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Glyphosate Carryover in Seed Potato: Effects on Mother Crop and Daughter Tubers

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Abstract Field studies were conducted in 2008 and 2009 in Aberdeen, ID, Ontario, OR, and Paterson, WA to determine the effect of simulated glyphosate drift on 'Ranger Russet' potato during the application year and the crop growing the next year from the daughter tubers. Glyphosate was applied at 8.5, 54, 107, 215, and 423 g ae ha^{-1} which corresponds to 1/00, 1/16, 1/8, ¼, and 1/2 of the lowest recommended single-application rate for glyphosate-resistant corn and sugar beet of 846 g ha^{-1}. Glyphosate was applied when potato plants were at 10 to 15 cm tall (Early), or at stolon hooking (H), tuber initiation (TI), or during mid-bulking (MB). In general, the MB applications caused less visual foliar injury to the mother crop than earlier applications at ID or OR, and H applications at WA. Mother crop injury increased as glyphosate rate increased regardless of location, application timing, and rating date. U.S. No.1 and total tuber yields were usually related to the injury level resulting from glyphosate application timings and rates. Although injury to the mother crop from glyphosate applied at MB usually was the lowest compared to injury from other application timings, when daughter tubers from that timing were planted the following year, emergence, plant vigor, and yield was most detrimentally impacted compared with that of daughter tubers from other timing treatments. MB daughter tuber emergence was less than 30 % of the nontreated control tuber emergence while emergence of daughter tubers from the other treatments was 60 to 95 %. As rate of glyphosate applied to the mother crop increased, daughter tuber emergence decreased. When MB daughter tubers did emerge, plants were chlorotic and stunted as if the plants had been directly sprayed with glyphosate. Regardless of whether the daughter tubers had defects or not, results the following year were the same. Implications are that if a mother seed crop encounters glyphosate during bulking, injury may not even be noticeable on the foliage or the tubers, however, emergence, vigor, and yield of the crop growing the following year from the daughter tubers could be greatly impacted.

Resumen En Aberdeen, ID, Ontario, OR, y Paterson, WA, se desarrollaron estudios de campo en 2008 y 2009, para determinar el efecto de simulación de acumulación de glifosato en papa "Ranger Russet" durante el año de aplicación y el crecimiento del cultivo del siguiente año de semilla de esa cosecha. Se aplicó el glifosato a 8.5, 54, 107, 215 y 423 g ia ha^{-1}, lo que corresponde a 1/00, 1/16, 1/8, ¼, y ½ de la dosis más baja recomendada para una sola aplicación para maíz resistente al glifosato y remolacha de 846 g ha^{-1}. Se aplicó el producto cuando las plantas de papa alcanzaron de 10 a 15 cm de altura (temprano), o al enganchamiento del estolón (H), a la iniciación del tubérculo (TI), o a medias de la tuberización (MB). En general, las aplicaciones a MB causaron menos daño foliar visual al cultivo madre que las aplicaciones más tempranas en ID u OR, y que las aplicaciones H en WA. Aumentó el daño del cultivo madre a medida que aumentó la dosis del glifosato, independientemente de la localidad, tiempo de aplicación, y fecha de lectura. La calidad U.S. No. 1 y los rendimientos totales de tubérculo estuvieron generalmente relacionados al nivel del daño que resultó de los tiempos y dosis de aplicación del producto. Aun cuando el daño al cultivo madre por el

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glifosato aplicado a MB generalmente fue el más bajo comparado con otras etapas de aplicación, cuando los tubérculos resultantes de esa etapa se plantaron al año siguiente, la emergencia, el vigor de la planta y el rendimiento estuvieron más impactados en detrimento, en comparación con aquellos de tubérculos hijos de otros tratamientos o etapas de aplicación. La emergencia de tubérculos resultantes de MB fue menor al 30 % de la de los tubérculos del testigo no tratado, mientras que la emergencia de los tubérculos hijos de los otros tratamientos fue de 60 al 95 %. A medida que aumentó la dosis del glifosato aplicado al cultivo madre, disminuyó la emergencia de los tubérculos hijos. Cuando emergieron los tubérculos resultantes de MB, las plantas fueron cloróticas y pequeñas, como si hubieran sido asperjadas directamente con glifosato. Independientemente de que si los tubérculos hijos tuvieran o no defectos, los resultados del año siguiente fueron los mismos. Las implicaciones son de que si un cultivo madre para semilla se encuentra con el glifosato durante plena tuberización, posiblemente el daño no podría notarse en el follaje o en los tubérculos, no obstante, la emergencia, el vigor y el rendimiento del cultivo del siguiente año con tubérculo-semilla hijo pudiera impactarse grandemente.

Keywords *Solanum tuberosum* · Glyphosate · Application timing · Rate · Mother crop · Daughter tuber

Introduction

Glyphosate is a nonselective postemergence herbicide used to control annual and perennial weeds in reduced tillage cropping systems, herbicide resistant crops, non-crop areas and industrial sites, the home and garden market, and for crop pre-plant or preemergence burn-down or late-season weed control (Anonymous 2012). Glyphosate acts by inhibiting a metabolic pathway enzyme present in all plants, bacteria and fungi, but not in animals (Carlisle and Trevors 1988). Since 1996 with the introduction of glyphosate resistant crops, glyphosate has become the most widely used herbicide in the world (Gianessi 2004). In fact, at 82 to 84 MT, glyphosate was the most used herbicide in the U.S. agriculture sector in 2007–which is as much as the total of the next 11 most-used herbicides (Grube et al. 2011). In the Pacific Northwest (PNW), glyphosate is applied directly to many tolerant crops including alfalfa (*Medicago sativa L.*), corn (*Zea mays L.*), as well as sugar beets (*Beta vulgaris L.)* which were launched in the PNW in 2008. The increasing number of fields planted to glyphosate resistant crops and probable multiple applications of glyphosate during the season increase the chance of off-target drift to susceptible crops in adjacent fields. Research has shown that downwind herbicide drift concentrations can be from 1 to 16 % of the target dose (Bode 1987; Maybank et al. 1978) and even low herbicide concentrations can cause severe injury to susceptible crops (Al-Khatib et al. 2003).

