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Seed Potato Growth and Yield as Affected by Mother Plant Exposure to Herbicides

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In a repeated multi-year study, mother potato plants were exposed to herbicides at rates that simulated off-target application, such as through tank contamination. Following exposure of mother plants to herbicides, seed from mother plants was planted in the following growing season and crop growth, yield and tuber quality were quantified. Visual injury from herbicides was observed both in the mother plant and daughter tuber growing seasons and occasional impacts on tuber yield were noted. However, an inconsistent relationship was observed for herbicide related injury and tuber yield reductions of mother potato plants with daughter tuber growth and yield. The lack of consistency in the relationship between visual potato injury in the mother plant production and adverse daughter tuber growth and yield in the following year challenges traditional crop scouting as a tool to predict off-target herbicide risk near seed potato production.
Nomenclature: 2,4-D; aminopyralid; cloransulam-methyl; dicamba; flumiclorac; fluthiacet; glyphosate; mesotrione; metribuzin; metsulfuron-methyl; *S*-metolachlor; tembotrione; thifensulfuron-methyl; topramezone; tribenuron-methyl; potato, *Solanum tuberosum* L.
Key words: herbicide sprayer tank contamination, daughter tuber.

En un estudio repetido varios años, plantas madres de papa fueron expuestas a herbicidas a dosis que simularon aplicaciones accidentales, tales como las que se dan por contaminación en el tanque. Después de la exposición de las plantas madre a los herbicidas, semilla de estas plantas madre fue plantada en la siguiente temporada de crecimiento y se cuantificó el crecimiento del cultivo, el rendimiento y la calidad de los tubérculos. El daño visual causado por los herbicidas fue observado tanto en las temporadas de crecimiento de la planta madre como el de las plantas hijas y ocasionalmente se notó un impacto en el rendimiento de tubérculos. Sin embargo, se observó una relación inconsistente entre el daño y reducciones en el rendimiento de tubérculos en las plantas de papa madre causados por el herbicida y el crecimiento y rendimiento de tubérculo de plantas hijas. La ausencia de consistencia en la relación entre daño visual en la papa durante la producción de la planta madre y efectos adversos en el crecimiento y rendimiento de plantas hijas el siguiente año desafían la utilidad del muestreo tradicional del cultivo como herramienta para predecir el riesgo de daño accidental por herbicidas cerca de áreas para la producción de semilla de papa.

Potato accounts for 15% of total US vegetable sales, more than any other vegetable (USDA-ERS 2016). In 2014, the national potato crop was valued at \$3.66 billion from production on about 425,000 ha in over 30 states. Wisconsin ranked third in overall potato production, with a crop valued at \$274 million and produced on 25,900 ha (USDA-NASS 2015). When factoring in processing, potato production is a strong contributor to Wisconsin's rural economy, representing \$349 million in annual economic activity and accounting for 2,770 jobs (Arledge-Keene and Mitchell 2010).

This value, however, is dependent upon consistent potato crop quantity and quality. As early as 1985, researchers began documenting negative effects of mother potato plant exposure to simulated off-target herbicides on daughter tuber growth and yield. Worthington (1985) reported that exposure of mother plants to glyphosate at 18 g ae ha^{-1} reduced daughter tuber emergence and resulted in malformed shoots. Potato yield response to glyphosate herbicide has been a subject of renewed research interest in recent years in response to widespread adoption of glyphosate-resistant agronomic crops near potato production. Hutchinson et al. (2014) evaluated the effect of several glyphosate rates applied to potato at 10- to 15-cm plant height, stolon hooking, tuber initiation, and mid-bulking. While glyphosate applications at mid-bulking caused the least foliar

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injury, they had a greater impact on daughter tuber emergence and growth than the other application timings. Daughter tubers derived from mother plants that were treated with glyphosate at mid-bulking had emergence rates as low as 30% of the emergence rate of daughter tubers of untreated plants, and displayed characteristic symptoms of glyphosate exposure such as chlorotic growing points. The authors pointed out that the discrepancy between the lack of visual foliar injury or tuber malformation in the mother plant and the poor emergence and appearance of injury in the daughter plants makes scouting of such situations a challenge in commercial production.

Such research was not limited to glyphosate. Wall (1994) investigated the impact of simulated drift of dicamba, clopyralid, and tribenuron on in-season mother plant injury and yield and daughter tuber growth the following season. While no tuber malformations were observed in the simulated drift year, marketable yields were reduced up to 75%. In the following season, daughter plant injury was observed in 2 out of 3 study years, but tuber yields were unaffected.

