Chapter 2

Potato Production near Glyphosate-resistant Crops — Injury Potential

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Additional information is available at the end of the chapter

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Abstract

The herbicide glyphosate is used in many countries because of low cost and effective weed control, but low levels of glyphosate on potato can reduce yield, marketability, and seed quality. Glyphosate is a phloem-mobile herbicide that can translocate to tubers, causing malformations that reduce the quality of current-season production. Potato plants are most susceptible to glyphosate at the hooking or tuber initiation stage. Tubers exposed at these stages often will become malformed and yield loss can occur. Seed production can be affected because glyphosate degradation is slow and it translocates to tubers. Seed potato exposed to glyphosate can store glyphosate residues until they are planted the next season. Tubers planted with glyphosate residues will have an erratic and slow emergence pattern, bending and twisting of leaves, multiple shoots from eyes, "candelabra" or "cauliflower" formation of shoots, or completely inhibited shoot growth, depending on the rate and cultivar. Glyphosate-affected seed tubers produce less tuber set and tubers with reduced weight. Tubers suspected to have glyphosate injury should be tested at a reputable laboratory to confirm glyphosate residues are present. Good management practices can help prevent potato from being exposed to glyphosate.

Keywords: "Red Norland", "Russet Burbank", elephant hide, growth cracks, graded yield

1. Introduction

Introduced in 1974 as a nonselective postemergence herbicide, glyphosate has become the most commonly applied herbicide in the world with approximately 80% of the transgenic crops worldwide as glyphosate resistant [1]. Glyphosate-resistant crops were first introduced in 1996 for soybean [*Glycine max* (L.) Merr.] and canola (*Brassica napa* L.), followed by cotton (*Gossypium hirsutum* L.) in 1997, corn (*Zea mays* L.) in 1998, alfalfa (*Medicago sativa* L.) in 2006, and sugar beet (*Beta vulgaris* L.) in 2007. Green [2] attributed the unprecedented increase in glyphosate usage due to broad-spectrum weed control and more profitable yields with the glyphosate-resistant crop systems. However, glyphosate also is commonly applied preplant to kill existing vegetation prior to planting spring-seeded crops and preharvest on glyphosate-resistant and non-glyphosate-resistant crops such as barley (*Hordeum vulgare* L.), flax (*Linum usitatissimum* L.), lentil (*Lens culinaris* Medic.), pea (*Pisum arvense* L.), safflower (Carthamus tinctorius L.), sunflower (*Helianthus annuus* L.), and wheat (*Triticum aestivum* L.) [3].

Glyphosate is often applied multiple times in a year, using either ground or aerial equipment. Ding et al. [4] reported that the average number of glyphosate applications in glyphosate-resistant soybean and cotton was 2.6 and 3.1, respectively. Numerous studies have reported injury from simulated glyphosate drift on conventional corn [5], cotton [6], onion (*Allium cepa* L.) [7], peanut (*Arachis hypogaea* L.) [8], potato (*Solanum tuberosum* L.) [9], rice (*Oryza sativa* L.) [10], tomato (*Lycopersicon esculentum* Mill.) [11], soybean [12], and wheat [13]. Glyphosate spray drift is the physical movement of glyphosate particles onto an off-target plant and can occur during applications when weather conditions promote drift. In virtually all pesticide applications, a small fraction of the pesticide moves downwind and onto off-target surfaces. The amount of spray particles moving off-target depends on many factors such as environmental conditions, herbicide formulation, droplet size spectrum from specific nozzles, and spray release height above the target [14,15]. Bode [14] reported that between 1% and 16% of the applied rate could drift downwind from the intended target. Glyphosate drift is particularly important because the herbicide is nonselective and highly active on sensitive plant species at low doses, but also because conventional (non-glyphosate-resistant) crops are frequently planted adjacent to glyphosate-resistant crops.

2. Commercial potato production

Potato production originated in the Andean region of South America as early as 7,000 years ago [16]. The first record of potato coming to Europe from South America was approximately 1570 AD. Potato reached North America by the early 1700s and is currently grown in over 95 countries through the world. Potato ranks fourth among all food crops in total production. The United States ranks fifth behind China, Russia, Poland, and Germany in potato production. However, in North Dakota, potato is one of the most important vegetable and horticultural crops with approximately 31,566 ha harvested in 2013 and a farm-gate value over $232.9 million [17].

2.1. Potato growth stages

Potato growth and deployment can be separated into five stages. The first stage is when a whole or cut seed tuber is planted, dormancy is broken, and sprouts begin to develop from the eyes and grow toward the soil surface. The second stage begins when the shoot emerges and vegetative growth continues until tuber initiation. Stage three, or tuber initiation, is when tubers form at the end of stolons. Flowering of many potato cultivars occurs close to this time or at the end of tuber initiation. The fourth stage is tuber bulking, or when tubers enlarge. This is the most critical stage for tuber growth and yield. The final stage consists of leaf and stem senescence and tuber maturation [18].

