Weed Technology 2014 28:671–678

Relationship between Visual Injury from Synthetic Auxin and Glyphosate Herbicides and Snap Bean and Potato Yield

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Agronomic crops with resistance to the herbicides dicamba and 2,4-D are currently in the regulatory approval process. The potential increased use of these herbicides has raised concern among vegetable producers about potential off-target movement and implications to crop yield. The overall goal of this research was to describe the relationship between visually estimated crop injury and snap bean and potato yield and quality. In snap bean in 2011, injury from dicamba 7 d after treatment (DAT) ranged from 19% at the 1.2 g ae ha^{-1} application rate to 45% at the 7.0 g ae ha^{-1} application rate. By 28 DAT in 2011, injury from 2,4-D was similar to the nontreated control. However, early-season injury in 2011 delayed snap bean flowering and reduced crop yield compared to the nontreated control for all treatments except where the 1.4 g ae ha^{-1} rate of 2,4-D and glyphosate at 7.0 g ae ha^{-1} were applied. Snap bean injury from dicamba was greater than that from 2,4-D at all rating timings in 2011 and two of three rating timings in 2012, and crop yield was reduced compared to where 2,4-D was applied and the nontreated control in both years. Potato tuber size distribution was variable and total yield did not differ among treatments and the nontreated control in 2011. In 2012, tuber size distribution was again variable, but more nonmarketable cull potatoes were harvested when dicamba was applied to 25-cm potato plants at the 7.0 g ae ha^{-1} rate compared to any other treatment. Snap bean injury observations about 3 wk prior to harvest were strongly correlated with crop yield ($r = -0.84$ and -0.88 in 2011 and 2012, respectively), allowing time to make informed harvest decisions relative to crop quality. In contrast, the relationship between potato injury and tuber yield was poor and highly variable in both years.

Nomenclature: 2,4-D; dicamba; glyphosate; potato, *Solanum tuberosum* L.; snap bean, *Phaseolus vulgaris* L.

Key words: Herbicide drift; herbicide volatility; minor crops; vegetables.

Cultivos agronómicos con resistencia a los herbicidas dicamba y 2,4-D están actualmente en proceso de aprobación regulatoria. El potencial incremento en el uso de estos herbicidas ha generado preocupación entre los productores de vegetales por el riesgo potencial de deriva y las implicaciones de esta en el rendimiento de sus cultivos. El objetivo general de esta investigación fue el describir la relación entre el daño del cultivo estimado visualmente y el rendimiento y la calidad del frijol y de la papa. En frijol en 2011, el daño producido por dicamba a 7 días despúes del tratamiento (DAT) varió de 19% con la dosis de aplicación de 1.2 g ae ha^{-1} a 45% con la dosis de aplicación de 7.0 g ae ha^{-1}. A 28 DAT en 2011, el daño causado por 2,4-D fue similar el testigo no-tratado. Sin embargo, el daño, temprano en la temporada en 2011, retrasó la floración del frijol y redujo el rendimiento del cultivo en comparación con el testigo no-tratado para todos los tratamientos, excepto donde se aplicó una dosis de 1.4 g ae ha^{-1} de 2,4-D y glyphosate a 7.0 g ae ha^{-1}. El daño de dicamba en el frijol fue mayor que el producido por 2,4-D en todos los momentos de evaluación en 2011 y en dos de los tres momentos de evaluación en 2012, y el rendimiento del cultivo se redujo en comparación con el testigo no-tratado y parcelas tratadas con 2,4-D, en ambos años. La distribución de tamaños de tubérculo de papa fue variable y el rendimiento total no difirió entre tratamientos y el testigo no-tratado, en 2011. En 2012, la distribución de tamaños de tubérculos fue nuevamente variable, pero se cosecharon más papas no comercializables cuando se aplicó a plantas de papa de 25 cm una dosis de dicamba de 7.0 g ae ha^{-1}, en comparación con cualquier otro tratamiento. Las observaciones de daño del frijol cerca de 3 semanas antes de la cosecha estuvieron fuertemente correlacionadas con el rendimiento del cultivo ($r = -0.84$ y -0.88 en 2011 y 2012, respectivamente), lo que dio tiempo para la toma informada decisiones acerca de la cosecha en relación a la calidad del cultivo. En contraste, la relación entre el daño de la papa y el rendimiento de tubérculo fue pobre y altamente variable en ambos años.

