*Weed Technology* 2017 31:21–31


# Carryover of Common Corn and Soybean Herbicides to Various Cover Crop Species

Cody D. Cornelius, and Kevin W. Bradley*

The recent interest in cover crops as component of Midwest corn and soybean production systems has led to the need for additional research, including the effects of residual corn and soybean herbicide treatments on fall cover crop establishment. Field studies were conducted in 2013, 2014, and 2015 in Columbia, Missouri to investigate the effects of common residual herbicides applied in corn and soybean on establishment of winter wheat, tillage radish, cereal rye, crimson clover, winter oat, Austrian winter pea, Italian ryegrass, and hairy vetch. Cover crops were evaluated for stand and biomass reduction 28 d after emergence (DAE). Rainfall from herbicide application to cover crop seeding date was much greater in 2014 and 2015, which resulted in less carryover in these years compared to 2013. When averaged across all herbicides evaluated in these experiments, the general order of sensitivity of cover crops to herbicide carryover, from greatest to least was Austrian winter pea = crimson clover > oilseed radish > Italian ryegrass > hairy vetch > wheat > winter oat > cereal rye. Cereal rye had the fewest instances of biomass or stand reduction with only four out of the 27 herbicides adversely effecting establishment. Pyroxasulfone consistently reduced Italian ryegrass and winter oat biomass at least 67% in both the corn and soybean experiments. In the soybean experiment, imazethapyr- and fomesafen-containing products resulted in severe stand and biomass reduction in both years while flumetsulam-containing products resulted in the greatest carryover symptoms in the corn experiment. Results from these experiments suggest that several commonly used corn and soybean herbicides have the potential to hinder cover crop establishment, but the severity of damage will depend on weather, cover crop species, and the specific herbicide combination.

**Nomenclature:** Flumetsulam; fomesafen; imazethapyr; pyroxasulfone; Austrian winter pea, *Pisum sativum* L; cereal rye, *Secale cereale* L; corn, *Zea mays* L, crimson clover, *Trifolium incarnatum* L; hairy vetch, *Vicia villosa* Roth; Italian ryegrass, *Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot; oat, *Avena sativa* L; oilseed radish, *Raphanus sativus* L; soybean, *Glycine max* (L.) Merr; wheat, *Triticum aestivum* L.

**Key words:** Herbicide carryover, residual herbicides, stand reduction.

El reciente interés en el uso de cultivos de cobertura como componente de los sistemas de producción de maíz y soja en el medio oeste ha llevado a la necesidad de realizar investigación adicional que incluya los efectos de los tratamientos de herbicidas residuales en maíz y soja sobre el establecimiento de cultivos de cobertura en el otoño. Estudios de campo fueron realizados en 2013, 2014, y 2015 en Columbia, Missouri, para investigar los efectos de herbicidas residuales comunes aplicados en maíz y soja sobre el establecimiento de trigo de invierno, rábano, centeno, *Trifolium incarnatum*, avena de invierno, guisante, *Lolium perenne*, y *Vicia villosa*. Los cultivos de cobertura fueron evaluados por reducciones en el establecimiento y la biomasa 28 d después de la emergencia(DAE). La precipitación desde la aplicación del herbicida hasta la siembra del cultivo de cobertura fue mucho mayor en 2014 y 2015, lo que resultó en menos efecto residual de los herbicidas en estos años al compararse con 2013. Cuando se promediaron todos los herbicidas evaluados en estos experimentos, el orden general de sensibilidad de los cultivos de cobertura a los residuos de herbicidas de mayor a menor fue guisantes = *T. incarnatum* > rábano > *L. perenne* > *V. villosa* > trigo > avena de invierno > centeno. El centeno tuvo el menor número de instancias en que se redujo la biomasa o el número de plantas establecidas con solamente cuatro de 27 herbicidas afectando negativamente el establecimiento. Pyroxasulfone redujo consistentemente la biomasa de *L. perenne* y avena de invierno al menos 67% en los experimentos de maíz y soja. En el experimento de soja, productos que contenían imazethapyr y fomesafen resultaron en reducciones severas en el establecimiento y la biomasa en ambos años mientras que productos conteniendo flumetsulam resultaron en los mayores síntomas de daño por residuos de los herbicidas en el experimento de maíz. Los resultados de estos experimentos sugieren que varios herbicidas comúnmente usados en maíz y soja tienen el potencial de reducir el establecimiento de cultivos de cobertura, pero la severidad del daño dependerá del clima, la especie de cultivo de cobertura, y la combinación específica de herbicidas.

DOI: 10.1614/WT-D-16-00062.1

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According to a survey of cover crop users in the United States, the second biggest challenge to the adoption of cover crops is successful establishment in a corn or soybean production system (SARE 2014). Additionally, certain residual herbicides applied in a corn and soybean rotation have the potential to carry over in the soil and inhibit successful establishment of fall-seeded cover crops (Curran et al. 1996). The adoption of no-tillage systems in recent years has shifted weed control tactics away from an emphasis on tillage and towards the use of non-selective pre-plant and residual herbicides that allow growers to plant into weed-free fields and keep the fields weed free for several weeks after planting. In addition, overreliance on glyphosate has resulted in an increase in glyphosate- and multiple-herbicide resistant weeds (Heap 2016), leading many growers to apply additional residual, soil-applied herbicides in order to achieve adequate weed control (Hager et al. 2003; Riggins and Tranel 2012). For example, the use of diphenyl ether and dinitroaniline herbicides increased by approximately 24% in the United States from 2006 to 2012, while the percentage of soybean acres that received at least one pre-emergence residual herbicide application increased by approximately 19% from 2001 to 2006 (USDA 2015).