Spot-spraying glyphosate in or around a field or inadequate sprayer and tank clean-out after glyphosate use also can be the cause of crops encountering glyphosate, By inhibiting the EPSP synthase enzyme, glyphosate disrupts the skikimic acid pathway which produces aromatic amino acids in plants needed for protein synthesis and plant growth (Senseman 2007). Amino acid synthesis inhibitors can reduce potato leaf size and internode length (Eberlein et al. 1997). New leaves can turn chlorotic and plant growth may be greatly reduced. Even though above-ground potato foliage may appear to recover from herbicide injury or not ever show any symptoms, overall yields can be reduced and tubers can have numerous growth cracks and folds resulting in loss of quality and worth of the crop (Eberlein and Guttieri 1994; Hutchinson et al. 2007). Glyphosate is absorbed across leaves and stems and translocated in the phloem from the source leaves to sink tissues following sucrose movement (Gougler and Geiger 1981) and since bulking tubers are the major sink in potatoe plants, can be translocated down to and absorbed into developing tubers being grown for seed.

Results of simulated drift studies on potatoes to determine the effect of herbicides other than glyphosate have been published (Eberlein and Guttieri 1994; Seefeldt et al. 2013; Wall 1994). Potato studies have been conducted with glyphosate to determine effectiveness of glyphosate for volunteer potato control (Smid and Hiller 1981; Lutman and Richardson 1978; Masiunas and Weller 1988), late-season applications for potato sprout suppression in storage (Vijay and Ezekiel 2006), and to develop a greenhouse assay with potato plants to indicate potential effects of off-target herbicide movement in field situations (Pfleeger et al. 2008). Results from a 1982 to 1983 trial conducted in England showed that daughter tubers cv Pentland Squire planted in boxes mid-April 1983 and allowed to grow for approximately 5 weeks, were affected by glyphosate rates as low as 0.018 kg ha^{-1} applied to the mother crop in August of the previous year 1982 (Worthington 1985). Hatterman-Valenti (2014) conducted a trial to determine the effect of a late-season glyphosate application on potatoes and on seed tubers. Since a potato crop can encounter glyphosate during the entire growing season, not just late-season, the objective of this study was to apply various glyphosate rates in simulated drift spray to the mother potato crop at four different times during the growing season and determine effect on growth and yield of the mother crop as well as emergence, growth, and yield of plants grown from the daughter tubers the following year. Observations from this study will be useful to commercial and seed potato growers for symptomology indicating their crop has possibly encountered glyphosate and what effects on tuber yield and quality, if any, might occur the same year. In addition, growers planting seed of a mother crop afflicted by glyphosate could use information from this study to begin identifying cause for problems with the crop growing from that seed, especially if it was not known that the mother crop had encountered glyphosate the previous year.

Materials and Methods

Unless noted, material and methods presented were used at all trial locations.

Trial Initiation Year–mother Crop

In 2008, potato variety 'Ranger Russet' was planted in field trials in southeast ID–Aberdeen; eastern OR–Ontario, and eastern WA–Paterson. Seed spacing was 22.5 cm in rows spaced 91, 91, and 86 cm apart, at ID, OR, and WA, respectively. Ranger Russet variety was chosen because it is one of the top five potato varieties grown in the major potato producing states (NASS 2012) and common to the three research trial areas Potatoes were grown with standard production practices for each area including cultivation, fertilization, irrigation, and pest management. Trials were established in a split-plot design with treatments arranged in randomized complete block in four replications. Four herbicide application timings formed the main plots and five rates of isopropylamine salt of glyphosate were randomly assigned to split-plots. Plots size was 2.7 m wide (4 rows) by 9.1 m long or 2.6 m (4 rows) wide by 11 m long at the ID/OR or WA sites, respectively. Just prior to potato emergence, a hilling operation was performed, and in order to help maintain weed-free conditions season-long so that effects on the crop would not be due weed competition, S-metolachlor tank-mixed with pendimethalin at 1,060 and 1,420 g ai ha, respectively, was applied and sprinkler incorporated on the entire trial area. Periodic hand weeding also was performed as needed during the season.

Glyphosate application timings occurred when potato plants were 10 to 15 cm tall (Early), or at hooking (H), tuber initiation (TI), or tuber mid-bulking (MB) (tubers in nontreated control were beginning to reach 113 g wt). Glyphosate rates evaluated were 8.5, 54, 107, 215, and 423 g per ha, which corresponds to 1/100, 1/32, 1/8, 1/4, and 1/2, respectively, of the lowest recommended single application rate of 846 g ha^{-1} for glyphosate in transgenic corn and sugar beet (Anonymous 2008). The timings were chosen to coincide with possible glyphosate application times to the tolerant corn and sugar beet or for weed control in small grains just prior to grain harvest. All glyphosate treatments were applied with ammonium sulfate at 2.5 % v/v in a total spray volume of 187 L ha^{-1} using a backpack compressed-CO2 sprayer operated at 186 to 241 kPa depending upon location. Spray swath covered the two center rows of each 4-row plot with the appropriate rate leaving the outside rows as buffer between plots. Rated and harvested area of the two center rows was bordered on each end of the plot by 1.5 to 2.2 m. A nontreated control also was included.