Agronomic crops genetically modified to tolerate synthetic auxin herbicides, such as 2,4-D and dicamba, are currently under development and being considered for commercial introduction. The

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DOI: 10.1614/WT-D-14-00033.1

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desire for these herbicide resistance traits has largely been driven by the increase in glyphosate-resistant weeds in crops such as soybean [*Glycine max* (L.) Merr.] and cotton (*Gossypium hirsutum* L.). Globally, glyphosate resistance has been reported in 24 weed species, an increase from five species about a decade ago (Heap 2013). Nine and 15 glyphosate-resistant weed species have been reported in soybean and cotton production systems, respectively (Heap 2013).

The introduction of synthetic auxin-resistant crops such as soybean and cotton may broaden the weed control spectrum and address some of the glyphosate-resistant weed concerns in the short term. However, nearby minor crop producers have expressed concern that off-target movement through volatility, particle drift, or spray tank contamination could result in crop injury, yield reduction, and pesticide residue issues. The effect of off-target synthetic auxin herbicides is fairly well reported in the literature for sensitive agronomic crops. Everitt and Keeling (2009), for example, investigated simulated 2,4-D and dicamba drift in cotton at four growth stages and at four application rates. They reported that across all growth stage applications, 2,4-D caused greater injury and yield loss than dicamba. Additionally, they noted that injury visually estimated during the growing season was not a good indicator of potential cotton yield loss. Similar observations were reported by Marple et al. (2007, 2008). The ability of cotton to compensate for stress through indeterminate growth may reduce the correlation between visually estimated injury and yield. Johnson et al. (2012) reported that visually estimated injury from 2,4-D, dicamba, or glufosinate applied at simulated drift rates was moderately correlated with soybean and peanut (*Arachis hypogaea* L.) yield, but poorly correlated with cotton yield.

Similar research on the relationship among off-target synthetic auxin herbicide exposure, crop injury, and yield is more limited for specialty crops such as vegetables. Attention in this area has been primarily focused on crops anecdotally observed to be sensitive to such exposure and grown in close proximity to where synthetic auxin herbicides are commonly used. Kruger et al. (2012) conducted dose-response studies for two tomato (*Solanum lycopersicum* L.) cultivars exposed to glyphosate or dicamba at either the vegetative or early flowering growth stages. They concluded that both tomato cultivars were more sensitive to dicamba than to glyphosate, and that exposure to these herbicides at the early flowering stage was more damaging than earlier exposure at a vegetative stage. Similar results were reported earlier by Jordan and Romanowski (1974).

Processing vegetables, including snap bean and potato, are economically important crops in the upper Midwestern United States. Wisconsin, for example, ranks second nationally in vegetable processing. Wisconsin produces 40% of the national snap bean crop, with a total annual economic value in the state of $63 million. The total impact of Wisconsin potato production is estimated at $349 million annually and is responsible for 2,770 jobs (Arledge-Keene and Mitchell 2010). The high value of these and other specialty crops grown in the region, as well as their close spatial proximity to surrounding agronomic crops, has caused anxiety among growers and processors with regard to the potential introduction of agronomic traits that confer resistance to synthetic auxin herbicides, particularly in soybean grown nearby. More specifically, the specialty crop industry and associated research community would benefit from greater knowledge of the susceptibility of these crops to synthetic auxin herbicides and the ability to relate varying degrees of injury to potential crop yield and quality losses.

We acknowledge that synthetic auxin formulations may change prior to or soon after the introduction of herbicide resistance traits in agronomic crops and that the volume of carrier water differs broadly between tank contamination and spray drift scenarios. Although the carrier volume used in this study would be consistent with a sprayer tank contamination scenario, it is not intended to resemble that experienced in an herbicide drift situation. Banks and Schroeder (2002) demonstrated the importance of using water carrier volume proportionate to the herbicide dose in simulated spray drift studies. The research presented here differs from that previously reported in that our overall goal was to relate visually estimated injury symptoms to crop yield and quality to enable growers and processors to make decisions informed by the best available science instead of anecdotal observations. With this in mind, the specific objectives of this research were to (1) document

Table 1. Herbicide sources for studies in Arlington and Hancock, WI, in 2011 and 2012.