While several studies have explored the relationship between simulated exposure to off-target herbicides and in-season crop growth in potato (Eberlein et al. 1997; Felix et al. 2011; Olszyk et al. 2010), few have investigated the relationship between mother plant exposure and daughter tuber growth in relation to herbicides other than glyphosate. Moreover, relatively new herbicides, such as topramezone and fluthiacet, are active at very low doses, but their off-target crop risks and effect on subsequent potato seed growth are unknown. The risk of off-target herbicide exposure through tank contamination is particularly relevant for producers who contract pesticide application from commercial applicators whose spray equipment is used for a broad range of crops, as many producers in Wisconsin do. The goal of this research was to determine the effect of simulated off-target herbicide exposure on mother potato plants (injury, yield, and quality) and their daughter potato plants (injury, yield, and quality) grown the following season. Herbicides evaluated here are commonly used in Wisconsin corn, soybean, and small grain fields, as well as pastures.

Materials and Methods

Two-year studies were initiated in 2013 and 2014 at the University of Wisconsin Hancock Agricultural Research Station. Mother potato plants were grown in the first year of each study, and the resulting daughter tubers were planted and grown in the second year. Soil type was a Plainfield loamy sand (sandy, mixed, mesic Typic Udipsamment) with 0.8% organic matter and a pH of 6.5. Experiments were arranged in a randomized complete block design with four replications, with the identity of the replicates maintained for the duration of each two-year study. In the mother plant production year, individual plots measured 6.1 by 3.7 m, with four potato rows spaced 76 cm apart. In the daughter plant year, individual plots were 6.1 m long and consisted of a single row. The mother plants were planted on April 30, 2013 and May 5, 2014 and harvested on September 11, 2013 and September 18, 2014. The daughter plants were planted on May 5, 2014 and April 22, 2015 and harvested on September 17, 2014 and September 22, 2015.

The herbicides listed in Table 1 were applied with a tractor-mounted air pressure sprayer calibrated to deliver 187 L ha^{-1} at 186 kPa with Teejet® XR8003VS nozzle tips (Spraying Systems Co., P.O. Box 7900, Wheaton, IL 60187). Simulated off-target herbicide rates were selected based on 1% of the local commercial use rate in nearby agronomic crops. The herbicides were applied when tuber initiation was observed by digging potato hills in guard rows during crop scouting. Adjuvants were included as directed by the herbicide product label with concentrations adjusted to reflect 1% of the standard commercial application rates. The tuber initiation growth stage was chosen for herbicide application as it aligned with when applications would occur on nearby agronomic crops, such as corn (*Zea mays* L.), soybean (*Glycine max* [L.] Merr.), and small grains. Two additional glyphosate rates were included that were within the range used in related studies (Hutchinson et al. 2014). All plants were sprayed with *S*-metolachlor (1.1 kg ai ha^{-1}) and metribuzin (0.56 kg ai ha^{-1}) to control weeds. All other production practices, including fertilizer application, insect and disease management, and tuber storage between production seasons followed typical commercial practices (Colquhoun et al. 2016).

Data collection in the mother plant production year included visual estimation of potato foliar injury and tuber yield and quality. Foliar injury was estimated on a scale of 0% to 100%, where 100% represents plant death. Tubers were harvested at crop maturity from one of the two center rows of each

Table 1. Sources of herbicide used for studies in Hancock, WI from 2013 to 2015.

Herbicide	Product name	Manufacturer	Location
2,4-D	Amine 4 2,4-D	Loveland Products, Inc.	Greeley, CO
Aminopyralid	Milestone®	Dow AgroSciences	Indianapolis, IN
Cloransulam-methyl	FirstRate®	Dow AgroSciences	Indianapolis, IN
Dicamba	Clarity®	BASF Corporation	Research Triangle Park, NC
Flumiclorac	Resource®	Valent U.S.A Corp.	Walnut Creek, CA
Fluthiacet	Cadet®	FMC Corp.	Philadelphia, PA
Glyphosate	Roundup PowerMax®	Monsanto Co.	St. Louis, MO
Mesotrione	Callisto®	Syngenta Crop Protection, Inc.	Greensboro, NC
Metribuzin	Metribuzin 75DF	MANA, Inc.	Raleigh, NC
Metsulfuron-methyl	Escort®	Dow AgroSciences	Indianapolis, IN
S-Metolachlor	Dual Magnum®	Syngenta Crop Protection, Inc.	Greensboro, NC
Tembotrione	Laudis®	Bayer CropScience	Research Triangle Park, NC
Thifensulfuron-methyl	Harmony®	Dupont Crop Protection	Wilmington, DE
Topramezone	Impact®	Amvac Chemical Corporation	Los Angeles, CA
Tribenuron-methyl	Express®	Dupont Crop Protection	Wilmington, DE

plot and graded according to US Department of Agriculture Agricultural Marketing Service standards (USDA-AMS 2013). Tuber specific gravity, a measure of tuber density that reflects potato processing quality, was determined using the water displacement method described by Dean and Thornton (1992). Data collection in the daughter plant year included the same parameters as described for the mother plant production year, plus stand density and affected plant incidence. The additional parameters were evaluated by counting the number of emerged plants and the number of injured plants in the rows that would be harvested. Data were subjected to ANOVA to determine if there was a year-by-variety interaction using PROC GLM in Statistical Analysis Software (SAS Institute Inc., Cary, NC 27513). An interaction was observed, and therefore data were analyzed and presented by crop and year. Means were separated using Fisher's LSD at $P = 0.05$.