Soil characteristics such as pH, organic matter, cation exchange capacity, and soil texture have been shown to play a major role in the degradation of soil-applied herbicides. Soil persistence of herbicides like imazaquin and imazethapyr has been found to increase as soil pH decreases, as a result of greater adsorption that results in the herbicide being less available for microbial degradation (Cantwell et al. 1989; Loux and Reese 1993). In soils with greater than 3% organic matter, herbicide carryover potential is increased (Curran 2001). Soil texture also plays a role in the likelihood of herbicide carryover; Westra et al. (2014) found that the half-life ($DT_{50}$) of pyroxasulfone ranged from 104 to 134 d in a fine clay loam soil and from 46 to 48 d in a fine sandy loam soil. In addition, Kerr et al. (2004) found that herbicide persistence is more likely when soil cation exchange capacity levels are higher. Environmental factors, such as the amount of rainfall and the temperature after application, also play a major role in herbicide degradation. For example, Bauer and Calvet (1999) found that the dissipation rate of simazine, atrazine, diuron, and sulcotrione increased as soil moisture increased, while Zimdahl et al. (1984) and Tharp and Kells (2000) showed that pendimethalin degraded more quickly with increasing amounts of rainfall, causing less injury to subsequent crops. In addition, Westra et al. (2014) observed that, regardless of sand or clay content, pyroxasulfone and *S*-metolachlor dissipation rates were positively correlated with the amount of irrigation. In reduced tillage systems, research results on the effects of environmental factors on herbicide carryover have been mixed, but most authors indicate that climatic variables such as rainfall and temperature have a greater impact on herbicide carryover than does residue management (Kells et al. 1990; Locke and Bryson 1997).

Few studies have examined the potential carryover effects of common soil residual herbicides applied to corn and soybean to fall-seeded cover crops. In one Michigan study, pendimethalin and metolachlor were found to reduce stand densities of Italian ryegrass by 46% and 94%, respectively, 40 d after treatment (Tharp and Kells 2000). Hanson and Thill (2001) found that imazethapyr applied to lentil (*Lens culinaris* Medik) and Austrian winter pea reduced the biomass of a subsequently planted wheat crop by 35% to 51% (Hanson and Thill 2001). Walsh et al. (1993a) reported winter wheat injury of 25% five months after an application of clomazone in soybean. These same authors also reported cotton injury as high as 33% following imazaquin, and corn and grain sorghum [*Sorghum bicolor* (L.) Moench ssp. *bicolor*] injury from 7% to 24% following metribuzin + chlorimuron, imazaquin, clomazone, or imazethapyr. Walsh et al. (1993b) also found that a 2 × rate of clomazone reduced spring-planted winter oat biomass by 44%, while imazaquin and imazethapyr did not cause significant carryover symptoms. Overall, few studies have examined the effects of within-season applications of residual herbicides on fall-seeded cover crops, and many of those that have been conducted have not investigated some of the species that are currently being promoted and/or investigated for inclusion in corn and soybean production systems. Therefore, the objectives of this research were to determine the potential of common corn and soybean residual herbicides to reduce stand densities and biomass of subsequent fall-seeded cover crop species.

## Materials and Methods

**General Trial Information.** Field experiments were conducted in 2013 and repeated in 2014 and

2015 in Boone County at the University of Missouri Bradford Research Center near Columbia, Missouri (38°53'53.22''N, 92°22'14.42''W). The soil was a Mexico silt loam (fine, smectic, mesic Aeric Vertic Epiaqualf) with 2.3% organic matter and a pH of 6.5 in 2013, 2.1% organic matter and a pH of 6.4 in 2014, and 2.2% organic matter and a pH of 6.3 in 2015. Corn and soybean were planted into a no-till seedbed in rows spaced 76 cm apart at rates of 71,661 and 444,789 seeds ha$^{-1}$, respectively. Corn herbicides were applied once corn reached the V2 stage of growth. Soybean herbicides were applied POST once the soybeans reached the V2 to V3 stage of growth, except in the case of flumioxazin, sulfentrazone, metribuzin, sulfentrazone + cloransulam, and chlorimuron, which were applied PRE based on crop safety requirements. Herbicides were applied using a $CO_2$-pressurized backpack sprayer equipped with XR 8002 flat fan nozzle tips (TeeJet®, Spraying Systems Co., P.O. Box 7900, Wheaton, IL 60187) delivering 140 L ha$^{-1}$ at 117 kPa. All treatments were arranged in a split-plot design with four replications. Whole plots consisted of herbicide treatments, while subplots consisted of cover crop species. Subplots were 3 by 3 m in size. Dates of major field operations and specific rainfall between herbicide application and cover crop planting dates are shown in Table 1. Monthly rainfall totals and average temperatures for each year are presented in Table 2. A list of all herbicide formulations evaluated and their respective application timing can be found in Table 3. Following removal of the previous corn or soybean crop for forage, seven winter annual cover crops were planted on September 11, 12, and 10 in 2013, 2014, and 2015, respectively, at the following seeding rates: 'Roane' winter wheat at 135 kg ha$^{-1}$, cereal rye at 123 kg ha$^{-1}$, 'Marshall' Italian ryegrass at 28 kg ha$^{-1}$, winter oat at 78 kg ha$^{-1}$, crimson clover at 34 kg ha$^{-1}$, Austrian winter pea at 56 kg ha$^{-1}$, hairy vetch at 34 kg ha$^{-1}$, and 'Tillage Radish' oilseed radish at 9 kg ha$^{-1}$. All cover crops were planted with a 750 no-till drill (Deere & Company, 1 John Deere Place, Moline, IL 61265).

**Treatment Evaluation and Data Collection.** All cover crop species were evaluated for stand and biomass reduction 28 d after emergence (DAE). Stand counts were performed by counting all emerged plants within two 1/3 m$^2$ quadrats in each subplot. In a similar manner, aboveground biomass was collected within one 1/3 m$^2$ quadrat from each subplot. Biomass samples were weighed after being dried at 49 C for 96 hr. Percent stand and biomass reductions were calculated by dividing the differences between the treated and non-treated plots by the non-treated plot values.