Herbicide	Trade name	Manufacturer	Location
2,4-D	Amine 4 2,4-D®	Loveland Products, Inc.	Greeley, CO
Dicamba	Clarity®	BASF Corporation	Research Triangle Park, NC
Fomesafen	Reflex®	Syngenta Crop Protection, Inc.	Greensboro, NC
Glyphosate	Roundup PowerMax®	Monsanto Co.	St. Louis, MO
Metribuzin	Metribuzin 75DF®	MANA, Inc.	Raleigh, NC
S-metolachlor	Dual Magnum®	Syngenta Crop Protection, Inc.	Greensboro, NC

snap bean and potato susceptibility to 2,4-D and dicamba and (2) investigate the relationship between visual estimates of crop injury and crop yield at harvest, with the ultimate goal of informing the research-based discussion about potential increased synthetic auxin herbicide use.

Materials and Methods

Snap bean studies were conducted in 2011 and 2012 in Arlington, WI, at the University of Wisconsin Arlington Agricultural Research Station on a Joy silt loam soil (fine-silty, mixed, superactive, mesic Aquic Hapludolls) with a pH of 7.0 and 4.2% organic matter. Potato research was conducted in the same years at the Hancock Agricultural Research Station in Hancock, WI, on a Plainfield loamy sand (sandy, mixed, mesic, Typic Udipsamment) with a pH of 6.9 and 0.9% organic matter. Soil moisture was monitored and supplemental irrigation was delivered through a pivot system at the Hancock site as is standard commercial practice in that region.

'Hercules' snap bean was planted on June 6, 2011, and June 1, 2012, in rows spaced 76 cm apart with a 4-cm in-row seed spacing. Individual plots measured 3.0 m wide by 6.1 m long and included four snap bean rows. The study was arranged in a randomized complete block design with four replications of each treatment. Each individual plot was surrounded by a similar area of nontreated snap bean to act as a buffer against off-target movement among treatments. The entire area planted to snap bean was sprayed with *S*-metolachlor (1.1 kg ai ha^{-1}) plus fomesafen (0.14 kg ai ha^{-1}) PRE (prior to weed and crop emergence, after planting) to suppress weeds (Table 1). Dicamba and 2,4-D were evaluated at three simulated off-target rates (1.4, 4.2, and 7.0 g ae ha^{-1}), as well as glyphosate at the 7.0 g ae ha^{-1} rate. Herbicide rates in this study were selected based on the range reported in the literature for similar studies (Everitt and Keeling 2009; Johnson et al. 2012; Jordan and Romanowski 1974; Kruger et al. 2012; Marple et al. 2007, 2008; Wall 1994). Herbicide treatments were applied when snap beans were in the one- to two-trifoliate leaf growth stage, which coincides with the likely POST herbicide application timing in soybeans. Herbicides 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., North Avenue, Wheaton, IL 60187). All other production practices, including fertilizer and maintenance insecticide applications, followed typical commercial practices (Bussan et al. 2014). Snap bean injury was visually estimated on a scale of 0 (no injury) to 100% (plant death). The center two rows of each plot were machine-harvested on August 2, 2011, and August 3, 2012, when the crop was mature in the nontreated check and graded according to U.S. Department of Agriculture (USDA) standard sieve sizes for snap bean (USDA-AMS 2013a).

'Russet Burbank' potato seed were planted on April 28, 2011, and May 1, 2012, in rows spaced 91 cm apart and with a 31-cm in-row spacing. Individual plots measured 3.7 m wide by 6.1 m long and included four potato rows, arranged in a randomized complete block design with four replications of each treatment. Individual treatment plots were surrounded by a similarly sized nontreated potato buffer as described for the snap beans. Weeds were controlled in all areas planted to potato with *S*-metolachlor (1.1 kg ai ha^{-1}) plus metribuzin (0.56 kg ai ha^{-1}) applied PRE, after potato hilling but prior to potato and weed emergence. In potato, dicamba herbicide was evaluated at three simulated off-target rates (1.4, 4.2, and 7.0 g ae ha^{-1}). 2,4-D was not evaluated in potato given that it has a registration for use in red potatoes in some production areas to enhance early tuber skin color and the crop tolerance is commonly

Table 2. Effect of dicamba, 2,4-D, and glyphosate on visually estimated snap bean injury and yield in 2011 in Arlington, WI.