Results and Discussion

Mother Potato Plant Growth. Potato foliar injury was 10% by 5 d after treatment (DAT) where mesotrione was applied, and remained in that range through 20 DAT. Injury consisted primarily of bleached and stunted new foliage. Dicamba injury was 17% by 13 DAT, and remained high through the 29-d evaluation period. Similar injury severity was observed where aminopyralid was applied. Symptomology for both herbicides consisted of severely cupped leaves at the meristematic stem ends. Mother potato plant foliar injury was 5% or less in all other treatments (Table 2). A higher incidence of injury was observed in 2014 than in 2013. We hypothesize that this may be due to environmental conditions near the time of herbicide application in 2014 that favored uptake and translocation, combined with subtle differences in the transition in sinks from the vegetative foliage to the initiating tubers among individual potato plants. Foliar injury patterns from dicamba and aminopyralid in 2014 were similar to those in 2013, with minimal early injury followed by 12% to 17% injury 12 DAT that persisted for the remainder of the 28-d evaluation period. Injury from mesotrione 4 DAT was 11%, but dissipated to 1% by 28 DAT. In contrast to 2013, potato plant injury caused by the acetolactate synthase–inhibiting herbicides cloransulam-methyl, tribenuron-methyl, and metsulfuron-methyl was 10% or more at all evaluation times and was as high as 34% in some cases (Table 3).

Mother Potato Plant Yield. In 2013, minimal crop injury resulted in no differences in yield between the non-treated potato plants and the potato plants receiving herbicide treatments. Even where potato plant foliar injury from dicamba and aminopyralid persisted 29 DAT, no impact on potato yield or quality (assessed by cull tuber yield) was observed relative to non-treated potato plants (Table 4). In general, much greater yield response to herbicides

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Table 2. Visual estimation of mother potato plant foliar injury in 2013 in Hancock, Wisconsin.

Treatment	Herbicide rate	Adjuvant rate	Visual estimation of potato foliar injury			
			5 DAT[a]	13 DAT	20 DAT	29 DAT
	g ai or ae ha^{-1}	g ha^{-1} or % v/v[b]	%			
Non-treated	–		0	0	0	0
2,4-D	5		0	0	0	0
Dicamba + AMS	6	28	0	17	25	16
Glyphosate + AMS[a]	9	19	0	0	0	0
Glyphosate + AMS	19	38	0	1	0	0
Glyphosate + AMS	38	76	3	1	0	0
Mesotrione + AMS + COC[a]	1	19 + 0.01	10	12	11	1
Topramezone + AMS + MSO[a]	0.2	19 + 0.01	1	2	0	0
Tembotrione + AMS + MSO	0.9	19 + 0.01	5	1	2	0
Fluthiacet + AMS + NIS[a]	0.06	17 + 0.01	0	0	0	0
Cloransulam-methyl + AMS + NIS	0.4	22 + 0.0025	1	1	1	0
Flumiclorac + COC	0.6	16	0	0	0	0
Thifensulfuron-methyl + AMS + NIS	0.04	22 + 0.0025	0	2	0	0
Tribenuron-methyl + AMS + NIS	0.2	22 + 0.0025	1	1	1	0
Aminopyralid + NIS	0.9	0.0025	0	14	21	18
Metsulfuron-methyl + NIS	0.1	0.0025	0	0	0	0

[a] Abbreviations: AMS, ammonium sulfate; COC, crop oil concentrate; DAT, d after treatment; MSO, methylated seed oil; NIS, non-ionic surfactant.

[b] AMS rates are in g ha^{-1}. COC, MSO, and NIS rates are in % v/v.

was observed in 2014 compared to 2013. For example, in 2014 all herbicide treatments except topramezone reduced the yield of tubers weighing 113 to 169 g compared to non-treated potato plants. The yield of cull tubers, those malformed or blemished beyond marketability, was greatest among

Table 3. Visual estimation of mother potato plant foliar injury in 2014 in Hancock, Wisconsin.

Treatment	Herbicide rate	Adjuvant rate	Visual estimation of potato foliar injury			
			4 DAT[a]	12 DAT	19 DAT	28 DAT
	g ai or ae ha^{-1}	g ha^{-1} or % v/v[b]	%			
Non-treated	–		0	0	0	0
2,4-D	5		1	1	0	0
Dicamba + AMS	6	28	2	12	15	17
Glyphosate + AMS[a]	9	19	0	0	0	0
Glyphosate + AMS	19	38	3	4	2	1
Glyphosate + AMS	38	76	8	7	6	3
Mesotrione + AMS + COC[a]	1	19 + 0.01	11	24	6	1
Topramezone + AMS + MSO[a]	0.2	19 + 0.01	7	3	3	0
Tembotrione + AMS + MSO	0.9	19 + 0.01	4	4	2	0
Fluthiacet + AMS + NIS[a]	0.06	17 + 0.01	2	1	1	0
Cloransulam-methyl + AMS + NIS	0.4	22 + 0.0025	10	18	24	13
Flumiclorac + COC	0.6	16	0	0	0	0
Thifensulfuron-methyl + AMS + NIS	0.04	22 + 0.0025	3	2	0	0
Tribenuron-methyl + AMS + NIS	0.2	22 + 0.0025	10	17	11	9
Aminopyralid + NIS	0.9	0.0025	6	11	10	16
Metsulfuron-methyl + NIS	0.1	0.0025	13	34	34	21