After each application timing, damage to the potato plant foliage was rated visually on a scale of 0 (no damage) to 100 % (total plant death) at 7, 21, and 42 days after treatment (DAT). At the end of the growing season, 6 m of each of the two center rows in every plot were harvested with a mechanical harvester and tuber yield and quality determined according to USDA grading standards (Anonymous 1991). Subsample of daughter tubers harvested from each plot were stored over the winter at each location for planting spring 2009 in order to determine the effect of the different glyphosate application rates and timings to the mother crop on daughter crop emergence, growth, and yield. The crop planted and sprayed with the various glyphosate treatments in 2008 will be referred to as the "mother" crop. The crop grown from the tubers harvested in 2008 and planted in 2009 will be referred to as the "daughter tuber" crop. Mother crop planting, application, and harvest dates at each location are included in Table 1.

Stand and stems counts in the daughter tuber crop were performed in each plot shortly after full emergence of the nontreated control plots. Visible injury ratings were conducted periodically, and at season-end, tubers from all emerged plants in both rows were harvested and graded as previously described.

Seed Tuber Planting Year–daughter Tuber Crop

Twenty seed pieces, each cut from a different daughter tubers harvested from each 2008 plot were planted in 2-row plots in 2009. In-and between-row spacing was the same as with the mother crop. Plots consisted of two rows with 10 seed pieces–each from a different daughter tuber, in each row. Some daughter tubers harvested from the 2008 plots had defects. In order to determine if a visual inspection of daughter tubers

Table 1 2008 planting, application timing, and harvest dates for glyphosate mother crop potato trials at Aberdeen, ID, Ontario, OR, and Paterson, WA

	Aberdeen, ID	Ontario, OR	Paterson, WA
Planting	May 13	April 23	March 19
Application timings			
Potato plants 10 to 15 cm tall	June 20	May 26	April 9
Hooking stage	July 1	June 5	May 1
Tuber initiation stage	July 10	June 13	May 27
Mid-bulking stage	Aug 14	July 1	June 13
Harvest	Oct 7	Sept 19	Sept 11

could be used to discriminate between glyphosate-and non-glyphosate affected tubers, Row 1 in each plot was planted with seed pieces from tubers which had visible damage such as growth cracks, bud-end folds, elephant hiding, and/or were misshapen. Tubers used for Row 2 seed pieces were from the same plot as those in Row 1 and had no visible defect. Treatments were arranged in a Randomized Complete Block Design with four replications. Crop stand in each plot was determined after full emergence was reached in the nontreated control plots and visual foliar damage was rated periodically during the growing season on the same scale used for the mother crop. At the end of the season, every plant producing tubers was harvested by hand and tuber yield and quality for each treatment determined by the USDA grading standards used for the mother crop.

Statistical Analyses

Data were subjected to ANOVA using PROC GLM (SAS version 9.2, SAS Institute Inc., Cary, NC). Data were not transformed as conditions of normality were satisfied. Location, glyphosate rate, and application timing interactions were tested and data were pooled across location, rate, or timing when there were no significant interactions. Application timing means comparisons were performed using Fisher's Protected LSD Tests at a probability level of≤0.05. If the rate effect was significant then trend analyses ($P \leq 0.05$) were performed to determine whether the response was linear or quadratic. Since the rates were of unequal spacing, PROC IML was used to generate appropriate trend analyses coefficients for the statistical procedure.

Results

Mother Crop Foliar Injury

Foliar injury consisted of chlorosis and/or necrosis of the newest leaves and some plant stunting. At 7, 21, and 42 DAT there were significant location interactions, and within locations, significant rate by application timing interactions. When data were sorted by location, however, ranking of % injury at each timing remained similar within rates, therefore, timing data was ombined over rates for each location. Overall, regardless of rating date in WA, injury resulting from application timing at that location usually ranked H≥TI≥MB≥ Early, whereas, injury at the other locations generally ranked Early≥H≥TI≥MB (Fig. 1). As mentioned, glyphosate disrupts the shikimic acid pathway in plants. Felix et al. (2011) suggest greater potato plant sensitivity to glyphosate at the H stage compared with E, TI, or MB since they found that a lower glyphosate dose is required to trigger shikimic acid accumulation in the plant at H than the dose required at the other times.

Regardless of location, as the glyphosate rate increased, injury at 7, 21, or 42 DAT also increased therefore data were combined over location (Table 2). However, there were rate x timing interactions so data were sorted by timing and rate effect determined within timings for each rating date (Table 2). A gyphosate rate increased during each timing, injury increased and increase was quadratic except for Early, H, MB at 7 DAT, MB 21DAT, and Early and MB 42 DAT, which was linear. In general, injury caused by the lowest glyphosate rate was less than 10 % (Table 2). Injury from the highest rate applied during MB did not reach more than 30 % on any rating date (Table 2). In contrast, the highest rate of glyphosate applied at E, H, and TI timings caused as much as 50 to 85 % injury. Injury from application at H was relatively similar to injury from application at Early or TI when rated 7 and 21 DAT but by 42 DAT, H application injury was greater than at Early or TI.