Treatment	Herbicide rate	Snap bean injury[a] 7 DAT[b]	Snap bean injury[a] 18 DAT	Snap bean injury[a] 28 DAT	Snap bean yield Sieve size 1–3[c]	Snap bean yield Sieve size 4–5	Snap bean yield Total yield
	g ae ha^{-1}	%			kg ha^{-1}		
Nontreated	—	0 f	3 d	0 d	1,150 bcd	4,850 a	6,000 a
Dicamba	1.4	19 c	43 b	11 b	850 de	280 d	1,130 d
Dicamba	4.2	26 b	40 b	14 b	780 e	130 d	910 d
Dicamba	7.0	45 a	53 a	24 a	410 f	100 d	510 d
2,4-D	1.4	4 ef	3 d	1 cd	1,380 ab	4,450 a	5,830 a
2,4-D	4.2	6 e	9 cd	1 cd	1,550 a	2,520 b	4,080 b
2,4-D	7.0	11 d	10 c	1 cd	1,370 abc	1,460 c	2,830 c
Glyphosate	7.0	5 e	3 d	4 c	1,040 cde	4,430 a	5,460 a

[a] Means followed by the same letter are not different according to Fisher's protected LSD test at $P = 0.05$.

[b] Abbreviation: DAT, days after treatment.

[c] Snap beans were graded according to U.S. Department of Agriculture Agricultural Marketing Service standards (USDA-AMS 2013a).

known through commercial practice (Bussan et al. 2014). Herbicide treatments were sprayed at two application timings: when the potato plants were 25 cm tall and at potato tuber initiation using the tractor-mounted sprayer described above. The application timings were selected based on the window of likely POST herbicide application to soybeans in the production region. All other general production and pest management practices followed typical commercial standards. Potato injury was visually estimated using the same scale as for the snap bean studies. Potato tubers were harvested on September 19, 2011, and September 17, 2012, from a single row using a mechanical harvester and graded according to USDA grade standards for potato (USDA-AMS 2013b). Tuber specific gravity, a parameter of particular importance in potato processing quality, was determined using the water displacement method described by Dean and Thornton (1992).

Data were subjected to ANOVA to determine if there was a treatment effect and a year by treatment interaction using PROC GLM in SAS. Means were separated using Fisher's LSD at $P = 0.05$. Additionally, Pearson correlation coefficients were determined for crop yield and injury estimates.

Results and Discussion

A significant interaction between treatment and year was observed in all cases, thus data were analyzed and presented by crop and year.

Snap Bean. The injury symptoms that were visually estimated included leaf cupping, stem epinasty, and most importantly, delayed and deformed snap bean flowers. At all injury evaluation timings in 2011, snap bean injury was greater at all dicamba rates as compared to 2,4-D or glyphosate applications. Additionally, snap bean plants recovered faster following 2,4-D exposure than following dicamba treatments. Snap bean injury was greatest at all evaluation timings where dicamba was applied at the 7.0 g ae ha^{-1} rate (Table 2).

The injury caused by the synthetic auxin herbicides was reflected in reduced snap bean yield in 2011 where dicamba was applied, regardless of herbicide rate, and where 2,4-D was applied at the 4.2 and 7.0 g ae ha^{-1} rates. Total snap bean yield was similar to the nontreated check where 2,4-D was applied at the 1.4 g ae ha^{-1} rate and in the glyphosate treatment (Table 2). No snap bean quality issues, such as twisted or deformed pods, were observed. Reductions in crop yield compared to the nontreated snap beans are presumed to be a result of delayed or deformed flowering. Although it is not known if snap beans with delayed flowers would have eventually produced a crop, in commercial production this question would have no relevance given the precise scheduling of harvests around perishability concerns of nearby production fields. Additionally, growers are obligated to meet contracted crop delivery dates to the processor. In other words, injured fields without viable flowers would be bypassed and never harvested.

Table 3. Effect of dicamba, 2,4-D, and glyphosate on visually estimated snap bean injury and yield in 2012 in Arlington, WI.