2.2. Determinate and indeterminate

Potato cultivars can be classified as determinate, semi-determinate, or indeterminate. Short-season cultivars are often assumed to be determinate. They tend to have shorter vine lengths and fewer flower clusters. These plants grow leaves for a determined period, approximately 10–13 leaves, flower, and cease vine growth once tuber initiation begins. The longer-season potatoes are those of a semi-determinate or indeterminate nature. These plants will continue to grow leaves, flowers, and can initiate tubers throughout the growing season, requiring a longer season to complete their growth cycle.

3. Glyphosate injury to potato

The widespread adoption of glyphosate-resistant crops has increased glyphosate applications and widened the application window. Reddy et al. [19] reported that the number of observed herbicide drift cases onto nontarget crops increased by 60% from 2007 to 2008 in Mississippi. Glyphosate drift caused 58% of all drift cases. In general, grass species are more sensitive to glyphosate than broadleaf species; thus, glyphosate drift onto crops such as corn, rice, and wheat can cause significant yield reduction, especially if the drift occurs during a sensitive growth stage [5,13,19, 20]. However, the economic loss in these crops may not be as great as from drift to less sensitive high-value broadleaf crops that are consumed with little processing and have no Environmental Protection Agency (EPA) tolerance level, such as many fruits and vegetables.

Potato injury from glyphosate can occur from spray or particle drift, misapplication, or tank contamination. Particle drift often occurs when herbicides are applied under windy conditions (> 16 kph) and when environmental conditions favor volatilization and redisposition [21]. Many factors, including temperature inversion, affect particle drift, but the most important factor is the initial size of the droplet. Droplets smaller than 100 microns are considered highly driftable and can move over 61 m downwind in a 16-kph wind [22]. Felsot et al. [23] suggested that between 1% and 10% of the applied herbicide rate moved off-target during an application. However, Maybank et al. [24] reported that as much as 16% of the target dose drifted downwind from an unshielded sprayer. Most spray drift studies on crop injury in the United States have utilized sublethal doses in “controlled” experimental situations [23]. The objective of many simulated drift studies is to evaluate plant growth and development in response to low doses of a particular herbicide. Similarly, the intent of the rest of this chapter is to describe potato response to sublethal glyphosate doses.

3.1. Current-season symptomology

Glyphosate inhibits the synthesis of the 5-enolpyruvylshikimate-3-phosphate synthase enzyme, which disrupts the shikimic acid pathway that produces aromatic amino acids such as phenylalanine, tyrosine, and tryptophan used for protein synthesis and plant growth [25]. Visually, a sublethal glyphosate dose may cause chlorosis of the newest potato leaves as early as 7 days after treatment (DAT) depending on the glyphosate rate and potato growth stage [9]. They estimated that 30.5 g ae ha^{-1} glyphosate would be required to produce 5% visual injury. Glyphosate sprayed onto 10-cm plants caused new shoots to be produced from the tuber seed piece, which did not display injury symptoms. However, treated seed pieces were delayed in development compared to the nontreated. Plants at the hooking stage (BBCH-scale 40) appeared to be the most sensitive to glyphosate. They estimated the glyphosate dose resulting in 50% injury was approximately four and 53 times greater when potato plants were sprayed at the 10-cm height and bulking stage, respectively, compared to the hooking stage.

Hatterman-Valenti and Auwarter [26] reported chlorosis at the growing points, but indicated that this could be quite transient depending on glyphosate dose and environmental conditions. They also noted that little to no potato injury symptoms occurred when glyphosate was applied at the late bulking stage. Similarly, Crook and Hatterman-Valenti [27] reported no visible injury symptoms when glyphosate doses lesser than one-fourth of the lowest recommended single application rate of 846 g ha^{-1}were applied to "Red Norland" plants at the late bulking stage (BBCH-scale 47) but concluded that the lack of plant symptomology was because the determinant plants had flowered and stopped foliar growth.

3.2. Current-season tuber yield and quality

When glyphosate comes in contact with potatoes during the growing season, the herbicide enters the plant and is translocated to the growing points, both above and below ground. Daughter tubers form at the terminal end of stolons, which are lateral stems growing horizontally below ground from buds of the underground part of the stems. Morphologically, tubers are also modified stems that constitute the main storage organs of the potato plant [28]. Developing tubers act as a below ground growing point accumulating assimilates produced by the leaves and other exogenous compounds, including glyphosate, that is translocated by the plant. Tuber symptomology from glyphosate exposure may consist of skin cracking, tuber malformations, and tissue death, which may allow entry to secondary pathogens. Crook and Hatterman-Valenti [27] reported tuber cracking as early as 3 days after treating with glyphosate. Early tuber cracks and malformations from glyphosate-treated plants tend to increase as the tubers bulk or increase in size. This results in reduced marketability of tubers. Tuber cracking may be mistaken for growth cracks, but tuber cracks from glyphosate generally tend to cross the apical end of the tuber and often make an "X" configuration (Figure 1). Other tuber symptoms include elephant hide where small surface cracks make the tuber appear scaly. With red cultivars, the red skin color fades or has portions that appear as brown skin along with elephant hide. With the glyphosate dose at 215 g ha^{-1} and potatoes in the tuber initiation growth stage at application, some tubers continue to crack with little growth and look like large pieces of popcorn.