[a] Abbreviations: AMS, ammonium sulfate; COC, crop oil concentrate; DAT, d after treatment; MSO, methylated seed oil; NIS, non-ionic surfactant.

[b] AMS rates are in g ha^{-1}. COC, MSO, and NIS rates are in % v/v.

Table 4. Mother potato plant tuber yield in 2013 in Hancock, Wisconsin.

Treatment	Herbicide rate	Adjuvant rate	Potato tuber yield[a]								
			B size[b]	Cull	57-112 g	113-169 g	170-282 g	283-368 g	369-454 g	>454 g	Total
	g ai or ae ha^{-1}	g ha^{-1} or % v/v[c]	kg ha^{-1}								
Non-treated	–		264	7,115	7,493	16,153	27,772	8,841	5,367	4,848	77,852
2,4-D	5		272	7,481	7,070	16,868	30,994	10,697	3,789	4,013	81,184
Dicamba + AMS	6	28	128	6,139	8,330	14,644	30,897	13,374	3,793	5,590	82,896
Glyphosate + AMS[d]	9	19	319	6,932	7,308	14,500	30,636	9,489	6,775	3,692	79,651
Glyphosate + AMS	19	38	128	7,542	6,371	14,654	25,727	12,670	5,230	6,127	78,450
Glyphosate + AMS	38	76	325	4,492	8,875	18,952	31,954	12,628	4,684	2,899	84,808
Mesotrione + AMS + COC	1	19 + 0.01	258	5,875	7,855	15,470	27,937	11,642	4,588	3,498	77,122
Topramezone + AMS + MSO	0.2	19 + 0.01	183	5,529	6,875	14,305	29,522	12,402	6,141	4,486	79,444
Tembotrione + AMS + MSO	0.9	19 + 0.01	201	6,830	6,844	15,777	31,594	13,000	4,541	4,728	83,516
Fluthiacet + AMS + NIS	0.06	17 + 0.01	177	6,769	6,838	14,783	33,135	10,530	7,698	3,124	83,054
Cloransulam-methyl + AMS + NIS	0.4	22 + 0.0025	283	9,371	8,802	16,496	26,963	10,882	5,899	5,861	84,556
Flumiclorac + COC	0.6	16	463	7,033	7,639	15,716	31,094	11,296	6,133	3,498	82,873
Thifensulfuron-methyl + AMS + NIS	0.04	22 + 0.0025	289	4,919	7,139	17,850	34,316	10,764	5,493	3,838	84,607
Tribenuron-methyl + AMS + NIS	0.2	22 + 0.0025	293	8,721	7,999	16,199	32,067	11,908	3,446	2,765	83,398
Aminopyralid + NIS	0.9	0.0025	185	5,550	10,705	18,637	29,171	8,538	4,125	1,813	78,722
Metsulfuron-methyl + NIS	0.1	0.0025	232	6,891	8,178	15,866	29,272	10,615	6,161	2,496	79,712

[a] Means within columns followed by the same letter are not significantly different according to Fisher's protected LSD test at $P \leq 0.05$. No significant differences within a column were observed when no letters are included.

[b] B size potatoes include those with a diameter of 4.4 cm or less.

[c] AMS rates are in g ha^{-1}. COC, MSO, and NIS rates are in % v/v.

[d] Abbreviations: AMS, ammonium sulfate; COC, crop oil concentrate; MSO, methylated seed oil; NIS, non-ionic surfactant.

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Table 5. Mother potato plant tuber yield in 2014 in Hancock, Wisconsin.