		Snap bean injury[a]			Snap bean yield		
Treatment	Herbicide rate	7 DAT[b]	14 DAT	22 DAT	Sieve size 1–3[c]	Sieve size 4–5	Total yield
	g ae ha^{-1}	%			kg ha^{-1}		
Nontreated	—	0 d	0 d	0 d	1,830 a	2,510 a	4,340 a
Dicamba	1.4	6 c	38 b	28 b	570 b	150 b	720 b
Dicamba	4.2	10 ab	48 a	40 a	120 b	0 b	120 b
Dicamba	7.0	11 a	43 ab	29 b	100 b	10 b	110 b
2,4-D	1.4	8 bc	6 cd	5 cd	2,040 a	2,660 a	4,700 a
2,4-D	4.2	8 bc	6 cd	5 cd	1,880 a	2,350 a	4,230 a
2,4-D	7.0	8 bc	11 c	10 c	1,920 a	2,170 a	4,090 a
Glyphosate	7.0	5 c	9 cd	6 cd	1,860 a	2,780 a	4,640 a

[a] Means followed by the same letter are not different according to Fisher's protected LSD test at $P = 0.05$.

[b] Abbreviation:DAT, days after treatment.

[c] Snap beans were graded according to U.S. Department of Agriculture Agricultural Marketing Service standards (USDA-AMS 2013a).

At 7 DAT in 2012, snap bean injury was greater than the nontreated check following all herbicide treatments. Dicamba applied at the 7.0 g ae ha^{-1} rate caused greater injury than any rate of 2,4-D or glyphosate. By 14 and 22 DAT, crop injury was greater where dicamba was applied, regardless of rate, compared to 2,4-D, glyphosate, and the nontreated check. Snap bean injury was similar at the 14 and 22 DAT evaluation timings in the glyphosate treatment, the nontreated check, and where 2,4-D was applied at the 1.4 and 4.2 g ae ha^{-1} rates (Table 3). These results were similar to those observed in 2011.

The persistent injury caused by dicamba in 2012 resulted in reduced snap bean yield at all sieve sizes, and in total, compared to the other herbicide treatments and the nontreated check. Crop yield was comparable to the nontreated check where 2,4-D (all herbicide rates) and glyphosate were used (Table 3).

Potato. The injury symptoms that were visually estimated on potato after treatment consisted primarily of smaller cupped leaves near the terminal end of the youngest stems; the remainder of the potato plant appeared healthy and without symptoms. Similarly, Wall (1994) reported minor leaf cupping and stem twisting from simulated dicamba drift. At the earliest evaluation timing in 2011, potato injury was 33% where dicamba was applied to 25-cm-tall potato plants at the 7.0 g ae ha^{-1} rate; 20% injury was observed with the 4.2 g ae ha^{-1} rate applied to 25-cm-tall potato plants and injury was comparable to the nontreated potatoes at the 1.4 g ae ha^{-1} rate. In subsequent evaluation timings, injury was consistently comparable to the nontreated check only where dicamba was applied to 25-cm-tall potato plants at the 1.4 g ae ha^{-1} rate (Table 4).

Although significant differences within tuber grade and weight classes were observed in 2011, there were no discernible trends that could easily be explained based on injury estimates and no differences in total tuber yield were observed (Table 5). The only exception may be where dicamba was applied to 25-cm-tall potato plants at the 7.0 g ae ha^{-1} rate. This treatment also coincides with the greatest injury observed at the first evaluation timing. Fewer large tubers (171 to 284 g and 285 to 370 g) were recorded in this treatment as compared to the nontreated check. However, B-size tubers and tubers less than 113 g were among the greatest of all treatments, and therefore total yield did not differ from any other treatment. No difference in tuber specific gravity was observed in either year (data not shown; average specific gravity was 1.07 and 1.08 in 2011 and 2012, respectively).

Although total potato tuber yield was not affected by herbicide treatments in 2011 in this study, off-target herbicides may cause additional issues beyond yield, such as when potatoes are grown for seed that is planted in the following year. Wall (1994) simulated dicamba drift on potatoes and planted the harvested tubers as seed in the following year. Potato injury in the year following dicamba application was noted in 2 of 3 yr of the study,

Table 4. Effect of dicamba on visually estimated potato injury in 2011 and 2012 (years analyzed separately) in Hancock, WI.