3.3. Simulated glyphosate drift trial

Worthington [29] may have been the first researcher to show that low doses of glyphosate would affect the growth and yield of potato mother plants. To better understand how potato

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Figure 1. Tubers from two plants where glyphosate drift was suspected. Tuber symptoms are typical from glyphosate exposure during plant hooking or tuber initiation growth stages.

growth stage could alter this affect, a two-year field study treated “Russet Burbank” plants at four growth stages—hooking (H)(BBCH-scale 40), tuber initiation (TI)(BBCH-scale 41), early bulking (EB)(BBCH-scale 43), and late bulking (LB)(BBCH-scale 47)—to evaluate glyphosate injury to the current-season crop. Plants within each of the growth stages received a sublethal dose of glyphosate, which corresponded to one-fourth, one-eighth, one-sixteenth, or one-thirty-second the lowest recommended single application rate for glyphosate at 846 g ha^{-1}. Plants at the H stage were an exception with only one sublethal dose (215 g ha^{-1}) applied at this stage. The last treatment of this 14-treatment trial, arranged as a randomized complete block with four replicates, was the nontreated check, which consisted of spraying the plants with a water plus ammonium sulfate solution. The middle two rows of each plot were harvested and graded in October. Data were subjected to analysis of variance (ANOVA) using PROC GLM (SAS version 9.2, SAS Institute Inc., Cary, NC) and, where appropriate, Fisher’s protected least significant difference (LSD) tests, at a probability level of ≤ 0.05, were used for mean separation. Data could not be pooled across years for all yield and grade data and thus were analyzed separately.

3.3.1. Simulated glyphosate drift trial: Yield

The nontreated plots produced the greatest total yield in 2008, but this did not differ from the total yields when plants received sublethal glyphosate doses during LB or when plants received the lowest two glyphosate doses during TI or EB (Table 1). The greatest total yield in 2007 occurred when plants in the EB stage received the lowest glyphosate dose of 27 g ha^{-1}. However, similar total yields were also obtained with nontreated plants, plants that received the lowest two glyphosate doses during TI, plants that received glyphosate doses during EB, or when plants received the lowest three glyphosate doses during LB. Plants that received 215 g ha^{-1} glyphosate during H in 2007 had the lowest total yield, almost 5.5 times less than the nontreated and almost half the total yield, when compared to plants receiving the same glyphosate dose but at the TI stage. Similarly, Hutchinson et al. [30] reported that a sublethal glyphosate dose to potato at the H stage reduced yields more than 40% compared to the nontreated yields. However, in their study, they also subjected plants to sublethal glyphosate doses when the plants were only 10–15 cm tall and concluded that these plants would most likely recover even from relatively high glyphosate doses.

		Growth stage	Tuber yield			
		when	Marketable		Total	
	Rate	treated	2007	2008	2007	2008
	g ha^{-1}		MT ha^{-1}			
Glyphosate	215	H[a]	5.7 c[b]	15.7 c	9.9 d	29.3 bc
Glyphosate	215	TI	10.5 c	10.6 c	20.9 c	29.9 bc
Glyphosate	107	TI	26.6 b	13.7 c	41.8 ab	36.9 bc
Glyphosate	54	TI	39.2 ab	29.4 b	49.3 a	45.5 ab
Glyphosate	27	TI	47.3 a	41.5 ab	54.4 a	53.8 a
Glyphosate	215	EB	43.5 a	12.6 c	50.2 a	28.0 c
Glyphosate	107	EB	45.5 a	21.0 c	52.2 a	34.7 bc
Glyphosate	54	EB	49.0 a	39.1 ab	55.6 a	56.3 a
Glyphosate	27	EB	49.6 a	39.9 ab	55.8 a	55.8 a
Glyphosate	215	LB	28.2 b	40.3 ab	34.6 b	55.6 a
Glyphosate	107	LB	39.2 ab	40.7 ab	45.2 ab	57.2 a
Glyphosate	54	LB	44.6 a	39.8 ab	51.9 a	53.6 a
Glyphosate	27	LB	42.2 a	40.6 ab	48.4 a	53.4 a
Non-treated			50.5 a	43.4 a	55.1 a	60.2 a

[a] Abbreviations: H = hooking, TI = tuber initiation, EB = early bulking, LB = late bulking.
[b] Means within a column with a different letter are significantly different according to a Fisher's protected LSD test performed at the 0.05 level of probability.

Table 1. Effect of glyphosate dose on Russet Burbank tuber yield.

Marketable yields mimicked total yields for most treatments (Table 1). Both years suggested that plants treated in the H and TI stages would have the greatest marketable yield reduction if plants would come in contact with sublethal doses of glyphosate. However, in 2007, marketable yield was not influenced if plants received ≤ 215 g ha^{-1} glyphosate during the EB stage, while in 2008, marketable yield was not influenced if plants received ≤ 215 g ha^{-1} glyphosate during the LB stage.