Treatment	Herbicide rate	Adjuvant rate	Potato tuber yield[a]								
			B size[b]	Cull	57-112 g	113-169 g	170-282 g	283-368 g	369-454 g	>454 g	Total
	g ai or ae ha^{-1}	g ha^{-1} or % v/v[c]	kg ha^{-1}								
Non-treated	–		1,464 bc	3,822 ef	10,197 a	17,559 a	22,481 ab	4,736 bc	2,937 bc	1,637 b-e	65,253 a
2,4-D	5		1,400 bcd	5,478 ef	9,300 ab	14,097 b	20,690 abc	6,406 bcd	1,958 bcd	766 def	61,071 a
Dicamba + AMS	6	28	1,260 bcd	4,513 ef	9,072 abc	13,644 b	20,419 abc	7,501 abc	3,450 ab	4,370 ab	64,560 a
Glyphosate + AMS[d]	9	19	1,329 bcd	7,013 def	7,328 b-e	12,672 bc	19,139 bc	7,059 abc	3,690 ab	2,369 a-e	60,748 a
Glyphosate + AMS	19	38	1,719 b	3,740 ef	8,469 a-d	13,333 bc	23,300 ab	7,520 abc	2,346 bcd	910 c-f	61,858 a
Glyphosate + AMS	38	76	1,003 cd	5,509 ef	7,208 b-e	11,727 bc	23,233 ab	9,603 a	5,702 a	2,507 a-e	67,570 a
Mesotrione + AMS + COC	1	19 + 0.01	939 cd	6,190 def	8,851 abc	13,679 b	16,712 c	8,162 ab	3,287 ab	3,490 abc	62,015 a
Topramezone + AMS + MSO	0.2	19 + 0.01	1,067 bcd	4,543 ef	7,145 b-e	14,551 ab	24,995 a	8,311 ab	4,135 ab	2,913 a-d	68,050 a
Tembotrione + AMS + MSO	0.9	19 + 0.01	1,084 bcd	3,334 f	6,922 cde	11,912 bc	21,466 abc	10,080 a	4,580 ab	5,636 a	65,253 a
Fluthiacet + AMS + NIS	0.06	17 + 0.01	1,230 bcd	3,893 ef	8,290 a-d	13,199 bc	22,562 ab	7,280 abc	3,746 ab	4,582 ab	65,926 a
Cloransulam-methyl + AMS + NIS	0.4	22 + 0.0025	814 d	14,616 bc	6,052 e	7,151 de	11,060 d	4,463 c	2,555 bcd	2,848 a-e	50,283 bc
Flumiclorac + COC	0.6	16	882 cd	3,791 ef	8,227 a-e	13,488 bc	23,526 ab	7,813 abc	3,942 ab	2,980 a-d	65,342 a
Thifensulfuron-methyl + AMS + NIS	0.04	22 + 0.0025	938 cd	12,329 cd	8,111 a-e	10,107 cd	19,690 bc	7,539 abc	3,098 ab	2,385 a-e	64,838 a
Tribenuron-methyl + AMS + NIS	0.2	22 + 0.0025	1,355 bcd	45,057 a	6,438 de	6,574 e	4,738 e	375 d	366 cd	0 f	65,218 a
Aminopyralid + NIS	0.9	0.0025	1,509 bc	9,951 cde	9,898 a	12,648 bc	16,388 c	4,941 bc	2,222 bcd	484 ef	59,022 ab
Metsulfuron-methyl + NIS	0.1	0.0025	3,068 a	20,196 b	9,942 a	6,777 de	5,054 e	273 d	0 d	0 f	45,620 c

[a] Means within columns followed by the same letter are not significantly different according to Fisher's protected LSD test at $P \leq 0.05$. No significant differences within a column were observed when no letters are included.

[b] B size potatoes include those with a diameter of 4.4 cm or less.

[c] AMS rates are in g ha^{-1}. COC, MSO, and NIS rates are in % v/v.

[d] Abbreviations: AMS, ammonium sulfate; COC, crop oil concentrate; MSO, methylated seed oil; NIS, non-ionic surfactant.

Table 6. Daughter potato plant stand density, number of affected plants and visual estimation of foliar injury in 2014, the year after herbicide exposure, in Hancock, Wisconsin.

			Stand density		Affected plants		Visual estimation of foliar injury		
Treatment	Herbicide rate	Adjuvant rate	30 DAP[a,b]	35 DAP	42 DAP	48 DAP	36 DAP	42 DAP	48 DAP
	g ai or ae ha^{-1}	g ha^{-1} or % v/v[c]	plants ha^{-1}				%		
Non-treated	–		24,757 ab	34,983	3,229	0	1	8	0
2,4-D	5		31,933 a	34,983	0	718	0	0	1
Dicamba + AMS	6	28	28,345 ab	35,521	2,691	2,153	8	11	1
Glyphosate + AMS[b]	9	19	29,242 ab	34,086	538	538	0	10	1
Glyphosate + AMS	19	38	22,425 b	33,727	359	359	3	4	1
Glyphosate + AMS	38	76	26,013 ab	35,521	1,435	0	0	5	0
Mesotrione + AMS + COC	1	19 + 0.01	28,345 ab	35,521	718	1,076	9	4	1
Topramezone + AMS + MSO	0.2	19 + 0.01	25,116 ab	35,521	1,794	538	2	4	1
Tembotrione + AMS + MSO	0.9	19 + 0.01	29,601 ab	34,983	179	0	0	1	0
Fluthiacet + AMS + NIS	0.06	17 + 0.01	22,425 b	34,624	5,203	3,229	4	10	2
Cloransulam-methyl + AMS + NIS	0.4	22 + 0.0025	25,654 ab	35,521	0	0	3	0	0
Flumiclorac + COC	0.6	16	30,498 ab	35,880	0	0	0	0	0
Thifensulfuron-methyl + AMS + NIS	0.04	22 + 0.0025	25,654 ab	35,521	2,332	3,050	5	8	2
Tribenuron-methyl + AMS + NIS	0.2	22 + 0.0025	31,036 ab	34,983	179	0	0	6	0
Aminopyralid + NIS	0.9	0.0025	30,498 ab	36,418	5,561	718	2	11	1
Metsulfuron-methyl + NIS	0.1	0.0025	28,704 ab	34,086	179	1,076	2	3	1