Mother Crop Tuber Yields

Yields were combined across location and rate, U.S. No. 1 (tubers weighing >113 g with no defects) and total tuber yields ranged from 21.4 to 49.4 and 33.9 to 59.4 MT ha^{-1}, respectively (Fig. 2). Yields seemed to reflect the level of foliar injury resulting from glyphosate application rate or timing during the season. At 21.4 and 22.4 MT ha^{-1}, the H and TI application U.S. No 1 tuber yields, respectively, were less than the 37.4 and 49.4 MT ha^{-1} from the Early application and nontreated control, respectively (Fig. 2). H total tuber yields were less than yields in the control and all other timings except TI (Fig. 2). Compared with the control yield, application at mid-bulking caused a slight decrease in U.S. No. 1 but not total tuber yield (Fig. 2).

As expected, and regardless of application timing, as glyphosate rate increased U.S. No. 1 and total tuber yields decreased and that decrease was quadratic and linear, respectively (Table 3). Glyphosate rate and timing also impacted U.S. No. 1 and malformed cull (tubers of any weight with more than one defect) yield as a % of total tuber yields (Fig. 3, Table 3). Defects consisted of bud-end folding, some cracking, and misshape. The nontreated control U.S. No. 1 yield as a % of total tuber yield was greater than that of any application timing and yields from those timings ranked from highest to lowest as: Early>MB >H>TI (Fig. 3). At 43 and 28 %, culls as a % of total tuber yields were greater when glyphosate was applied at TI or H, respectively, compared with the 6, 13, or 16 % of total yields from the nontreated control, Early, or MB applications, respectively (Fig. 3). U.S. No. 1 increased and cull yields as a % of total tuber yield decreased both in a quadratic manner as glyphosate rate increased regardless of application timing (Table 3).

Daughter Tuber Crop Emergence and Vigor

Daughter tuber crop emergence, injury, stem number, and tuber yields were the same regardless of whether or not a seed

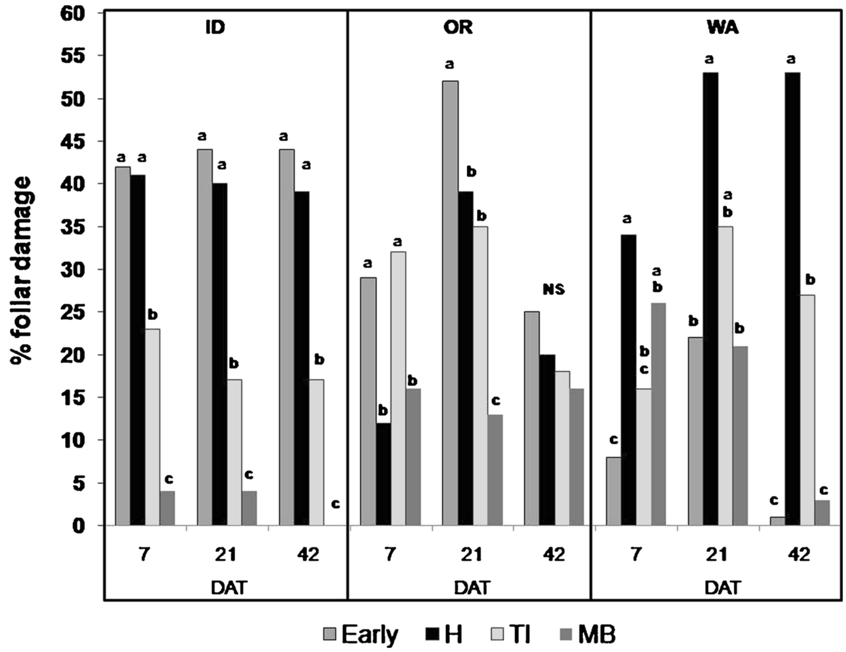

Fig. 1 Effect of glyphosate application timing–early (10 to 15 cm tall plants), hooking (H), tuber initiation (TI), or mid-bulking (MB) pooled over rates on Ranger Russet mother crop foliar injury in 2008 at Aberdeen, ID, Ontario, OR, or Paterson, WA 7, 21, or 42 DAT. *Bars* with a different letter within a location and rating date are significantly different according to a Fisher's Protected LSD Test performed at the 0.05 level of probability

piece was cut from a daughter tuber with or without symptoms so all data were combined over this factor. Even though mother crop injury was generally less from glyphosate applied at MB than at Early, H, and TI in ID and OR and H and TI in WA, MB daughter tuber emergence and stems per plant was less than that of daughter tubers coming from those other mother crop application timings (Fig. 4)., Pooled across locations and rates, the 95 % Early timing daughter tuber emergence was greater than the 64 and 72 % emergence from H and TI daughter tubers, respectively, all of which were greater than the 27 % emergence of the MB daughter tubers (Fig. 4). Stems per plant followed the same pattern.

The effect on daughter tuber crop emergence and stems per plant from increasing glyphosate rate applied to the mother crop was not the same for each application timing so rate effect data were sorted by timings and rate within ting effect determined. Emergence and stem number remained similar as glyphosate rate increased even to the highest rate within the Early timing (Table 4). Otherwise, daughter tuber emergence and stems per plant as a % of the control decreased in a linear manner as the mother crop glyphosate application rate increased during H, TI, and MB timings except for emergence at MB which decreased quadratically (Table 4).