The response difference could be partially explained once the maximum and minimum air temperatures were plotted for the two growing seasons (Figure 2). In 2007, many of the days during the plant H and TI stages had maximum and minimum air temperatures greater than the 30-year average (normal). Thus, the lower set number and lower tuber number per plant in 2007 were understandable. In addition, 2007 air temperatures had been high just prior to the glyphosate dose at EB, but on the application day and the next 2 days, both maximum and minimum air temperatures were below normal. A similar event occurred during LB in 2008 along with a 6 °C drop in soil temperature (data not shown). It was concluded that these decreases in air temperature, especially at night, allowed a quicker recovery and the resumption of tuber bulking. Felix et al. [9] conducted a similar trial with "Ranger Russet" and concluded that injury was greater to potato plants receiving a glyphosate dose of 54 g ha^{-1} or more during the H or TI stages as compared to the other stages. Tuber yield at Paterson, WA, was reduced by 84% and 77% compared to the nontreated when plants received 107 g ha^{-1} glyphosate at H and TI, respectively, while at Ontario, OR, the yield reduction was only 54% and 52%. Thus, environmental conditions or other plant stresses may greatly influence plant recovery from sublethal glyphosate doses. To further confound matters, Hatterman-Valenti et al. [31] reported that russet cultivars respond differently to sublethal glyphosate doses with "Bannock" as the most sensitive cultivar of the four evaluated.

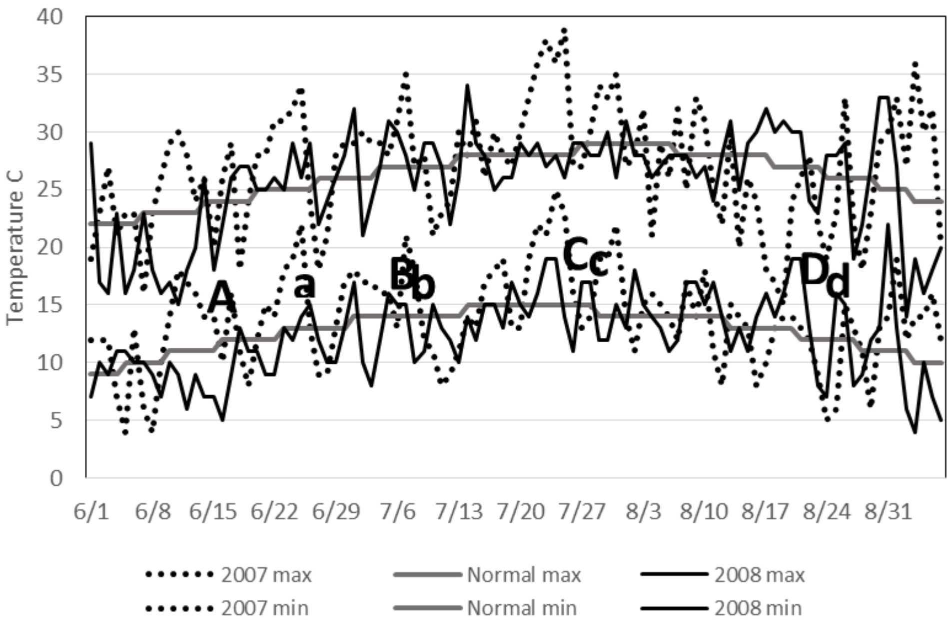

Figure 2. Minimum and maximum air temperatures along with normal minimum and normal maximum temperatures. Capital letters (A, B, C, D) represent when glyphosate doses were applied to potatoes during 2007. Small letters (a, b, c, d) represent when glyphosate doses were applied to potatoes during 2008.

3.3.2. Simulated glyphosate drift trial: Tuber grade

Tuber grade showed an increase in cull-sized tubers (< 113 g) compared to the nontreated when plants received ≥ 54 g ha^{-1} glyphosate at the TI stage but only in 2007 (Table 2). In 2008, the amount of cull-sized tubers were doubled and, often, tripled in comparison to 2007. However, tuber distribution as a percentage of the total yield showed that the nontreated had approximately 25% of the tubers at culls both years, suggesting that 2008 was a more productive year to grow "Russet Burbank" (Table 3). As grade size increased in 2007, plants that received the highest glyphosate dose at H, TI, and LB tended to produce few tubers in each grade level compared to the nontreated (Tables 2 and 3). As grade size increased in 2008, plants that received the two highest glyphosate doses at H, TI, and EB tended to produce few tubers in each grade level compared to the nontreated.