[a] Stand density and affected plant means within columns followed by the same letter are not significantly different according to Fisher's protected LSD test at $P \leq 0.05$. No significant differences within a column were observed when no letters are included.

[b] Abbreviations: AMS, ammonium sulfate; COC, crop oil concentrate; DAP, d after planting; MSO, methylated seed oil; NIS, non-ionic surfactant.

[c] AMS rates are in g ha^{-1}. COC, MSO, and NIS rates are in % v/v.

Table 7. Daughter potato plant stand density, number of affected plants and visual estimation of foliar injury in 2015, the year after herbicide exposure, in Hancock, Wisconsin.

			Stand density		Affected plants		Visual estimation of foliar injury		
Treatment	Herbicide rate	Adjuvant rate	35 DAP[a,b]	43 DAP	49 DAP	56 DAP	43 DAP	49 DAP	56 DAP
	g ai or ae ha^{-1}	g ha^{-1} or % v/v[c]	plants ha^{-1}				%		
Non-treated	–		29,601 ab	32,292 b	179 cd	1,794 cd	1	1	1
2,4-D	5		32,830 a	34,983 ab	0 d	0 d	6	0	0
Dicamba + AMS	6	28	28,704 ab	33,727 ab	20,631 a	10,226 ab	50	37	7
Glyphosate + AMS[b]	9	19	29,242 ab	34,983 ab	0 d	718 d	5	0	0
Glyphosate + AMS	19	38	31,036 ab	34,983 ab	538 cd	359 d	16	2	0
Glyphosate + AMS	38	76	23,860 bc	31,933 b	6,279 b	4,664 bc	18	30	5
Mesotrione + AMS + COC	1	19 + 0.01	34,624 a	35,880 a	538 cd	718 d	10	1	0
Topramezone + AMS + MSO	0.2	19 + 0.01	33,189 a	34,983 ab	0 d	0 d	5	0	0
Tembotrione + AMS + MSO	0.9	19 + 0.01	34,086 a	34,983 ab	538 cd	0 d	4	1	0
Fluthiacet + AMS + NIS	0.06	17 + 0.01	33,727 a	34,983 ab	0 d	0 d	6	0	0
Cloransulam-methyl + AMS + NIS	0.4	22 + 0.0025	31,933 a	35,880 a	718 bcd	0 d	8	3	0
Flumiclorac + COC	0.6	16	29,242 ab	33,727 ab	718 bcd	718 d	5	2	0
Thifensulfuron-methyl + AMS + NIS	0.04	22 + 0.0025	30,139 ab	34,983 ab	3,947 bc	1,615 d	8	5	1
Tribenuron-methyl + AMS + NIS	0.2	22 + 0.0025	31,395 ab	34,624 ab	0 d	0 d	3	0	0
Aminopyralid + NIS	0.9	0.0025	19,375 c	25,654 c	21,887 a	17,043 a	58	54	35
Metsulfuron-methyl + NIS	0.1	0.0025	26,910 abc	33,189 ab	1,615 bcd	538 d	10	6	0

[a] Stand density and affected plant means within columns followed by the same letter are not significantly different according to Fisher's protected LSD test at $P \leq 0.05$. No significant differences within a column were observed when no letters are included.

[b] Abbreviations: AMS, ammonium sulfate; DAP, d after planting; COC, crop oil concentrate; MSO, methylated seed oil; NIS, non-ionic surfactant.

[c] AMS rates are in g ha^{-1}. COC, MSO, and NIS rates are in % v/v.

Table 8. Daughter potato plant tuber yield in 2014, the year after herbicide exposure, in Hancock, Wisconsin.