**Statistical Analysis.** All stand and biomass reduction data were analyzed in SAS® version 9.3 (SAS Institute Inc., Cary, NC) using the PROC GLIMMIX

Table 1. Dates of major field operations and rainfall following herbicide application in 2013, 2014, and 2015 at the University of Missouri Bradford Research Farm in Boone County, Missouri and at the Moberly Missouri site in Randolph County, Missouri.[a]

| Field operation | Date of operation and rainfall following herbicide application | | |
|---|---|---|---|
| | 2013 | 2014 | 2015 |
| Corn experiment | | | |
| Corn seeding date | 6/12 | 5/19 | 6/16 |
| Date of herbicide application | | | |
| V2 | 6/26 | 6/11 | 6/30 |
| Cover crop seeding date | 9/11 | 9/11 | 9/13 |
| Rainfall from herbicide application to cover crop seeding date | 96 cm | 362 cm | 331 cm |
| Soybean experiment | | | |
| Soybean seeding date | 6/12 | 6/3 | 7/14 |
| Dates of herbicide application | | | |
| PRE | 6/13 | 6/6 | 7/14 |
| V2-V3 | 7/2 | 6/17 | 7/28 |
| Cover crop seeding date | 9/11 | 9/11 | 9/13 |
| Rainfall from herbicide application to cover crop seeding date | | | |
| PRE | 131 cm | 404 cm | 218 cm |
| POST V2-V3 | 90 cm | 358 cm | 127 cm |

[a] Abbreviations: V2, two leaves; V2-V3, two to three leaves; PRE, pre-emergence; POST, post-emergence.



https://doi.org/10.1614/WT-D-16-00062.1 Published online by Cambridge University Press

Table 2. Monthly rainfall and average monthly temperatures in 2012, 2013, 2014, and 2015 at the Bradford Research Center in Boone County, Missouri, with 30-yr averages for comparison.

| | Rainfall | | | | | Temperature | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Month | 2012 | 2013 | 2014 | 2015 | 30-yr avg[a] | 2012 | 2013 | 2014 | 2015 | 30-yr avg |
| | mm | | | | | C | | | | |
| January | 26 | 61 | 23 | 24 | 56 | 1 | 1 | -4 | 0 | -1 |
| February | 55 | 98 | 35 | 36 | 63 | 3 | 1 | -4 | -4 | 2 |
| March | 113 | 84 | 31 | 39 | 81 | 14 | 4 | 5 | 8 | 8 |
| April | 171 | 188 | 210 | 84 | 114 | 14 | 12 | 13 | 14 | 14 |
| May | 25 | 249 | 78 | 144 | 138 | 21 | 18 | 19 | 19 | 18 |
| June | 39 | 52 | 129 | 192 | 132 | 24 | 23 | 23 | 24 | 24 |
| July | 18 | 62 | 37 | 213 | 115 | 29 | 24 | 23 | 25 | 26 |
| August | 49 | 48 | 75 | 80 | 114 | 25 | 24 | 25 | 23 | 25 |
| September | 46 | 62 | 156 | 29 | 109 | 20 | 22 | 19 | 20 | 21 |
| October | 68 | 72 | 259 | 25 | 85 | 13 | 14 | 14 | 14 | 14 |
| November | 25 | 37 | 34 | – | 105 | 8 | 6 | 4 | – | 8 |
| December | 42 | 43 | 56 | – | 64 | 4 | -1 | 3 | – | 1 |

[a] 30-yr averages (1981 to 2010) obtained from the National Climatic Data Center (2011).

procedure. Herbicide treatment and cover crop species were considered fixed effects in the model, while environment and replicate were considered random effects. Results revealed significant interactions between years, likely due to the considerable differences in rainfall (Table 2); therefore, results are presented by year. Means were separated using Fisher's protected LSD at $\alpha = 0.05$.

## Results and Discussion

**Carryover of Soybean Herbicides.** In general, herbicide degradation is more rapid with adequate soil moisture and warm temperatures (Zimdahl 2007). In 2013 and 2015, there was a significant cover crop species by herbicide treatment interaction for biomass and stand reduction, but this interaction was not significant in 2014 (Table 4). This can be attributed to the fact that there was substantially more rainfall from the time of herbicide application to cover crop planting in 2014: from the time of the herbicide applications to the cover crop planting date, these plots received at least 268 and 186 mm more rainfall in 2014 than they did in 2013 and 2015, respectively (Table 1).

Winter wheat biomass was reduced in 2013 following imazethapyr, pyroxasulfone, and fomesafen + *S*-metolachlor treatment, but no significant carryover was observed in 2015 (Tables 5 and 6). Imazethapyr, pyroxasulfone, and fomesafen + *S*-metolachlor treatments resulted in a 26% to 41% reduction in winter wheat biomass in 2013. When averaged across all herbicide treatments, winter wheat biomass was reduced 28% in 2014, and no carryover was observed in 2015 (Table 7).

Oilseed radish density and biomass were reduced following fomesafen, imazethapyr, and fomesafen + *S*-metolachlor in 2013 and 2015 (Tables 5 and 6). In 2013, imazethapyr and fomesafen + *S*-metolachlor resulted in 62% to 76% oilseed radish biomass reduction, while fomesafen resulted in less biomass reduction (51%) than imazethapyr, but a similar level to that provided by fomesafen + *S*-metolachlor. Additionally, sulfentrazone + cloransulam reduced oilseed radish biomass by 26% in 2013, but no stand or biomass reduction were observed following this herbicide treatment in 2015, most likely due to the higher rainfall in 2015 compared to 2013 (Tables 1 and 2). Throughout both experiments, certain



https://doi.org/10.1614/WT-D-16-00062.1 Published online by Cambridge University Press