		Growth stage	Tuber yield									
		when	≤ 113 g		114–170 g		171–283 g		284–340 g		≥ 341 g	
	Rate	treated	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008
	g ha^{-1}		MT ha^{-1}									
Glyphosate	215	H[a]	4.0 d[b]	13.1 bc	2.6 e	6.1 bc	2.4 c	5.3 c	0.4 c	2.0 c	0.2 d	2.9 a
Glyphosate	215	TI	9.8 b	16.6 bc	5.3 d	3.5 c	4.4 c	3.3 c	0.6 c	0.5 c	0.0 d	0.3 bc
Glyphosate	107	TI	14.4 a	23.1 a	10.2 ab	8.7 b	11.3 b	4.3 c	2.7 bc	0.4 c	1.6 cd	0.0 c
Glyphosate	54	TI	9.6 b	17.3 bc	10.6 a	13.6 a	17.5 ab	11.4 b	4.9 ab	1.9 bc	5.2 bc	2.1 ab
Glyphosate	27	TI	6.9 bcd	13.8 bc	8.7 bc	13.8 a	18.9 ab	18.2 a	7.5 a	4.1 a	11.5 ab	4.0 a
Glyphosate	215	EB	6.3 bcd	17.9 b	8.1 bc	6.5 bc	16.1 a	4.1 c	6.4 a	0.5 c	12.3 a	0.6 bc
Glyphosate	107	EB	6.6 bcd	15.4 bc	8.0 bc	13.2 a	17.2 a	7.8 bc	5.2 ab	0.9 c	14.8 a	0.4 bc
Glyphosate	54	EB	6.5 bcd	15.5 bc	8.7 bc	14.4 a	20.2 ab	17.5 ab	5.9 ab	3.0 ab	13.9 a	3.0 a
Glyphosate	27	EB	6.1 bcd	12.1 c	9.5 bc	12.8 a	19.6 ab	17.2 ab	6.7 a	4.1 a	13.5 a	5.0 a
Glyphosate	215	LB	6.3 bcd	15.6 bc	7.0 cd	14.8 a	12.5 ab	17.6 ab	2.6 bc	3.1 ab	5.1 bc	3.7 a
Glyphosate	107	LB	5.9 bcd	15.4 bc	8.8 bc	14.6 a	15.2 ab	17.6 ab	5.0 ab	3.8 a	9.7 ab	3.8 a
Glyphosate	54	LB	7.3 bc	13.8 bc	9.4 bc	15.1 a	16.7 ab	17.8 ab	6.1 ab	4.1 a	11.9 ab	3.1 a
Glyphosate	27	LB	6.1 bcd	13.4 bc	8.2 bc	14.5 a	16.4 ab	18.1 a	5.7 ab	3.1 ab	11.7 ab	4.4 a
Non-treated			4.6 cd	14.5 bc	7.4 bc	14.5 a	18.6 ab	18.9 a	8.6 a	3.5 ab	15.5 a	5.5 a

[a] Abbreviations: H = hooking, TI = tuber initiation, EB = early bulking, LB = late bulking.
[b] Means within a column with a different letter are significantly different according to a Fisher's protected LSD test performed at the 0.05 level of probability.

Table 2. Effect of glyphosate rate on Russet Burbank tuber grade.

The effect of glyphosate on tuber growth is most evident when examining tuber distribution as a percentage of total yields (Table 3). In 2007, plants that received the highest glyphosate dose at H and TI had at least 70% of their tubers considered culls, while in 2008, plants that received the highest glyphosate dose at H and TI had 47%–64% of their tubers considered culls. Reductions in the 171–283-g grade are extremely important to processors of frozen French fries as this grade is ideal for long French fries. During both years, the nontreated plants had approximately 32% of their tubers in this category. However, plants in the H and TI stages that received sublethal glyphosate doses in 2007, with the exception of plants receiving 27 g ha^{-1}, had a lower percentage of tubers in the 171–283-g category than the nontreated. In 2008, plants in the H, TI, and EB stages that received sublethal glyphosate doses, with the exception of plants receiving 27 g ha^{-1} and plants in the EB stage receiving 54 g ha^{-1}, had a lower percentage of tubers in the 171–283-g category than the nontreated.

		Growth stage	Tuber yield									
		when	≤ 113 g		114–170 g		171–283 g		284–340 g		≥ 341 g	
	Rate	treated	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008
	g ha^{-1}						%					
Glyphosate	215	H[a]	70 a[b]	47 abc	17 cd	18 b	10 cd	20 b	1 e	4 cd	1 f	9 a
Glyphosate	215	TI	76 a	64 a	14 d	20 b	8 d	11 c	1 e	1 e	0 f	1 cd
Glyphosate	107	TI	59 a	63 a	20 bc	24 ab	15 c	12 c	3 de	1 e	2 ef	0 d
Glyphosate	54	TI	41 b	37 cd	22 a	29 a	25 b	24 b	5 bcd	4 cd	4 de	4 bc
Glyphosate	27	TI	33 bc	25 e	21 ab	27 a	29 a	33 a	8 ab	7 ab	9 bc	7 ab
Glyphosate	215	EB	29 bc	60 ab	23 a	21 b	30 a	14 bc	7 bc	1 e	11 b	1 cd
Glyphosate	107	EB	31 bc	45 bc	20 bc	29 a	31 a	20 b	6 bcd	2 de	11 b	1 cd
Glyphosate	54	EB	33 bc	28 de	20 bc	28 a	28 a	32 a	6 bcd	6 ab	12 ab	6 ab
Glyphosate	27	EB	33 bc	23 e	21 ab	25 a	27 a	33 a	8 ab	8 a	10 b	10 a
Glyphosate	215	LB	41 b	28 de	22 a	27 a	26 ab	32 a	4 cde	5 bc	6 d	6 ab
Glyphosate	107	LB	32 bc	27 de	25 a	27 a	28 a	31 a	6 bcd	7 ab	9 bc	7 ab
Glyphosate	54	LB	34 bc	26 e	23 a	27 a	26 ab	33 a	7 bc	8 a	9 bc	6 ab
Glyphosate	27	LB	33 bc	25 e	22 a	27 a	28 a	34 a	7 bc	6 ab	10 b	8 a
Non-treated			24 c	25 e	20 bc	26 a	32 a	33 a	11 a	6 ab	14 a	9 a

[a] Abbreviations: H = hooking, TI = tuber initiation, EB = early bulking, LB = late bulking.
[b] Means within a column with a different letter are significantly different according to a Fisher's protected LSD test performed at the 0.05 level of probability.