Treatment	Herbicide rate	Adjuvant rate	Potato tuber yield[a]								
			B size[b]	Cull	57-112 g	113-169 g	170-282 g	283-368 g	369-454 g	>454 g	Total
	g ai or ae ha^{-1}	g ha^{-1} or % v/v[c]	kg ha^{-1}								
Non-treated	–		1,168	7,694	6,991	10,173	16,686	10,564 ab	7,196	4,297	57,826
2,4-D	5		945	11,055	6,580	9,612	21,563	10,007 ab	4,896	2,913	58,013
Dicamba + AMS	6	28	1,159	9,841	6,342	9,950	19,189	6,184 c	3,956	3,861	51,075
Glyphosate + AMS[d]	9	19	954	8,315	7,730	11,392	18,591	8,754 abc	3,002	3,844	55,233
Glyphosate + AMS	19	38	1,271	5,188	5,562	10,971	21,410	9,048 abc	5,648	2,234	56,396
Glyphosate + AMS	38	76	993	10,055	7,312	11,626	21,420	10,523 ab	6,574	2,580	61,719
Mesotrione + AMS + COC	1	19 + 0.01	435	13,935	5,066	9,624	16,280	8,064 bc	6,828	3,851	50,613
Topramezone + AMS + MSO	0.2	19 + 0.01	1,093	7,798	5,689	10,510	17,422	10,533 ab	6,194	3,431	55,037
Tembotrione + AMS + MSO	0.9	19 + 0.01	929	6,808	5,859	10,500	20,007	8,572 abc	5,809	4,763	56,717
Fluthiacet + AMS + NIS	0.06	17 + 0.01	968	12,965	5,775	9,633	22,052	10,985 ab	4,860	4,268	59,101
Cloransulam-methyl + AMS + NIS	0.4	22 + 0.0025	1,119	10,786	6,340	10,988	19,901	6,306 c	4,714	2,753	52,394
Flumiclorac + COC	0.6	16	810	10,218	6,334	8,713	21,524	10,603 ab	7,174	6,502	62,104
Thifensulfuron-methyl + AMS + NIS	0.04	22 + 0.0025	936	7,671	6,005	11,251	17,775	10,585 ab	4,897	2,624	54,330
Tribenuron-methyl + AMS + NIS	0.2	22 + 0.0025	1,410	10,250	7,348	10,679	20,351	6,195 c	4,642	2,446	53,429
Aminopyralid + NIS	0.9	0.0025	1,155	7,814	7,615	11,124	21,954	9,070 abc	3,654	1,755	56,654
Metsulfuron-methyl + NIS	0.1	0.0025	913	10,736	5,579	8,567	20,278	12,246 a	7,695	6,535	62,175

[a] Means within columns followed by the same letter are not significantly different according to Fisher's protected LSD test at $P \leq 0.05$. No significant differences within a column were observed when no letters are included.

[b] B size potatoes include those with a diameter of 4.4 cm or less.

[c] AMS rates are in g ha^{-1}. COC, MSO, and NIS rates are in % v/v.

[d] Abbreviations: AMS, ammonium sulfate; COC, crop oil concentrate; MSO, methylated seed oil; NIS, non-ionic surfactant.

Table 9. Daughter potato plant tuber yield in 2015, the year after herbicide exposure, in Hancock, Wisconsin.

Treatment	Herbicide rate	Adjuvant rate	Potato tuber yield[a]								
			B size[b]	Cull	57-112 g	113-169 g	170-282 g	283-368 g	369-454 g	>454 g	Total
	g ai or ae ha^{-1}	g ha^{-1} or % v/v[c]	kg ha^{-1}								
Non-treated	–		519	4,627	8,382 bcd	18,846 ab	31,134	10,334	5,907	4,443	84,432 ab
2,4-D	5		697	7,906	8,620 bc	17,208 a-e	28,475	12,039	3,023	5,210	83,792 ab
Dicamba + AMS	6	28	632	5,309	9,505 ab	14,860 a-f	24,975	9,643	4,996	2,618	72,686 bc
Glyphosate + AMS[d]	9	19	699	3,690	11,052 a	18,054 a-d	25,421	10,591	2,851	3,687	76,325 ab
Glyphosate + AMS	19	38	614	6,226	8,514 bc	18,441 abc	28,436	13,159	4,348	5,153	85,811 a
Glyphosate + AMS	38	76	654	5,125	7,589 b-e	13,423 def	27,224	11,262	3,120	6,268	75,182 ab
Mesotrione + AMS + COC	1	19 + 0.01	567	6,051	7,763 bcd	13,543 c-f	27,440	10,493	7,310	8,032	81,925 ab
Topramezone + AMS + MSO	0.2	19 + 0.01	493	8,020	6,180 de	14,463 b-f	27,458	13,441	6,069	5,688	82,152 ab
Tembotrione + AMS + MSO	0.9	19 + 0.01	615	5,899	7,010 cde	16,445 a-e	29,730	11,425	5,015	5,228	81,543 ab
Fluthiacet + AMS + NIS	0.06	17 + 0.01	520	5,287	9,099 abc	13,971 b-f	28,678	11,337	4,108	3,372	76,698 ab
Cloransulam-methyl + AMS + NIS	0.4	22 + 0.0025	557	3,678	7,807 bcd	16,575 a-e	28,186	13,622	4,990	5,449	81,410 ab
Flumiclorac + COC	0.6	16	643	4,811	7,580 b-e	14,792 a-f	28,976	11,451	5,390	7,467	81,643 ab
Thifensulfuron-methyl + AMS + NIS	0.04	22 + 0.0025	358	5,466	7,466 b-e	19,543 a	32,495	9,230	3,204	6,286	84,360 ab
Tribenuron-methyl + AMS + NIS	0.2	22 + 0.0025	755	4,368	7,403 b-e	16,299 a-e	30,252	8,711	5,487	6,169	79,633 ab
Aminopyralid + NIS	0.9	0.0025	521	6,231	5,260 e	10,457 f	21,574	7,276	5,308	3,600	60,758 c
Metsulfuron-methyl + NIS	0.1	0.0025	490	6,770	7,395 b-e	12,814 ef	25,772	12,086	5,938	5,842	78,216 ab