Table 3 . Sources of herbicides used in the experiments

| Herbicide | Trade name | Formulation | Rate | Manufacturer | Address |
|---|---|---|---|---|---|
| Soybean Experiment | | | kg ai or ae $ha^{-1}$ | | |
| Acetochlor | Warrant® | 3 L | 1.26 | Monsanto | St. Louis, MO |
| Chlor + Thif | Synchrony® XP | 28.4 WG | 0.0057 + 0.0018 | DuPont | Wilmington, DE |
| Chlorimuron | Classic® | 25 DF | 0.0263 | DuPont | Wilmington, DE |
| Cloransulam | FirstRate® | 84 DF | 0.0353 | Dow AgroSciences | Indianapolis, IN |
| Flumioxazin | Valor® | 51 WG | 0.089 | Valent | Walnut Creek, CA |
| Fomesafen | Flexstar® | 1.88 L | 0.33 | Syngenta | Greensboro, NC |
| Imazethapyr | Pursuit® | 2 EC | 0.07 | BASF | Research Triangle Park, NC |
| Lactofen | Cobra® | 2 EC | 0.22 | Valent | Walnut Creek, CA |
| Metribuzin | Sencor® | 75 DF | 0.42 | Bayer CropScience | Research Triangle Park, NC |
| Pyroxasulfone | Zidua | 85 WG | 0.18 | BASF | Research Triangle, NC |
| *S*-met + Fom | Prefix® | 5.92 EC | 1.22 + 0.266 | Syngenta | Greensboro, NC |
| S-metolachlor | Dual II Magnum® | 7.64 EC | 1.43 | Syngenta | Greensboro, NC |
| Sulf + Clor | Authority First® | 70 DF | 0.28 + 0.036 | FMC Corporation | Philadelphia, PA |
| Sulfentrazone | Spartan® | 4 L[a] | 0.28 | FMC Corporation | Philadelphia, PA |
| Corn Experiment | | | | | |
| Acet + Clop + Flum | Surestart® | 47.24 L | 0.92 + 0.093 + 0.029 | Dow AgroSciences | Indianapolis, IN |
| Atrazine | Aatrex® | 4 L | 2.24 | Syngenta | Greensboro, NC |
| Clopyralid | Stinger® | 3 L | 0.21 | Dow AgroSciences | Indianapolis, IN |
| Flumetsulam | Python® | 80 WG | 0.056 | Dow AgroSciences | Indianapolis, IN |
| Isoxaflutole | Balance Flexx® | 2 SC | 0.088 | Bayer CropScience | Research Triangle Park, NC |
| Mesotrione | Callisto® | 4 L | 0.11 | Syngenta | Greensboro, NC |
| Nicosulfuron | Accent® Q | 54.5 WG | 0.034 | DuPont | Wilmington, DE |
| Pyroxasulfone | Zidua® | 85 WG | 0.18 | BASF | Research Triangle, NC |
| Rimsulfuron | Resolve® | 25 DF | 0.018 | DuPont | Wilmington, DE |
| S-met + Gly + Meso | Halex® GT | 4.4 SC | 1.17 + 1.17 + .117 | Syngenta | Greensboro, NC |
| Tembotrione | Laudis® | 3.5 L | 0.092 | Bayer CropScience | Research Triangle Park, NC |
| Thien + Tembo | Capreno® | 3.45 SC | 0.015 + 0.076 | Bayer CropScience | Research Triangle Park, NC |
| Topramazone | Impact® | 2.8 L | 0.018 | AMVAC | Newport Beach, CA |
| Crop Oil Concentrate | Relay® | 100 L | 1.4 L $ha^{-1}$ | Van Diest Supply Co. | Webster City, IA |
| Ammonium Sulfate | N-Pak® AMS | 3.4 L | 2.9 | Winfield Solutions | St. Paul, MN |
| Non-Ionic Surfactant | Astute® | 100 L | 0.35 L $ha^{-1}$ | MFA | Columbia, MO |

[a] Abbreviations: Chlor, chlorimuron; Thif, thifensulfuron; S-met, *S*-metolachlor; Fom, fomesafen; Sulf, sulfentrazone; Clor, cloransulam; Acet, acetochlor; Clop, clopyralid; Flum, flumetsulam; Gly, glyphosate; Meso, mesotrione; Thien, thiencarbazone; Tembo, tembotrione; L, liquid; WG, water-dispersible granule; DF, dry flowable; EC, emulsifiable concentrate; SC, soluble concentrate.

herbicides resulted in cover crop biomass reduction but no significant stand reduction, as was the case with sulfentrazone + cloransulam in 2013. This response is not uncommon, and is probably because the herbicides allowed seedlings to emerge, but as the seedlings developed their roots absorbed the herbicide residues resulting in injury and biomass reduction. In 2015, fomesafen, imazethapyr, and fomesafen + *S*-metolachlor resulted in 33% to 43% oilseed radish biomass reduction. Oilseed radish stand reduction was the greatest, 41%, following fomesafen, but stand reduction remained similar to imazethapyr and acetochlor; fomesafen + *S*-metolachlor also resulted in 19% stand reduction. The consistent carryover effects of fomesafen-containing products and imazethapyr in oilseed radish can be correlated with the herbicides' extended half-life in clay soils (Cantwell et al. 1989; Loux and Reese 1993; Mueller et al. 2014; Shaner et al. 2014) and the sensitivity of this cover crop to low residue levels of these herbicides.

Cereal rye stand was not reduced by any herbicide treatment in either year (Tables 5 and 6). These results are similar to those of Smith et al. (2015), who reported that cereal rye was not impacted by commonly used soybean herbicides across two years in Wisconsin and Indiana. However, in 2013 cereal rye biomass was reduced by at least 24% following flumioxazin and cloransulam. In 2015, sulfentrazone



https://doi.org/10.1614/WT-D-16-00062.1 Published online by Cambridge University Press

Table 4. Summary of effects of cover crop species and herbicide treatment on cover crop biomass and stand density reduction 28 days after emergence of corn or soybean.

| | Biomass reduction | | | Stand reduction | | |
|---|---|---|---|---|---|---|
| Variable | 2013 | 2014 | 2015 | 2013 | 2014 | 2015 |
| Corn experiment | P-value | | | | | |
| Cover crop species | <0.0001 | 0.0348 | 0.2164 | 0.0006 | 0.0180 | <0.0001 |
| Herbicide treatment | 0.0248 | 0.6737 | 0.0389 | <0.0001 | 0.0001 | 0.7387 |
| Herbicide treatment * cover crop | <0.0001 | 0.1402 | 0.9098 | <0.0001 | 0.9737 | 0.9859 |
| Soybean experiment | | | | | | |
| Cover crop species | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| Herbicide treatment | <0.0001 | <0.0001 | <0.0001 | 0.1123 | 0.7602 | <0.0001 |
| Herbicide treatment * cover crop | <0.0001 | 0.9476 | 0.0007 | 0.0190 | 0.9983 | 0.0002 |

reduced cereal rye biomass by 33%. In 2014, when averaged across all herbicide treatments, cereal rye biomass and stand density were reduced by 17% and 11%, respectively (Table 7). At near neutral pH, cloransulam has been shown to have a half-life as long as 200 d, which would help to explain the observed carryover to cereal rye (Shaner et al. 2014).