Table 3. Effect of glyphosate rate on Russet Burbank tuber number as a percent of the total.

Tuber yield and grade data suggest that in addition to a general shift toward smaller-sized tubers, fewer tubers may have been produced, but this was only true in 2007 when plants in the H stage received 215 g ha^{-1} glyphosate (Table 4). However, the percentage of marketable tubers in 2007 was less than with the nontreated for all treatments, except when plants in the EB stage received 27 g ha^{-1} glyphosate. The average number of tubers per plant was higher in 2008, and all treatments were similar in tubers per plant. The percentage of marketable tubers in 2008 was less when plants in the TI and EB stages received ≥ 107 g ha^{-1} glyphosate and when plants in the H stage received 215 g ha^{-1} compared to the nontreated. These results suggest that glyphosate doses at 215 g ha^{-1} or higher may reduce tuber numbers per hill, but only if glyphosate enters plants during the critical tuber development stages of H or TI and when other stresses that occur do not maximize tuber set. On the other hand, marketable and total yield reductions (from reduced tuber size) may be expected if potato plants in the H or TI stages come in contact with ≥ 107 g ha^{-1} glyphosate or a lower dose if plant stress conditions simultaneously occur.

		Growth stage	Tuber yield			
		when	Marketable		Total	
	Rate	treated	2007	2008	2007	2008
	g ha^{-1}		%		no.	
Glyphosate	215	H[a]	29 e[b]	53 bc	2.9 d	10.2 b
Glyphosate	215	TI	23 e	34 d	6.6 c	11.9 ab
Glyphosate	107	TI	39 d	37 d	10.7 a	14.5 a
Glyphosate	54	TI	57 c	62 ab	9.3 ab	12.4 ab
Glyphosate	27	TI	66 b	74 a	8.4 bc	11.8 ab
Glyphosate	215	EB	66 b	39 d	7.7 bc	10.7 b
Glyphosate	107	EB	69 b	52 bc	7.9 bc	11.1 b
Glyphosate	54	EB	69 b	71 a	8.3 bc	12.5 ab
Glyphosate	27	EB	70 ab	76 a	8.3 bc	10.9 b
Glyphosate	215	LB	58 c	72 a	6.1 c	12.5 ab
Glyphosate	107	LB	67 b	72 a	7.1 bc	12.8 ab
Glyphosate	54	LB	65 b	74 a	8.2 bc	11.7 ab
Glyphosate	27	LB	67b	75 a	7.4 bc	11.8 ab
Non-treated			75 a	75 a	7.4 bc	12.4 ab

[a] Abbreviations: H = hooking, TI = tuber initiation, EB = early bulking, LB = late bulking.
[b] Means within a column 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 glyphosate dose on Russet Burbank percent marketable and average number of tubers per plant.

3.3.3. Simulated glyphosate drift trial: Conclusions

In summary, results from this study indicated that plants at the H and TI stages were most sensitive to glyphosate drift when evaluating current-season tuber yield and grade. Indirectly, this study also indicated that "Russet Burbank" potato yield and grade were not affected when treated with ≤ 215 g ha^{-1} glyphosate during EB or LB and environmental conditions conducive to quick recovery and/or no additional stresses were present. The tolerance of potato to sublethal glyphosate doses later in the growing season was reinforced by Haidar et al. [32] when they applied three sequential applications of 100 g ha^{-1} glyphosate following a rimsulfuron application to control *Orobanche ramosa* and found no negative effect on tuber yield or quality. However, application intervals were 15 days, and an increase of glyphosate rates to 200 g ha^{-1} produced nonmarketable tubers.

3.4. Glyphosate residues in seed production

Asexual seed production in potato is essential to preserve the genetic identity of potato cultivars. However, utilizing asexual production can cause problems with herbicide residues because, as the tubers are stored during a dormant period, the herbicide residues can also be stored. The seed potato crop is sensitive to many classes of herbicides, but the herbicide of most recent interest has been glyphosate. The reason for this is that millions of crop hectares globally now receive glyphosate herbicide treatments during the growing season because of the widespread acceptance of genetically modified crops in many countries. Glyphosate is a commonly used herbicide in agriculture because of low cost and effective control of grasses and broadleaf weeds.

3.4.1. How glyphosate injury occurs

Seed tubers can be exposed to glyphosate in a variety of ways. The primary way would be through phloem transport from the leaves and stems to the tuber during the previous growing season. However, some growers have reported that using contaminated water for in-furrow fungicide and insecticide treatments at planting caused effects similar to glyphosate-contaminated seed.