[a] Means within columns followed by the same letter are not significantly different according to Fisher's protected LSD test at $P \leq 0.05$. No significant differences within a column were observed when no letters are included.

[b] B size potatoes include those with a diameter of 4.4 cm or less.

[c] AMS rates are in g ha^{-1}. COC, MSO, and NIS rates are in % v/v.

[d] Abbreviations: AMS, ammonium sulfate; COC, crop oil concentrate; MSO, methylated seed oil; NIS, non-ionic surfactant.

potato plants treated with cloransulam-methyl, thifensulfuron methyl, tribenuron-methyl, or metsulfuron-methyl. Where tribenuron-methyl was applied, the cull yield was almost as high as the Wisconsin state average total marketable yield for the 2014 production year (about 48,000 kg ha^{-1}) (USDA-NASS 2015). The yield of tubers in the largest grade categories was lowest where tribenuron-methyl and metsulfuron-methyl were applied, with no tubers weighing more than 454 g and reduced yield in the 283 to 368 g weight category compared to the yield of the non-treated potato plants. Total tuber yield from the plants treated with these two herbicides was also reduced compared to the yield of the non-treated potato plants (Table 5).

Daughter Potato Plant Growth. Tubers from the mother plants that were exposed to the herbicide treatments were planted as seed in the following season, and the daughter plants were monitored for evidence of herbicide injury and harvested to evaluate tuber yield and quality. In 2014, for the daughter plants grown from the 2013 mother plants, stand density and the number of plants expressing herbicide symptoms in all herbicide treatment groups was similar to that of the non-treated group. Visual estimations of potato foliar injury were 10% or 11% 42 d after planting (DAP) where dicamba, glyphosate at the lowest application rate, fluthiacet, or aminopyralid were applied to the mother plants in 2013. All other visual observations of potato foliar injury were lower than 10%, and injury was minimal in all herbicide treatments by 48 DAP (Table 6). The severity of herbicide injury and negative effect on tuber yield and quality observed in the mother plant study in 2014 persisted into the 2015 daughter plant study for several treatment groups. Stand density at 35 and 43 DAP was reduced where plants were treated with aminopyralid compared to the non-treated plots. The number of potato plants expressing herbicide symptomology 49 DAP was greater than 50% of the planted crop density in glyphosate (lowest rate) or aminopyralid treatment plots. Visual estimation of crop injury 43 DAP was 10% or greater where glyphosate was applied at the two highest rates and where mesotrione or metsulfuron-methyl was applied, and 50% or greater where dicamba or aminopyralid was applied. Injury from dicamba, glyphosate at the highest rate, and aminopyralid persisted 49 DAP and ranged from 30% to 54% (Table 7).

Daughter Potato Plant Yield. Potato seed planted in 2014 from the 2013 mother plant study exhibited minimal injury, and stand density was similar for the treated and non-treated potato plants. As a result, tuber yield and quality in the 2014 harvest was similar among all herbicide treatments and between the treatments and the non-treated check (Table 8). In 2015, however, some of the herbicides that had caused injury in the 2014 mother plants also reduced yield in the 2015 daughter crop. Tuber quality, indicated by the cull weight, did not differ among treatments or between treatments and the non-treated check. Glyphosate applied at the lowest rate increased tuber yield in the 57 to 112 g weight category. Injury from aminopyralid reduced the yield of the two lightest grade weight categories, and as a result reduced the total tuber yield compared to the non-treated check. Additionally, metsulfuron-methyl reduced tuber yield in the 113 to 169 g weight category compared the non-treated check. All other weight categories and total tuber yield were similar between herbicide-treated potato plants and the non-treated plants (Table 9).

The variability among production years in potato response and daughter tuber injury documented by Wall (1994) for the herbicides clopyralid, tribenuron, and dicamba was similar to what was observed in this study with a broader array of herbicide active ingredients. The lack of consistency in the connection between visual injury in the mother potato plant and affected daughter tuber growth and yield in the following year challenges traditional crop scouting as a tool to assess off-target herbicide risk. While somewhat variable, these results document that seed potato crops are at risk if off-target herbicide exposure does occur. Our current research is focused on non-visual measurement of potato injury, such as through spectral image sensing, that could be used in greenhouse assays during the time period between the mother plant seed production year and the following daughter tuber field season to predict risk of herbicide-induced growth issues.

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