Daughter tuber crop injury was only determined at the ID location and when glyphosate was applied at Early, H, or TI to the mother crop, was below 20 % while plants growing from the MB daughter tubers were injured 45 % averaged across locations and rates (data not shown). In fact, MB daughter tuber

Table 2 Effect of glyphosate rate x application timing – early (10 to 15 cm tall plants), hooking (H), tuber initiation (TI), or mid-bulking (MB), on 2008 Ranger Russet mother crop foliar injury 7, 21, and 42 DAT in ID, OR, and WA pooled across locations

	7 DAT				21 DAT				42 DAT			
Rate	Early	H	TI	MB	Early	H	TI	MB	Early	H	TI	MB
kg ae ha^{-1}	% injury											
8.5	3	4	3	1	3	6	3	2	0	2	1	0
54	17	11	12	9	12	23	4	6	1	14	5	2
107	25	19	20	11	43	46	22	10	19	35	13	5
215	34	39	35	20	57	68	50	16	35	60	34	9
423	53	71	48	34	75	84	67	29	52	84	50	15
	Pr>F											
Rate effect	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Linear trend	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Quadratic trend	0.1657	0.9281	0.0038	0.6576	0.0003	<0.0001	0.0046	0.7739	0.2093	0.0151	0.0183	0.6855

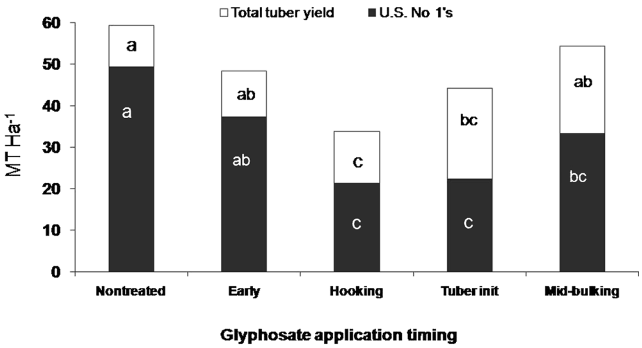

Fig. 2 Effect of glyphosate application timing – early (10 to 15 cm tall plants), hooking (H), tuber initiation (TI), or mid-bulking (MB) pooled over rates and location on Ranger Russet mother crop U.S. No. 1 (tubers weighing >113 g) and total tuber yields in 2008 at Aberdeen, ID, Ontario, OR, and Paterson, WA. *Bar* portions with the same color and a different letter are significantly different according to a Fisher's Protected LSD Test performed at the 0.05 level of probability

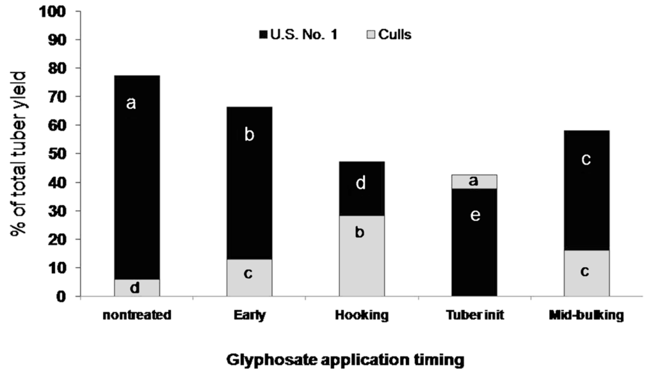

Fig. 3 Effect of glyphosate application timing–early (10 to 15 cm tall plants), hooking (H), tuber initiation (TI), or mid-bulking (MB) pooled over rates and locations on Ranger Russet mother crop U.S. No. 1 (tubers weighing >113 g) and cull (tubers of any weight with more than one defect) yields as a % of total tuber yields in 2008 at Aberdeen, ID, Ontario, OR, and Paterson, WA. *Bar* portions with the same color and a different letter are significantly different according to a Fisher's Protected LSD Test performed at the 0.05 level of probability

plants which did emerge had low vigor and exhibited foliar chlorosis and stunting damage as if glyphosate had been applied directly to the plants rather than to the mother crop. Daughter tuber foliar injury symptoms were generally the same at the other locations (personal communications J. Felix and R. Boydston). In addition, if daughter tubers came from TI or MB timings, as rate increased, daughter tuber crop injury also increased to as much as 65 % while injury remained below 20 % even when the daughter tubers came from the highest rate during applied Early or H timings (data not shown).

Daughter Tuber Crop Yields

U.S. No. 1 and total tuber yields ranged from 17 to 33 and 25 to 45 MT ha^{-1} (Fig. 5). As with emergence and plant vigor, daughter tuber crop yields also were affected by glyphosate rates and application timings to the mother crop. Averaged across locations and glyphosate rates, ranking of daughter tuber crop U.S. No. 1 yields was nontreated control≥Early≥H>TI>MB (Fig. 5). Nontreated control total tuber yields were greater than those of daughter tubers from H, TI, or MB timings (Fig. 5). Early timing daughter tuber yields remained the same regardless of glyphosate rate applied to the mother crop at that timing (Table 5). However, daughter tuber crop U.S. No. 1 and total tuber yields decreased in a linear, linear, or quadratic manner as glyphosate rate applied to the mother crop increased during the H, TI, or MB timings, respectively (Table 5). Early, H, and TI daughter tuber crop U.S. No. 1 and cull yields as a % of total tuber yield were similar to

Table 3 Effect of glyphosate rate on 2008 Ranger Russet mother crop yield in ID, OR, and WA pooled across application timings and locations

	Tuber yields			
Rate	U.S. No. 1's	Total	U.S. No. 1's	Culls
kg ae ha^{-1}	MT ha^{-1}		% of total	
0	48.6	57.4	70.4	5.7
8.5	47.1	57.3	75.4	5.7
54	33.9	54.0	67.7	12.3
107	27.7	46.4	54.0	24.8
215	16.8	36.3	37.5	36.2
423	9.2	27.6	27.2	47.8
	Pr>F			
Rate effect	<0.0001	<0.0001	<0.0001	<0.0001
Linear trend	<0.0001	<0.0001	<0.0001	<0.0001
Quadratic trend	0.0022	0.2277	0.0005	0.0138