Crimson clover stand or biomass was reduced following fomesafen and acetochlor in 2013 and 2015 (Tables 5 and 6). In 2013, crimson clover stand density was reduced by 23% following acetochlor. Biomass was similarly reduced by at least 29% following metribuzin, *S*-metolachlor, and acetochlor in 2013. In 2015, biomass was also reduced from 31% to 38% following sulfentrazone + cloransulam, fomesafen, imazethapyr, chlorimuron + thifensulfuron, and acetochlor in 2015. The consistent carryover observed from fomesafen can be attributed to the extended half-life of this herbicide. Acetochlor carryover to crimson clover is consistent with the 8 mo rotational restriction listed on the herbicide label (Anonymous 2016f).

Winter oat stand density or biomass was reduced in 2013 and 2015 following imazethapyr and pyroxasulfone (Tables 5 and 6). Imazethapyr reduced winter oat biomass by 42% and 52% in 2013 and 2015, respectively, but stand density was not impacted in either year. Pyroxasulfone reduced winter oat stand density by 45% in 2015, and reduced biomass by 68% in 2015. In 2015, winter oat biomass was also reduced by at least 31% following flumioxazin, acetochlor, and chlorimuron, while stand density was reduced 22% and 19% following fomesafen and sulfentrazone. When averaged across all cover crops, pyroxasulfone and imazethapyr resulted in a 32% and 25% reduction in stand density, respectively (Table 8). This consistent trend of pyroxasulfone carryover coincides with the results of Westra et al. (2014), who showed a pyroxasulfone half-life of 104 to 134 d in soils with high clay content.

Flumioxazin, metribuzin, fomesafen, and acetochlor reduced Austrian winter pea stand density or biomass in 2013 and 2015 (Tables 5 and 6). In 2013, flumioxazin, metribuzin, fomesafen, cloransulam, *S*-metolachlor, pyroxasulfone, and acetochlor reduced Austrian winter pea biomass by at least 26%, but stand density was not affected by any herbicide except flumioxazin. In 2015, sulfentrazone, flumioxazin, metribuzin, fomesafen, and acetochlor reduced Austrian winter pea biomass between 28% and 37%, while stand density was unaffected. Flumioxazin and sulfentrazone have been reported to have half-lives as long as 21 and 71 days, respectively, under field conditions (Mueller et al. 2014). In addition, flumioxazin, metribuzin, and fomesafen require at least a 4 mo rotational restriction before planting Austrian winter peas (Anonymous 2016b, 2016d, 2016e).

Italian ryegrass stand density and biomass were reduced by at least 57% and 67%, respectively, in response to previous applications of pyroxasulfone in 2013 and 2015 (Tables 5 and 6). Bond et al. (2014) reported that 0.16 kg ai $ha^{-1}$ pyroxasulfone provided 93% control of Italian ryegrass 180 d following a fall application. Therefore, the substantial reductions in Italian ryegrass stand and biomass can be attributed to the extended half-life and high level of sensitivity of this species to pyroxasulfone. In 2013, *S*-metolachlor also reduced Italian ryegrass biomass by 27%, but no significant carryover injury was observed in 2015 following an in-season application



https://doi.org/10.1614/WT-D-16-00062.1 Published online by Cambridge University Press

https://doi.org/10.1614/WT-D-16-00062.1 Published online by Cambridge University Press

Table 5. Influence of soybean herbicides on cover crop stand and biomass reduction 28 days after emergence in Columbia, Missouri in 2013.

| Herbicide | Winter wheat | | Oilseed radish | | Cereal rye | | Crimson clover | | Winter oat | | Austrian winter pea | | Italian ryegrass | | Hairy vetch | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Stand | Biomass | Stand | Biomass | Stand | Biomass | Stand | Biomass | Stand | Biomass | Stand | Biomass | Stand | Biomass | Stand | Biomass |
| | % Reduction | | | | | | | | | | | | | | | |
| Acetochlor | 22 | 12 | 6 | 10 | 15 | 15 | 23 | 32 | 14 | 9 | 0 | 27 | 32 | 15 | 11 | 49 |
| Chlorimuron | 27 | 13 | 7 | 9 | 14 | 7 | 2 | 4 | 13 | 0 | 18 | 0 | 17 | 4 | 14 | 8 |
| Chlorimuron + thifensulfuron | 19 | 19 | 3 | 0 | 16 | 20 | 8 | 9 | 14 | 13 | 8 | 20 | 17 | 0 | 6 | 16 |
| Cloransulam | 15 | 18 | 2 | 8 | 9 | 29 | 9 | 0 | 6 | 13 | 7 | 26 | 6 | 8 | 17 | 14 |
| Flumioxazin | 27 | 10 | 6 | 15 | 18 | 24 | 14 | 29 | 3 | 0 | 8 | 38 | 19 | 2 | 6 | 24 |
| Fomesafen | 22 | 13 | 28 | 51 | 5 | 16 | 27 | 8 | 8 | 5 | 17 | 26 | 11 | 0 | 1 | 19 |
| Fomesafen + *S*-metolachlor | 21 | 41 | 32 | 62 | 19 | 31 | 15 | 3 | 6 | 4 | 8 | 15 | 12 | 11 | 15 | 11 |
| Imazethapyr | 11 | 30 | 41 | 76 | 17 | 17 | 0 | 1 | 12 | 42 | 13 | 14 | 14 | 7 | 16 | 17 |
| Lactofen | 7 | 12 | 6 | 6 | 14 | 11 | 7 | 5 | 12 | 14 | 12 | 10 | 6 | 10 | 9 | 6 |
| Metribuzin | 43 | 13 | 2 | 3 | 22 | 23 | 11 | 13 | 9 | 7 | 23 | 32 | 20 | 4 | 11 | 40 |
| Pyroxasulfone | 20 | 26 | 2 | 9 | 17 | 15 | 13 | 13 | 33 | 14 | 4 | 27 | 57 | 67 | 0 | 46 |
| *S*-metolachlor | 38 | 18 | 5 | 4 | 18 | 12 | 20 | 43 | 13 | 7 | 21 | 43 | 14 | 27 | 15 | 31 |
| Sulfentrazone | 33 | 11 | 6 | 0 | 17 | 5 | 4 | 19 | 3 | 0 | 7 | 3 | 9 | 0 | 9 | 13 |
| Sulfentrazone + cloransulam | 13 | 9 | 18 | 26 | 3 | 10 | 6 | 7 | 14 | 0 | 2 | 8 | 5 | 0 | 7 | 9 |
| LSD (0.05): | 22 | 23 | 22 | 23 | 22 | 23 | 22 | 23 | 22 | 23 | 22 | 23 | 22 | 23 | 22 | 23 |