Exposure to glyphosate typically occurs through the leaves and stems. Glyphosate is translocated by the phloem to the metabolic sinks [33,34]. In potato, this would consist of the meristems, roots, and tubers, or the growing points above and below ground. New tubers developed by the plant, referred to as "daughter tubers," are a sink for assimilates produced by the leaves and for exogenous compounds (such as herbicides) that are translocated by the plant. The degradation of glyphosate within the plant can be slow as glyphosate is metabolized to aminomethylphosphonic acid [33]. This may be one of the reasons why glyphosate residues can be stored in tubers over time, until the next planting season.

3.4.2. Glyphosate uptake and translocation

Exposure to glyphosate can occur at any time after the shoots emerge from the soil. Hutchinson et al. [30] reported that visible injury tends to be greater when potatoes contact glyphosate during vegetative growth, while visible injury from glyphosate is less apparent when tubers are bulking and are the primary sink. When the daughter tubers, or next field generation of tubers, were planted back the next season, tubers that received glyphosate during bulking had a reduced emergence rate, stem number, and marketable yield. Exposure to glyphosate during bulking may be unseen, but it can have dramatic negative effects on the next field generation of seed. Often the contact of glyphosate with potato in the bulking timing occurs at the same time that temperatures tend to be the highest. When temperature is high (24 °C day and 13 °C night), more glyphosate is absorbed and translocated compared to a low temperature (13 °C day and 4 °C night), causing greater injury [34] and potentially more glyphosate stored in tubers.

3.4.3. Testing for residual residues

Seed potato plants or mother plants can become exposed to glyphosate at any growth stage. Visual symptoms of glyphosate may be difficult to detect, especially if the rates are low or the exposure to glyphosate occurs during bulking. If glyphosate exposure is suspected, a laboratory test is the most accurate way to determine its presence. When taking a sample for residue analysis, both a leaf sample from the youngest leaves and a tuber sample should be taken because glyphosate will translocate to the growing points. Multiple plants should be sampled, and samples can be composited into a large sample to be tested. Timely sampling is important to detect glyphosate residues. In a study of young potato plants, glyphosate accumulation in meristematic tissue and roots was greatest between 4 and 8 days after exposure and was less thereafter [35]. Plants that have tubers, and are exposed to glyphosate, store the glyphosate in tubers. The effects of glyphosate will be seen when tubers are planted the next season.

3.4.4. Certification and winter testing

Symptoms of low glyphosate rates are difficult to observe visually and field inspections may not detect the symptoms. Potato seed certification typically makes multiple trips to inspect fields. Inspections are completed when the first signs of disease will be apparent. This timing is intended to check for virus, disease, cultivar purity, and other factors associated with seed quality. Typically, a final inspection is done prior to vine kill to determine if bacterial ring rot is present or any other diseases or infection sources that could compromise the quality of the seed. The postharvest, or winter test, is used for recertification. Inspections focus is primarily on virus, but other factors such as cultivar mixture, herbicide damage, vigor, and other diseases are noted. One of the challenges with glyphosate residues is that residues can inhibit sprouting of tubers. When tubers do not sprout in a winter test, inspectors should dig seed tubers and observe why they have not sprouted. Suspect tubers should be sent to a reputable laboratory to test for glyphosate residues.

3.5. Yield effects from glyphosate residue carryover in seed potato

Potato seed quality is always a concern when a potato field does not emerge properly. Glyphosate-contaminated seed produces a variety of obvious symptoms, but symptoms similar to glyphosate injury may be misdiagnosed as glyphosate. This is why laboratory testing

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for glyphosate is essential for proper diagnosis. The effects of glyphosate-contaminated seed that is planted can reduce yield and quality of potato. Additionally, the relationship between the seed producer and the buyer can be damaged when an herbicide contamination is found in a seed lot.

3.5.1. Germination of glyphosate-affected seed potatoes

A variety of problems can occur when tubers with glyphosate residues are planted. Hatterman-Valenti [36] reported only 18 g ha^{-1} glyphosate applied the previous growing season was needed to inhibit sprouts by 14% and 282 g ha^{-1} glyphosate inhibited sprouts by 95%. Glyphosate is so effective at inhibiting sprouts that it has been tested as a sprout suppressant to help tubers store longer in environments where refrigerated storage is not available [37]. If tubers are intended to be used for seed, sprout suppressants should never be used.

3.5.2. Symptomology

The first general observation of a potato field planted with glyphosate-contaminated seed is an erratic emergence pattern throughout the field. Being a seed-borne problem, a pattern in the field should not occur. Rather a scattering of plants with different rates of emergence should be observed (Figure 3). The erratic emergence pattern is found because tubers contain various amounts of glyphosate, and the higher the glyphosate level at the tuber eye, the slower the sprouts are to emerge from the soil. Plants with glyphosate residues will often express symptomology in new leaves through malformed leaves that appear to twist or bend in unnatural ways (Figure 4). Leaves have been noted to become chlorotic in some cases [38].

Figure 3. Erratic potato plant emergence pattern due to glyphosate-contaminated seed.