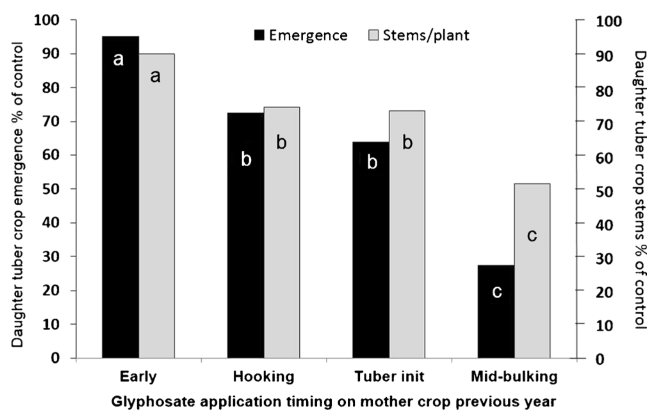

Fig. 4 Effect of 2008 Ranger Russet mother crop glyphosate application timing–early (10 to 15 cm tall plants), hooking (H), tuber initiation (TI), or mid-bulking (MB) pooled over rates and locations on 2009 daughter tuber crop emergence as a % of nontreated control emergence (*left* Y axis) at Aberdeen, ID, Ontario, OR, and Paterson, WA or daughter tuber crop foliar injury (*right* Y axis) pooled over timings at Aberdeen, ID. *Bars* of the same color with a different letter are significantly different according to a Fisher's Protected LSD Test performed at the 0.05 level of probability

Table 4 Effect of 2008 glyphosate rate x application timing to mother crop – early (10 to 15 cm tall plants), hooking (H), tuber initiation (TI), or mid-bulking (MB) on 2009 Ranger Russet daughter crop emergence and number of stems per plant in ID, OR, and WA pooled across locations

	Emergence				Stems per plant			
Rate	Early	H	TI	MB	Early	H	TI	MB
kg ae ha^{-1}	% of control							
8.5	96	89	82	64	91	91	86	72
54	96	85	79	30	88	87	85	64
107	96	83	66	21	94	83	69	47
215	93	60	56	12	87	74	67	43
423	93	45	37	11	90	37	59	32
	Pr>F							
Rate effect	0.5689	<0.0001	<0.0001	<0.0001	0.3529	<0.0001	<0.0001	<0.0001
Linear trend	0.1394	<0.0001	<0.0001	<0.0001	0.7426	<0.0001	0.0002	0.0001
Quadratic trend	0.7417	0.5606	0.4086	<0.0001	0.7749	0.1373	0.2108	0.1788

nontreated control yields whereas the MB daughter tuber crop had significantly less % U.S. No. 1 and greater % culls than the control (Fig. 6). As with the other daughter tuber crop results and averaged across locations and timings, as the glyphosate rate applied to the mother crop increased, daughter tuber U.S. No. 1 yields as a % of total tuber yield decreased (Table 5). U.S. No. 1 % increased from 67.6 to 47.6 % and culls % increased from 10.9 to 27.4 % both in a quadratic manner (Table 5).

Discussion

Mother Crop

At Aberdeen, little or no foliar symptoms were observed from glyphosate applications at MB, the timing which most affected the daughter tubers. It is possible, therefore, especially in a relatively short, cool temperature growing season area such as southeast ID, that a seed potato grower may not even know that the mother crop encountered glyphosate in some way during that period of the season. Hatterman-Valenti and Auwarter (2010) have presented similar conclusions that simulated glyphosate drift on to Russet Burbank in ND during bulking/early senescence did not result in easily identifiable foliar injury.

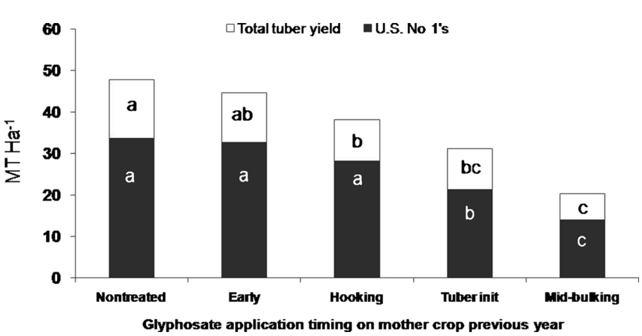

Fig. 5 Effect of 2008 Ranger Russet mother crop glyphosate application timing–early (10 to 15 cm tall plants), hooking (H), tuber initiation (TI), or mid-bulking (MB) pooled over rates and locations on 2009 daughter tuber crop U.S. No. 1 and total tuber yields at Aberdeen, ID, Ontario, OR, and Paterson, WA. *Bar* portions with the same color and a different letter are significantly different according to a Fisher's Protected LSD Test performed at the 0.05 level of probability

Plant injury and death from glyphosate is relatively slow (Stoller et al. 1975). Chlorosis on the foliage can take as long as 20 days after application to develop (Senseman 2007). Most likely because of the relatively shorter season and cooler temperatures, MB applications at ID did not cause as much mother crop injury as they did at the other locations especially since the potato plants at ID begin to naturally senesce sooner after the MB applications than at the other locations (general observations).

As with other crops such as rice (*Oryza sativa* L.), sorghum (*Sorghum bicolor* L.), and tobacco (*Nicotiana tabacum* L.), (Ellis et al. 2003; Koger et al. 2005; Al-Khatib et al. 2003; Burke et al. 2005), regardless of glyphosate application timing in our study, when rate increased, injury to the mother potato crop increased. Masiunas and Weller (1988) also observed increased potato injury with glyphosate applied at field use rates in their greenhouse/growth chamber study.