Table 6. Influence of soybean herbicides on cover crop stand and biomass reduction 28 days after emergence in Columbia, Missouri in 2015.

| Herbicide | Winter wheat | | Oilseed radish | | Cereal rye | | Crimson clover | | Winter oat | | Austrian winter pea | | Italian ryegrass | | Hairy vetch | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Stand | Biomass | Stand | Biomass | Stand | Biomass | Stand | Biomass | Stand | Biomass | Stand | Biomass | Stand | Biomass | Stand | Biomass |
| | % Reduction | | | | | | | | | | | | | | | |
| Acetochlor | 4 | 1 | 24 | 12 | 2 | 24 | 5 | 38 | 7 | 31 | 0 | 37 | 6 | 22 | 7 | 15 |
| Chlorimuron | 1 | 5 | 20 | 19 | 4 | 0 | 2 | 22 | 13 | 40 | 0 | 15 | 3 | 11 | 7 | 0 |
| Chlorimuron + thifensulfuron | 0 | 5 | 10 | 0 | 6 | 11 | 5 | 31 | 15 | 12 | 2 | 13 | 15 | 18 | 5 | 8 |
| Cloransulam | 3 | 0 | 5 | 0 | 1 | 0 | 3 | 19 | 17 | 9 | 0 | 10 | 0 | 0 | 12 | 0 |
| Flumioxazin | 8 | 6 | 19 | 4 | 3 | 16 | 17 | 25 | 13 | 32 | 4 | 30 | 18 | 13 | 12 | 18 |
| Fomesafen | 3 | 3 | 41 | 33 | 4 | 8 | 10 | 32 | 22 | 15 | 12 | 31 | 8 | 12 | 3 | 0 |
| Fomesafen + *S*-metolachlor | 4 | 0 | 19 | 43 | 8 | 0 | 3 | 17 | 17 | 23 | 0 | 12 | 20 | 14 | 2 | 4 |
| Imazethapyr | 1 | 3 | 32 | 39 | 4 | 20 | 7 | 38 | 17 | 52 | 7 | 25 | 14 | 2 | 8 | 0 |
| Lactofen | 2 | 1 | 6 | 0 | 6 | 5 | 1 | 15 | 6 | 6 | 0 | 22 | 6 | 2 | 0 | 4 |
| Metribuzin | 0 | 7 | 13 | 13 | 0 | 2 | 14 | 21 | 2 | 15 | 15 | 30 | 13 | 8 | 1 | 1 |
| Pyroxasulfone | 4 | 6 | 3 | 1 | 9 | 23 | 13 | 17 | 45 | 68 | 5 | 17 | 68 | 82 | 7 | 2 |
| *S*-metolachlor | 6 | 3 | 12 | 7 | 12 | 24 | 3 | 18 | 14 | 22 | 0 | 14 | 17 | 25 | 9 | 4 |
| Sulfentrazone | 13 | 9 | 19 | 13 | 13 | 33 | 8 | 17 | 19 | 25 | 3 | 28 | 19 | 33 | 14 | 6 |
| Sulfentrazone + cloransulam | 1 | 2 | 4 | 1 | 11 | 9 | 12 | 38 | 9 | 23 | 0 | 17 | 18 | 2 | 0 | 4 |
| LSD (0.05): | 17 | 26 | 17 | 26 | 17 | 26 | 17 | 26 | 17 | 26 | 17 | 26 | 17 | 26 | 17 | 26 |

Table 7. Cover crop stand and biomass reduction 28 days after emergence averaged across all herbicide treatments in 2014 and 2015 in corn and soybean experiments in Columbia, Missouri.

| | Soybean experiment | | Corn experiment | | |
|---|---|---|---|---|---|
| | 2014 | | | | 2015 |
| Cover crop | Biomass | Stand | Biomass | Stand | Stand |
| | % Reduction | | | | |
| Austrian winter pea | 30 | 5 | 15 | 8 | 19 |
| Cereal rye | 17 | 11 | 10 | 13 | 13 |
| Crimson clover | 30 | 22 | 10 | 9 | 12 |
| Hairy vetch | 8 | 6 | 12 | 12 | 6 |
| Italian ryegrass | 9 | 5 | 21 | 6 | 14 |
| Oilseed radish | 29 | 14 | 17 | 14 | 6 |
| Winter oat | 15 | 18 | 17 | 15 | 21 |
| Winter wheat | 28 | 16 | 14 | 16 | 10 |
| LSD (0.05): | 9 | 7 | 7 | 8 | 5 |

Table 8. Influence of soybean herbicides on the stand reduction of all cover crop species 28 days after emergence at Columbia, Missouri in 2014.

| Herbicide | % Reduction |
|---|---|
| Acetochlor | 10 |
| Chlorimuron | 26 |
| Chlorimuron + thifensulfuron | 13 |
| Cloransulam | 19 |
| Flumioxazin | 24 |
| Fomesafen | 21 |
| Fomesafen + *S*-metolachlor | 28 |
| Imazethapyr | 25 |
| Lactofen | 3 |
| Metribuzin | 23 |
| Pyroxasulfone | 32 |
| *S*-metolachlor | 15 |
| Sulfentrazone | 31 |
| Sulfentrazone + cloransulam | 21 |
| LSD (0.05): | 9 |

of this herbicide. In 2015, sulfentrazone reduced stand density and biomass by 19% and 33%, respectively, but no significant carryover injury was observed in 2013 following a PRE application of this herbicide.