			Potato injury					
			2011[b]			2012		
Treatment	Timing[a]	Herbicide rate	24/8 DAT[c]	30/14 DAT	38/22DAT	25/9 DAT	31/15 DAT	38/22 DAT
		g ae ha^{-1}	%					
Nontreated	—	—	0 c	0 e	0 c	1 c	1 c	1 b
Dicamba	Early	1.4	2 c	1 de	0 c	13 b	4 cd	1 b
Dicamba	Early	4.2	20 b	10 b	6 c	31 a	6 c	2 b
Dicamba	Early	7.0	33 a	19 a	14 b	33 a	15 b	8 a
Dicamba	Late	1.4	0 c	5 cd	14 b	2 c	6 c	5 ab
Dicamba	Late	4.2	0 c	8 bc	15 b	3 c	13 b	7 a
Dicamba	Late	7.0	0 c	10 b	23 a	5 c	20 a	9 a

[a] Early herbicide application timing was to 25-cm-tall potato plants; late timing was at potato tuber initiation.

[b] Means followed by the same letter are not different according to Fisher's protected LSD test at P = 0.05.

[c] Abbreviation: DAT, days after the early/late treatments.

although the injury never exceeded 6%, recovery was observed, and tuber yield was not affected in any study year.

In 2012, potato injury was greatest where dicamba was applied to 25-cm-tall potato plants at the 4.2 and 7.0 g ae ha^{-1} rate. This observation was consistent with results from the 2011 study. However, potatoes recovered from injury faster in 2012, and by the second and third evaluation timings injury was only greater than the nontreated check where dicamba was applied to 25-cm-tall potato plants at the 7.0 g ae ha^{-1} rate and at the 4.2 and 7.0 g ae ha^{-1} rates applied at potato tuber initiation (Table 4).

Despite generally less persistent crop injury in 2012 compared to 2011, total yield was less than that of the nontreated check in three of six herbicide treatments (Table 6). More tuber culls were observed where dicamba was applied to 25-cm-tall potato plants at 7.0 g ae ha^{-1} than any other treatment, but total yield was similar to the nontreated check. Similar to 2011 results, tuber yield was somewhat variable and difficult to explain in relation to the visually estimated injury ratings at the herbicide application rates tested in this study.

The strength of the relationship between the visually estimated injury and subsequent crop yield and quality would be useful knowledge for vegetable growers and processors as they assess the source,

Table 5. Effect of dicamba at two simulated drift application timings on potato tuber yield in 2011 in Hancock, WI.

			Tuber grade and weight distribution[b]								
Treatment	Timing[a]	Herbicide rate	cull	B[c]	< 113 g	114 to 117 g	171 to 284 g	285 to 370 g	371 to 454 g	> 454 g	Total yield
		g ae ha^{-1}	kg ha^{-1}								
Nontreated	—	—	1,460 ab	6,610 b	8,060 bc	13,780	11,420 ab	1,570 ab	340	220	43,460
Dicamba	Early	1.4	1,230 abc	8,740 b	9,860 ab	12,990	8,290 bc	900 bc	0	0	41,780
Dicamba	Early	4.2	900 bc	14,450 a	11,980 a	13,330	8,400 bc	780 bc	220	0	49,950
Dicamba	Early	7.0	1,230 abc	10,080 b	11,420 ab	13,330	6,830 c	340 c	0	0	43,230
Dicamba	Late	1.4	780 bc	6,380 b	8,510 abc	13,550	11,870 ab	2,130 a	560	0	43,790
Dicamba	Late	4.2	560 c	10,420 ab	8,400 bc	13,890	12,540 a	900 bc	110	220	47,040
Dicamba	Late	7.0	1,900 a	7,730 b	6,050 c	10,300	11,760 ab	2,240 a	110	0	40,990

[a] Early herbicide application timing was to 25-cm-tall potato plants; late timing was at potato tuber initiation.

[b] Means followed by the same letter are not different according to Fisher's protected LSD test at P = 0.05. If no letters are included for a tuber grade or size, then there were no statistical differences noted.

[c] "B" size potatoes defined by U.S. Department of Agriculture Agricultural Marketing Service as 3.8 to 5.7 cm in diameter.

Table 6. Effect of dicamba at two simulated drift application timings on potato tuber yield in 2012 in Hancock, WI.