Mother crop yields were generally related to level of injury during the season which was related to application timing and rate. For instance, H application U.S. No. 1 and total tuber yields were reduced 57 and 43 %, respectively, compared to the nontreated yields. In agreement with Seefeldt et al. (1995) who found that partially injured plants can compensate for injury over time with minimal effects on yield, potato plants injured during the Early application timing had time to recover before harvest. Somewhat similar to our results, Russet Burbank mother crop tuber yields were reduced when

Table 5 Effect of 2008 mother crop glyphosate rate x application timing – early (10 to 15 cm tall plants), hooking (H), tuber initiation (TI), or mid-bulking (MB) on 2009 Ranger Russet daughter crop U.S. No. 1 and total tuber yields and glyphosate rate effect on U.S. No. 1 and cull yields as a % of total tuber yields in ID, OR, and WA pooled across locations

	Tuber yields									
	U.S. No 1				Total				U.S. No 1	Culls
Rate	Early	H	TI	MB	Early	H	TI	MB		
kg ae ha^{-1}	MT ha^{-1}								% of total	
0	33.6	33.6	33.6	33.6	47.9	47.9	47.9	47.9	67.6	10.9
8.5	33.3	35.5	27.5	25.2	44.3	47.0	38.6	37.2	64.6	14.3
54	29.7	33.4	23.4	15.9	37.5	46.7	33.3	21.6	60.7	15.6
107	34.6	35.5	20.7	11.0	42.2	45.1	30.4	16.0	55.9	18.9
215	35.2	23.1	20.0	9.8	46.9	32.4	29.7	14.7	55.5	20.4
423	34.5	14.1	15.1	8.0	46.8	19.8	23.6	12.6	47.6	27.4
	Pr>F									
Rate effect	0.8376	<0.0001	<0.0001	<0.0001	0.6979	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Linear trend	0.4382	<0.0001	0.0004	<0.0001	0.5149	<0.0001	0.0002	<0.0001	<0.0001	<0.0001
Quadratic trend	0.8791	0.7204	0.1583	<0.0001	0.9711	0.7506	0.1139	<0.0001	0.2064	0.6709

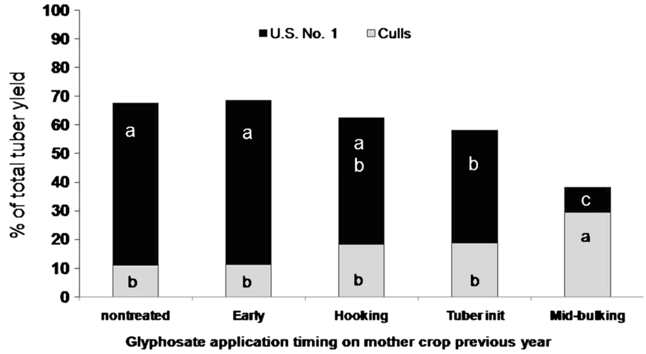

Fig. 6 Effect of 2008 Ranger Russet mother crop glyphosate application timing–early (10 to 15 cm tall plants), hooking (H), tuber initiation (TI), or mid-bulking (MB) pooled over rates and locations on 2009 daughter tuber U.S. No. 1 (tubers weighing >113 g) and cull (tubers of any weight with more than one defect) yields as a % of total tuber yields at Aberdeen, ID, Ontario, OR, and Paterson, WA. *Bar* portions with the same color and a different letter within U.S. No. 1 or cull yields are significantly different according to a Fisher's Protected LSD Test performed at the 0.05 level of probability

glyphosate applications were made at H compared with yields of the nontreated control in a North Dakota study (Auwarter and Hatterman-Valenti 2007). However, they also presented results from that same study of early-senescence applications reducing yields compared with nontreated yields. Pfleeger et al. (2008) reported reduced tuber yields in a short term greenhouse study from glyphosate applied 14 day after potato emergence which would be similar or even earlier than our Early application timing. Perhaps if the plants had more time to recover in that study as what occurred in our study, then tuber yields may not have been impacted from that application timing. Malformed cull yields in our study were greater from the H and TI applications than from Early, MB, and control treatments, and averaged across timings, increased as rate increased. Hatterman-Valenti and Auwarter (2009) have observed an increase of 'Red Norland','Red LaSoda' and 'Sangre' tubers with growth cracks and skin defects when glyphosate was applied TI and/or early-bulking compared with amount of defected tubers caused by early senescence/late-bulking applications. Seemingly, mother crop varietal response to glyphosate can vary which warrants future research with more varieties.

Daughter Tuber Crop

When glyphosate was applied to the mother crop at mid-bulking in our study, emergence from daughter tubers planted the following year was greatly reduced compared to emergence of daughter tubers from other application timings. The bulking tuber is the major sink so glyphosate applied to the mother crop at MB most likely moved into the tuber at that time, specifically to the eyes/buds as Smid and Hiller (1981) found during their volunteer potato control study, to affect emergence and plant vigor the following year. Hatterman-Valenti (2014) also found that when glyphosate was applied to Russet Burbank or Red LaSoda in ND during bulking, sprouting the following year of tubers produced by those plants was inhibited compared with that of tubers harvested from nontreated plants. As mentioned, seed potato growers may not know their crop has been affected by glyphosate because mother crop foliage injury caused by glyphosate applied in our study at this most crucial time was relatively low or not seen at all. Even if plants emerge from these affected tubers, as they did from some of the tubers in our study, chlorosis and stunting injury appears as if glyphosate had been applied directly to the plants. These symptoms on daughter tuber plants is most likely because food reserves are known to move from the seed piece into a growing potato plant as far into the season as tuber initiation (Smid and Hiller 1981). An unsuspecting grower experiencing daughter tuber emergence issues and plant injury will be able to use results and observations from our study as a possible starting point to determining the cause.