In 2013, hairy vetch biomass was reduced 31% to 49% following metribuzin, *S*-metolachlor, acetochlor, and pyroxasulfone, while flumioxazin reduced biomass by 24%; however, no herbicide resulted in carryover symptoms in 2015 (Tables 5 and 6). In addition, hairy vetch only exhibited a 7% and 6% reduction in biomass and stand density, respectively, across all herbicides in 2014 (Table 8). Hairy vetch proved to be one of the cover crop species least affected by herbicide carryover in these experiments.

**Carryover of Corn Herbicides.** There was a cover crop species by herbicide treatment interaction for corn herbicides in 2013, but not in 2014 or 2015 (Table 4). However, the main effect of cover crop species was significant in 2014 for stand and biomass reduction and for stand reduction in 2015. In a similar manner, the main effect of herbicide treatment was significant for stand and biomass reduction in 2014 and 2015, respectively. Rainfall from herbicide application to cover crop planting date was 362 and 331 cm in 2014 and 2015, respectively, but only 96 cm in 2013 (Table 1). This deficiency in rainfall helps to explain the cover crop by herbicide interaction observed in 2013.

Following nicosulfuron, winter wheat stand density and biomass were reduced by 27% and 54%, respectively, while no other herbicides reduced winter wheat stand density in 2013 (Table 9). The observed winter wheat stand and biomass reduction following nicosulfuron is consistent with the 4 mo rotational restriction stated on the herbicide label (Anonymous 2016a). In addition, when averaged across all herbicide treatments, winter wheat stand density was reduced by 16% and 10% in 2014 and 2015, respectively (Table 10). Winter wheat biomass was reduced similarly following atrazine, topramazone, isoxaflutole, flumetsulam, rimsulfuron, and clopyralid + acetochlor + flumetsulam + atrazine in 2013.

Flumetsulam reduced oilseed radish stand density by 55%, while flumetsulam and clopyralid + acetochlor + flumetsulam + atrazine resulted in an 80% and 56% biomass reduction, respectively (Table 9). The flumetsulam herbicide label lists a 26 mo rotational restriction for canola (*Brassica napus* L.), which is likely to have similar herbicidal sensitivity as oilseed radish (Anonymous 2016c). Shaner et al. (2014) also reported that across 23 soils, the half-life for flumetsulam ranged from 2 wk to 4 mo, with 80% of soils having a 2-mo half-life. Topramazone, isoxaflutole, and rimsulfuron also reduced oilseed radish biomass by 33% to 36% in 2013, but had no negative effect on stand density.

As in the soybean experiment, cereal rye showed very few herbicide carryover symptoms in the corn experiment (Table 9). Biomass and stand reduction did not exceed 13% when averaged across all



https://doi.org/10.1614/WT-D-16-00062.1 Published online by Cambridge University Press

Table 9. Influence of corn herbicides on cover crop stand and biomass reduction 28 days after emergence at Columbia, Missouri in 2013.[a]

| Herbicide | Winter wheat | | Oilseed radish | | Cereal rye | | Crimson clover | | Winter oat | | Austrian winter pea | | Italian ryegrass | | Hairy vetch | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Stand | Biomass | Stand | Biomass | Stand | Biomass | Stand | Biomass | Stand | Biomass | Stand | Biomass | Stand | Biomass | Stand | Biomass |
| | % Reduction | | | | | | | | | | | | | | | |
| Atrazine | 16 | 37 | 11 | 22 | 11 | 26 | 9 | 35 | 20 | 29 | 18 | 8 | 14 | 37 | 15 | 1 |
| Clop + Acet + Flum + Atra | 16 | 40 | 4 | 56 | 6 | 23 | 15 | 50 | 9 | 22 | 9 | 29 | 8 | 31 | 17 | 49 |
| Clopyralid | 16 | 1 | 20 | 7 | 16 | 12 | 57 | 82 | 23 | 24 | 21 | 36 | 12 | 0 | 23 | 39 |
| Flumetsulam | 11 | 45 | 55 | 80 | 6 | 18 | 9 | 30 | 18 | 9 | 13 | 30 | 10 | 6 | 5 | 58 |
| Gly + Mes + S-met + Atra | 19 | 16 | 18 | 31 | 14 | 8 | 4 | 26 | 14 | 6 | 18 | 31 | 39 | 51 | 26 | 33 |
| Isoxaflutole | 21 | 43 | 8 | 36 | 14 | 38 | 7 | 36 | 12 | 24 | 5 | 22 | 15 | 22 | 11 | 0 |
| Mesotrione | 12 | 29 | 15 | 30 | 17 | 8 | 15 | 32 | 19 | 3 | 20 | 42 | 14 | 28 | 11 | 35 |
| Nicosulfuron | 27 | 54 | 11 | 24 | 13 | 14 | 13 | 56 | 26 | 29 | 11 | 11 | 22 | 48 | 13 | 27 |
| Pyroxasulfone | 18 | 24 | 22 | 7 | 23 | 11 | 19 | 28 | 81 | 67 | 14 | 1 | 95 | 95 | 12 | 5 |
| Rimsulfuron | 17 | 28 | 6 | 33 | 6 | 23 | 9 | 20 | 11 | 13 | 13 | 0 | 25 | 46 | 11 | 32 |
| Tembotrione | 13 | 15 | 5 | 16 | 14 | 28 | 0 | 38 | 13 | 11 | 6 | 9 | 9 | 19 | 3 | 12 |
| Tembotrione + thiencarbazone | 12 | 19 | 16 | 18 | 10 | 5 | 7 | 16 | 29 | 21 | 11 | 4 | 19 | 50 | 17 | 17 |
| Topramazone | 18 | 51 | 7 | 36 | 13 | 14 | 11 | 30 | 27 | 36 | 20 | 25 | 13 | 46 | 3 | 19 |
| LSD (0.05): | 23 | 32 | 23 | 32 | 23 | 32 | 23 | 32 | 23 | 32 | 23 | 32 | 23 | 32 | 23 | 32 |

[a] Abbreviations: Clop, clopyralid; Acet, acetochlor; Flum, flumetsulam; Atra, atrazine; Gly, glyphosate; Mes, mesotrione; S-met, S-metolachlor.