			Tuber grade and weight distribution[b]								
Treatment	Timing[a]	Herbicide rate	cull	B[c]	< 113 g	114 to 117 g	171 to 284 g	285 to 370 g	371 to 454 g	> 454 g	Total yield
		g ae ha^{-1}	kg ha^{-1}								
Nontreated	—	—	6,780 b	8,640	3,330	11,260	26,050 ab	13,790	8,380	5,640 a	83,870 a
Dicamba,	Early	1.4	5,200 b	8,970	6,400	12,450	26,700 ab	10,390	4,360	3,200 abc	77,670 b
Dicamba	Early	4.2	6,570 b	8,080	6,360	11,000	22,300 bc	10,150	5,000	2,130 bc	71,600 c
Dicamba	Early	7.0	13,240 a	6,810	5,640	12,610	23,120 bc	12,960	4,230	1,300 c	79,920 ab
Dicamba	Late	1.4	6,110 b	9,120	5,460	12,850	21,390 c	10,590	4,620	4,720 ab	74,840 bc
Dicamba	Late	4.2	5,070 b	11,000	4,870	11,590	25,470 abc	12,370	5,930	2,080 bc	78,380 ab
Dicamba	Late	7.0	6,730 b	9,540	7,100	12,540	28,810 a	10,770	5,950	2,850 abc	84,280 a

[a] Early herbicide application timing was to 25-cm-tall potato plants;, late timing was at potato tuber initiation.

[b] Means followed by the same letter are not different according to Fisher's protected LSD test at P = 0.05. If no letters are included for a tuber grade or size, then there were no statistical differences noted.

[c] "B" size potatoes defined by U.S. Department of Agriculture Agricultural Marketing Service as 3.8 to 5.7 cm in diameter.

symptoms, and severity of potential damage from off-target herbicides. In both 2011 and 2012, the second and third injury evaluations were strongly correlated with total snap bean yield, as was the first injury evaluation in 2011 (Table 7). The strength of this relationship between visually estimated injury at least 3 wk prior to harvest and snap bean yield would allow sufficient time for investigation of potential off-target herbicide movement.

In contrast, the relationship between potato injury estimates and tuber yield was poor and highly variable in both years (Table 7). Correlations ranged from –0.22 to 0.23 among evaluation timings and crop years. Although injury ratings were as high as 33% with dicamba applications to 25-cm-tall potato plants at the 7.0 g ae ha^{-1} rate in both years, this treatment did not affect total tuber yield compared to the nontreated check in either year. The lack of relationship between visual estimates of injury and subsequent yield has been observed with other crops. Everitt and Keeling (2009) reported that visual estimates of cotton injury from 2,4-D and dicamba applied at the cotyledon to two-leaf growth stage were not a good predictor of yield loss and tended to overestimate potential yield loss.

Table 7. Correlation between visually estimated injury and crop yield in snap bean (Arlington, WI) and potato (Hancock, WI) in 2011 and 2012.

	Pearson correlation coefficients		
	First estimation timing	Second estimation timing	Third estimation timing
2011			
Snap bean total yield	−0.84	−0.90	−0.81
Potato total yield	0.23	−0.01	−0.05
2012			
Snap bean total yield	−0.43	−0.88	−0.82
Potato total yield	−0.22	0.19	0.04

It is important to note that the strength of the correlation between visually estimated injury ratings and crop yield is independent of any potential herbicide residue in the snap beans or potatoes. Therefore, crop injury ratings and crop yield could not be used to determine the potential human health risk associated with off-target herbicide movement. It is also worth noting that a visual observation of crop injury earlier in the season is not necessarily an indication of herbicide residue in the harvested portion of the crop; this relationship varies by crop, herbicide, environment, application timing, crop recovery and metabolism, and several other factors. The poor relationship between potato injury and yield also draws attention to the risk of harvesting potatoes that have been subject to off-target herbicide movement, where crop injury goes unnoticed and crop yield is unaffected, but additional effects such as those on subsequent daughter tuber germination are unknown. In the case of snap beans and with dicamba in particular, the effect on crop yield was striking enough and consistent in a way that would raise grower and processor awareness of a potential issue at harvest and at least stimulate further investigation.

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Received March 28, 2014, and approved July 25, 2014.