According to a technical note from the Scottish Agricultural College (Ballingall 2011), glyphosate can remain stable in a potato tuber for up to 8 months. As a general observation, the daughter tuber seed pieces from treated mother plants in our study remained intact for the entire growing season and there were some tubers weakly sprouting late-season in the plots which did not have many emerged plants earlier in the season. In a sprout inhibitor study conducted in India, a pre-harvest application of glyphosate at 0.833 kg ae ha^{-1} suppressed daughter tuber sprouting of two varieties 74 % to 85 % compared with sprouting of daughter tubers from the nontreated control (Vijay and Ezekiel. 2006). Higher glyphosate rates applied to the mother crop in the India trial resulted in buds with a cauliflower-like appearance. Normally on a potato tuber, only one dominant sprout emerges from a single eye. Smid and Hiller (1981) reported that clusters of severely suppressed sprouts i.e. cauliflower buds, appearing on glyphosate-treated tubers were a result of a glyphosate-induced loss of apical dominance.

The daughter tubers in our study were not analyzed for glyphosate residue due to funding challenges, and little to no information is currently published relating controlled study daughter tuber glyphosate concentrations to the impact on a crop growing from those tubers. However, as glyphosate rate applied to the mother crop increased in our study, the daughter crop was increasingly impacted, especially for emergence. Robinson and Hatterman-Valenti (2013) have reported after planting daughter tubers collected from mother crop grower fields with suspect glyphosate, that relatively high glyphosate concentrations in the daughter tubers inhibited sprouting all together. IT is possible that low glyphosate concentrations in daughter tubers may cause the underground multiple, "candelabra" sprouting observed in other varieties, not with the Ranger Russet in our study; the cauliflower bud appearance as observed in the aforementioned India sprout-inhibitor study; or as in our study, allow plants to emerged but remain of low vigor; or even produce a crop with no yield reduction.

When daughter tubers produced by potato plants sprayed with dicamba, clopyralid, or tribenuron were planted the following season, emerged plants exhibited injury symptoms, however, tuber yield and quality was not affected (Wall 1994). In our trial, however, daughter tuber crop yields were affected by glyphosate rates and application timings, especially during MB, to the mother crop.

Summary

As in our study, symptoms from early-season glyphosate in a grower field may seem severe, however, potato plants can most likely recover from glyphosate encountered at this time before hooking even at relatively high doses. Therefore, recommendations to a grower facing early-season glyphosate injury would include the possibility of keeping the crop growing with required input. At hooking, just as plants are beginning to grow quickly, mother crop plants may not be able to recover well from glyphosate encountered at that time. As a result of glyphosate at hooking and even at tuber initiation, the mother crop tuber yield and quality could be impacted detrimentally, more so than from glyphosate applied before hooking. At this point in time, a grower might feel that it is too late to plant a different crop so would most likely not want to crop destruct even though yield losses may occur. Yield differences among the H/TI timing treatments and nontreated control in our study could possibly translate to how much the grower yield and net return would be impacted from glyphosate encountered at this time, depending upon potato variety, environment, and growing conditions, and used to assess damages. As mentioned, H application yields were reduced more than 40 % compared to the nontreated yields. To put that in further perspective, in a 2002–03 Idaho study determining the effect of sulfometuron soil residues on Russet Burbank, a 5 or 20 % net return reduction was equivalent to a loss of $41 or 160 ha^{-1}, respectively, based on total production costs at that time subtracted from gross returns as determined by an incentive-adjusted processing contract pricing model (Hutchinson et al. 2007). As for later in the season, glyphosate encountered somehow by a potato crop at mid-bulking stage or after may not even cause noticeable injury to the foliage and tuber yield and quality loss may not occur.

Our study shows that when the mother crop encounters glyphosate during bulking while the daughter tubers are the main sink for resources, the herbicide apparently moves down into the tubers along with those resources. Harvested tubers with glyphosate residues may or may not exhibit symptoms of bud-end folding, elephant hiding, or other defects, therefore, daughter tubers with glyphosate would not always be visually detected and discarded. Since a seed grower may not notice mother crop foliar injury from glyphosate during bulking or tuber injury at harvest, the daughter tubers would be sold in good faith as seed for the following year and poor emergence, plant vigor, and yields that following year would have serious financial and reputation consequences.

Analyzing daughter tubers for glyphosate residue at harvest, during the winter, and/or spring just before planting, and correlating residue levels with impacts of known glyphosate doses to the mother crop would be quite useful and is slated for future studies if funding can be obtained. Meanwhile, current recommendations are for a grower to test foliage and/or tubers for glyphosate residues if symptoms such as what resulted from simulated glyphosate drift in our study appear on the mother crop and test the daughter tubers for glyphosate if emergence and plant vigor issues occur. Additional glyphosate mother and daughter crop research is ongoing with other potato varieties such as Russet Burbank' and 'Shepody' and specialty varieties also should be included in future research since impact of glyphosate may vary with variety and type. As a result of this study, more care has been taken by ID, MT, and other state's seed grower associations during winter grow-out to look for glyphosate type issues with the daughter tubers. However, recent, replicated research trial results including the same observations have been inconclusive and further research is needed.

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