Table 10. Influence of corn herbicides on the biomass and stand reduction of all cover crop species 28 days after emergence at Columbia, Missouri in 2014 and 2015.

| Herbicide | Biomass 2015 | Stand 2014 |
|---|---|---|
| | —% Reduction— | |
| Acetochlor + clopyralid + flumetsulam + atrazine | 20 | 6 |
| Atrazine | 14 | 15 |
| Clopyralid | 16 | 16 |
| Flumetsulam | 8 | 7 |
| Glyphosate + *S*-metolachlor + glyphosate + mesotrione | 23 | 9 |
| Isoxaflutole | 12 | 12 |
| Mesotrione | 11 | 5 |
| Nicosulfuron | 12 | 26 |
| Pyroxasulfone | 11 | 6 |
| Rimsulfuron | 18 | 14 |
| Tembotrione | 17 | 12 |
| Thiencarbazone + tembotrione | 13 | 12 |
| Topramazone | 16 | 11 |
| LSD (0.05): | 9 | 8 |

herbicide treatments in 2015 (Table 10). However, isoxaflutole reduced cereal rye biomass by 38% in 2013. Smith et al. (2015) also reported that cereal rye was not impacted by commonly used corn herbicides in a two-year study.

Clopyralid reduced crimson clover biomass and stand by 82% and 57%, respectively (Table 9). Nicosulfuron and clopyralid + acetochlor + flumetsulam + atrazine also reduced crimson clover biomass by 56% and 50%, respectively, while atrazine, tembotrione, and isoxaflutole reduced biomass by 35% to 38%. The observed carryover from clopyralid can be associated with its 12- to 70-d soil half-life (Shaner et al. 2014) and the sensitivity of the clover species to this synthetic auxin herbicide.

Winter oat biomass and stand was reduced by 67% and 81%, respectively, following in-season applications of pyroxasulfone (Table 9). When averaged across all cover crop species, pyroxasulfone also resulted in a 32% stand reduction in 2014 (Table 8). Topramazone also reduced winter oat biomass by 36%, which was comparable to the reduction observed following pyroxasulfone. However, topramazone resulted in a 27% winter oat stand reduction, which was a lower level of stand reduction relative to pyroxasulfone.

Austrian winter pea stand was not affected by any herbicides, but mesotrione and clopyralid reduced



https://doi.org/10.1614/WT-D-16-00062.1 Published online by Cambridge University Press

biomass by 42% and 36%, respectively (Table 9). Shaner et al. (2014) lists Austrian winter pea as susceptible to clopyralid with a rotational restriction of 18 mo and states that the soil half-life for clopyralid is dependent on soil and climatic conditions.

As in the soybean experiment, pyroxasulfone resulted in the highest level of Italian ryegrass stand and biomass reduction (95% for both) in the corn experiment (Table 9). Atrazine, topramazone, rimsulfuron, nicosulfuron, glyphosate + mesotrione + *S*-metolachlor + atrazine, and tembotrione + thiencarbazone resulted in 37% to 51% Italian ryegrass biomass reduction, but these levels of reduction were lower than those observed with pyroxasulfone. In addition to biomass reduction, rimsulfuron and glyphosate + mesotrione + *S*-metolachlor +atrazine also resulted in stand reductions of 25% and 39%, respectively.

Hairy vetch stand and biomass were reduced by 26% and 33% following glyphosate + mesotrione + *S*-metolachlor + atrazine (Table 9). Although no other herbicide treatment reduced hairy vetch stand, mesotrione, clopyralid, flumetsulam, and clopyralid + acetochlor + flumetsulam + atrazine resulted in a 35% to 58% biomass reduction. Each herbicide treatment that contained clopyralid or flumetsulam, either as stand-alone treatments or in combination with other herbicides, resulted in biomass reduction of hairy vetch. Therefore, herbicide applications containing either active ingredient should be avoided when establishing hairy vetch as a cover crop.

In conclusion, all herbicides evaluated, excluding lactofen, resulted in biomass or stand reduction of at least one cover crop. However, for each cover crop evaluated there were herbicide treatments that did not result in biomass or stand reduction. Italian ryegrass, oilseed radish, winter oat, and crimson clover, exhibited the highest levels of stand and biomass reduction in both experiments. In contrast, cereal rye was only impacted by 5 out of the 29 total herbicide treatments evaluated in these experiments. Additionally, none of the soybean herbicide treatments caused a stand or biomass reduction in consecutive years, and isoxaflutole was the only corn herbicide to significantly reduce cereal rye biomass. Previous research has shown that cereal rye has several agronomic benefits, such as reducing soil erosion, suppressing weed emergence, and increasing soil organic matter (Kuo et al. 1997; Sainju and Singh 1997; Webster et al. 2013). The fact that cereal rye can be effectively established following treatment with several corn and soybean herbicides should be considered as an additional benefit of the use of this species. These results indicate that certain residual herbicides have the potential to reduce stand and biomass of fall-seeded cover crops, but herbicide carryover is heavily dependent on rainfall after herbicide application. Additional research is needed to determine how much time and rainfall are needed prior to cover crop establishment following specific herbicide applications.

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*Received April 20, 2016, and approved August 19, 2016.*

*Associate Editor for this paper: Lawrence E. Steckel, University of Tennessee*