is the primary mulch material (Locke and Bryson 1997). However, a few studies have focused on interactions between common landscape herbicides and mulch materials. In a study by Chen et al. (2013), EPTC (Eptam 5G, Gowan USA Turf & Ornamental Co., Yuma, AZ) was applied at a rate of 0, 4.5, and 6.7 kg ai ha^{-1} either above or below pine straw (PS), pine bark (PB), or shredded cypress (SC) mulch to evaluate yellow nutsedge (*Cyperus esculentus* L.) control. Results indicated that better yellow nutsedge control was achieved when EPTC was applied under mulch, with the greatest effect noticed in SC mulch. This result may be due to the volatile nature of EPTC (4,530 mPa) (Abu-Qare and Duncan 2002; Baker et al. 1996), which possibly degraded more quickly when applied on top of mulch materials. On the basis of their results, Chen et al. (2013) recommended that EPTC be applied under mulch or before replenishing existing landscape beds with fresh mulch. Although conducted in rice fields, Chauhan and Abugho (2012) investigated the use of rice residue mulch with pendimethalin and oxadiazon, both common landscape PRE herbicides. In this study, rice residue was applied to the soil surface of pots filled with field soil at rates of 0, 5.3, and 10.6 g pot^{-1}. Pots were then treated at 0, 0.5, and 1.0 kg ai ha^{-1} of oxadiazon or 0, 1.0, and 2.0 kg ai ha^{-1} of pendimethalin using spray formulations, essentially making applications on top of mulch. Results varied by weed species, but overall data suggested that some weed seedlings may be able to survive herbicide treatment in the presence of residue (i.e., mulch), which acts to intercept herbicide. However, Chauhan and Abugho (2012) noted additional studies were needed with more weed species. Banks and Robinson (1984) investigated the effects of oryzalin applied to straw-covered and nonmulched soils. Presence of straw at the time of application reduced the amount of oryzalin reaching the soil surface, and soil oryzalin concentration declined as the amount of straw increased. A study by Crutchfield et al. (1986) investigating the effects of metolachlor (a common PRE herbicide labeled for landscape use) when applied to mulch showed that although soil concentrations of metolachlor were lower when applied in the presence of wheat straw mulch, weed control increased along with increasing mulch level, possibly because of the weed suppression ability of the mulch and because metolachlor is highly mobile (Sanchez-Martin et al. 1995). However, other reports suggest metolachlor interception by mulch materials results in significantly poorer weed control (Banks and Robinson 1986). In studies by Richardson et al. (2008), pine bark nuggets were applied to nursery containers at depths of 0, 3.8, and 7.6 cm and either treated with flumioxazin (Broadstar® 0.25G, Valent USA, Walnut Creek, CA) or left untreated (mulch only). In general, weed control increased with increasing mulch depth, regardless of herbicide treatment, indicating that in deeper mulch depths, weed control may be attributable more to mulch than to herbicides and that herbicides will have a more significant effect on efficacy at lower mulch depths.

Influence of Mulch Particle Size and Composition on Herbicide Efficacy. A series of experiments by Somireddy (2012) examined herbicide placement on various organic mulch materials and its effect on weed control. In one experiment, hardwood mulch and pine nuggets were used alone at depths of 3, 6, or 12 cm or in combination with liquid formulations of trifluralin (Treflan HFP, Dow AgroSciences) plus isoxaben (Gallery 75DF, Dow AgroSciences) (T+G) or a granular product containing both trifluralin (2%) and isoxaben (0.5%) (Snapshot 2.5TG, Dow AgroSciences) (SS), which were applied either above or below the mulch layer. Few differences were noted among different herbicide treatments within each of the highest two mulch depths, indicating that mulch depth alone provided satisfactory weed control. At the 3-cm depth, treatments providing the most consistent commercially acceptable weed control were SS over pine nuggets, T+G under pine nuggets, and T+G under hardwood. This result was possibly due to differences in particle sizes of the products; pine nuggets were more coarse textured than the hardwood mulch; thus, the granular material (SS) may have moved more readily to the soil surface below the mulch layer, whereas the spray (T+G) could have possibly bound more tightly to the mulch when applied on top or have lost more through runoff, photodecomposition, or volatilization (Weber 1990). In a study by Case and Mathers (2006), herbicides, including oryzalin, acetochlor, flumioxazin, and dichlobenil, were applied either over or under hardwood bark or pine nuggets and evaluated at 30, 60, 90, and 120 d (averaged together = early ratings) and again at 1 yr (late ratings). Within the hardwood bark mulch treatment at the early ratings, oryzalin was the only herbicide treatment that provided significantly better weed control when applied under hardwood bark; all other herbicides provided similar control both above and below the hardwood bark. Within the pine nugget treatments, no herbicide placement effects were noted during early ratings with the exception of flumioxazin, which provided better weed control when applied on top of pine bark nuggets. At 1 yr, few treatment differences were noted, and the same general trend was observed. Data from this trial and similar trials (Mathers and Case 2006) indicate better weed control was achieved in pine bark plots compared with hardwood mulch plots. These results would agree with findings by Somireddy (2012), in that better weed control may be achieved when applying herbicides to more coarse textured (larger particle size) mulches, such as pine bark, because herbicides are more likely to move down into the soil layer, specifically for granular materials, which are more commonly used in the landscape. Further illustrating this point, studies by Wilson et al. (1995) evaluating sprayable and granular formulations of trifluralin and isoxaben showed that minimal losses occurred when the granular formulations were applied to gravel compared with treatments applied to plastic or fabric surfaces.

Herbicide-Treated Mulches. These and similar results have led many researchers to recommend that most herbicides be applied under mulch for the best weed control (Wilen and Elmore 2007). In contrast, some extension publications recommend applying mulch first, and then herbicides (Appleton and Kauffman 2009). Very few publications have focused on herbicide–mulch interactions using common landscape herbicides and mulch materials; however, weed control data obtained from similar scenarios (i.e., ornamental crop production) could be used to develop mulch–herbicide recommendations or be used as a starting point for future studies. An innovative approach is the use of herbicide-treated mulches in the landscape as a means to simultaneously apply mulch and herbicide and thus offer labor savings and possibly improved weed control. Herbicide-treated mulches may also decrease calibration errors common during herbicide applications and reduce herbicide phytotoxicity and leaching (Knight et al. 2001; Somireddy 2012). Several studies have shown increased weed control with different herbicides when impregnated or incorporated into mulch than when the herbicide or mulch is used alone (Derr 1994; Lanphear 1968; Mathers 2003; Samtani et al. 2007; Wells et al. 1987). Dichlobenil granules incorporated into a peat moss mulch have been shown to provide better weed control than dichlobenil or mulch alone, possibly as a result of reducing herbicide losses to volatility (Lanphear 1968). Container studies by Mathers (2003) using herbicide-treated Douglas fir (*Pseudotsuga menziesii*) nuggets treated with oryzalin or flumioxazin provided better weed control than bark or herbicides applied alone. Furthermore, Mathers reported a 1.8-fold increase in herbicide efficacy and a 2.2-fold reduction in phytotoxicity when oryzalin or flumioxazin-treated mulches were used compared with bark or herbicides applied alone. Reduced phytotoxicity was also noted by Samtani et al. (2007) using rice hulls, leaf waste pellets, and pine bark as herbicide carriers for oryzalin and diuron [3-(3,4-dichlorophenyl)-1,1-dimethylurea), but weed control was similar among conventionally applied herbicides (with water as the carrier) and the herbicides applied using organic mulch carriers. A similar study (Mathers and Case 2010) showed Douglas fir and pine mulch treated with emulsifiable concentrate (EC) and microencapsulated (ME) formulations of acetochlor provided better weed control than bark or herbicides applied alone; however, bark plus herbicides (applied separately to the same pots) were not evaluated in these trials.

Knowledge Gaps and Future Research Needs

Although several studies have focused on various herbicide–mulch combinations in both field and container studies, there remains a significant knowledge gap in this area concerning interactions between the most common landscape herbicide and mulch combinations. For example, there are essentially no previous reports examining various landscape herbicides and pine straw mulch, one of the most common mulch materials in the southeastern United States, in terms of how herbicide efficacy is influenced by its use as a mulch in the landscape. Several new herbicides have become available to the landscape sector in recent years, including dimethenamid-P (Tower® and as a component of FreeHand®, BASF, Research Triangle Park, NC 27709), Specticle® (Bayer Environmental Science, Research Triangle Park, NC 27709), and new formulations of older materials such as isoxaben (Gallery® SC, Dow AgroSciences, Indianapolis, IN 46268). Another aspect to consider is the need, if any, to alter irrigation procedures after application to mulch in the landscape. Herbicides will need to be watered after application to be incorporated (Altland et al. 2003), but few studies have examined whether more irrigation is needed for improved efficacy in mulched landscape beds. Herbicide efficacy in soilless container substrates can be influenced by irrigation volume after application (Yang et al. 2013), and it would seem that more irrigation is likely needed to move herbicides through organic mulch layers for them to reach the soil surface to control germinating weeds. It is also important to note that most of the previous studies evaluated weed germination from underneath mulch layers. Richardson et al. (2008) showed that at shallow mulch depths, weed seed entering mulched areas are more likely to germinate than seeds on the soil surface. Although this finding is not significant at the time of installation when all weed seeds will be concentrated on the soil surface, it does become important over time because weed seed will likely be transported on top of existing mulch beds. Therefore, it is not only critical to examine different mulch–herbicide combinations, but also how weed seed placement (either existing on the soil floor or blown in after installation) affects weed germination through various mulch–herbicide combinations.

It is also important to determine how different mulch materials affect herbicide leaching and runoff after application. In a study by Wilson et al. (1995), maximum cumulative herbicide losses of isoxaben, oryzalin, and trifluralin occurred within the first 6 d after application, as similarly reported by Wauchope (1987) with atrazine. It is known that many different landscape mulch materials reduce soil erosion and slow water runoff (Chalker-Scott 2007), and different mulch materials have been shown to reduce herbicide movement and off-target contamination (Fawcett et al. 1994). Organic mulch materials used as herbicide carriers can reduce herbicide leaching by up to 74% in the landscape (Knight et al. 2001). More research is needed with common landscape herbicides to determine how different mulch materials affect leaching and runoff potential and whether environmental concerns resulting from herbicide runoff and leaching can be mitigated through the use of certain mulch materials.

Conclusions

Through examination of previous research, it appears that adequate weed control can be achieved with higher mulch depths ($\geq$ 7 cm), regardless of herbicide, herbicide placement, or rate, mostly because of the weed suppressive abilities of the mulch. However, thick mulch layers are not always ideal or suitable for many different ornamentals, which can be negatively affected by thick mulch layers (Billeaud and Zajicek 1989), and the herbicide, herbicide placement, application procedure, rate, and interaction between the herbicide and mulch becomes more and more significant as mulch depth decreases. To reduce increasing labor costs while meeting the demands of discerning homeowners and property managers, it is important to find the most efficient and effective herbicide–mulch combinations for use in the landscape. Determining which herbicides are best suited for different mulch types not only will provide improved weed control but also have the potential to decrease phytotoxicity concerns and alleviate environmental impacts, including herbicide leaching and runoff into urban and suburban waterbodies.

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