Figure 4. Plant symptoms from glyphosate-contaminated seed. Symptomology may be confused with those expected from drift of a plant growth regulator herbicide.

Figure 5. Multiple shoots emerging from a single eye of a glyphosate-contaminated tuber.

When tubers are uncovered from the soil, more symptoms can be observed that can help identify the problem as glyphosate. In many cases, swelling of shoots or a “candelabra” of branching formation on the shoots may occur. Unique to glyphosate, multiple shoots coming from a single eye may be observed (Figure5). When glyphosate residue levels are at higher levels in tubers, shoots will not elongate, but a “cauliflower”-like formation of shoots will appear around the eye (Figure 6) [29,38]. If a field has these types of symptomology, carefully inspect the field because differences will be apparent by cultivar and the amount of glyphosate present in the tubers.

Figure 6. The “cauliflower”-like formation of shoots appearing around a single eye of a glyphosate-contaminated tuber with higher residue levels.

3.5.3. Residue testing

If glyphosate is suspected, the best way to confirm glyphosate residues in seed tubers is through laboratory testing. To test seed for glyphosate residues, use a credible laboratory that can detect glyphosate residues down to 0.01 parts per million (ppm). Select tubers for testing that have not emerged, because these tubers will likely have a higher concentration of glyphosate, and this eliminates the potential of glyphosate drift contamination on newly emerged potato plants. Carefully remove the seed tubers from the soil and gently wash off all soil. Once tubers are clean, send the sample to the laboratory for analysis according to the laboratory directions. If results are positive, the presence of glyphosate is confirmed. The challenge from getting results from glyphosate residue testing is knowing the potential effects from the detected level of glyphosate. Robinson [38] reported that 0.015–0.036 ppm glyphosate was sufficient to reduce yield by 63% and tuber number by 38% compared to tubers with no glyphosate. However, this was a small study that compared only a few individual plants.

3.5.4. Yield loss

When herbicide injury occurs, a farmer expects to have some type of yield loss. With glyphosate-affected seed, a yield loss is often expected and, typically, a yield loss is found. The amount of reduction in yield will depend on the percentage of seed that contains glyphosate and the residue levels. But more importantly, the tuber size distribution is much wider than from a field that does not have glyphosate residues in the seed. Glyphosate-contaminated seed often produces plants that are slow to emerge compared to plants from uncontaminated seed. These normally emerging plants will outcompete the slower, or weaker, glyphosate-affected plants for sunlight and nutrients. This allows the stronger plant more resources, and as a result, tuber number and tuber size tend to be greater [38].

Research has demonstrated the amount of glyphosate, timing of glyphosate exposure to potato, and the environment has a direct effect on the seed and how it will perform when planted the next growing season. As expected, as glyphosate rates increase, so does reduction in emergence and yield. Rates studied have ranged from 8.5 to 423 kg ha^{-1} glyphosate [30, 36]. The cultivar "Ranger Russet" had the lowest total and marketable yield when glyphosate was applied at the bulking stage in comparison to earlier treatments [30]. Glyphosate applied to "Red LaSoda" and "Russet Burbank" during late bulking caused sprout inhibition with as little as 18 g ha^{-1} glyphosate, but 71 g ha^{-1} glyphosate was needed for a yield reduction [36]. Earlier exposure of the mother crop to glyphosate tended to have less effect on seed potato quality than later exposure [30].

4. Preventing potato injury from glyphosate

Some management strategies can prevent potato plants from being exposed to glyphosate. These include starting with clean seed that does not have abnormal malformation that could be from herbicide damage. If seed has possible herbicide injury symptoms, have it tested for glyphosate at a laboratory. Communicate with your neighbors who have fields near the potato field and let them know that potatoes are sensitive to glyphosate and special care should be taken to not drift on potato. If necessary, plant borders of a glyphosate-resistant crop around the potato field to help protect the field from unintended drift of herbicide. Have a dedicated sprayer for potatoes to eliminate any possible sprayer contamination problems. When applying pesticides, use proper storage of containers and spraying techniques. Farmers should

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be proactive to protect their potato crop. A small amount of herbicide can cause a great economical loss.

5. Conclusions

Glyphosate off-target movement onto potato may cause significant damage depending on the amount of glyphosate uptake into the plant, the cultivar and plant growth stage, the intended use of the daughter tubers, environmental conditions during and a few days after the off-target movement, and any other plant stress that would reduce plant recovery from a sublethal dose. Hutchinson et al. [39] reported that a 20% net return reduction in Idaho was equivalent to a loss of \$160 ha^{-1} based on total production costs at that time subtracted from gross returns as determined by an incentive-adjusted processing contract model. Therefore, the financial loss from glyphosate drift to a commercial potato field in the hooking or tuber initiation stage could be substantial. Plant injury symptomology may or may not be observed on the aboveground portion of the plant, and if symptoms are observed, tuber yield and grade reductions may or may not be affected. However, if glyphosate injury occurs during H or TI stages, visible tuber symptoms should occur.

By contrast, seed producers are at the greatest risk for serious financial loss and reputation consequences when glyphosate moves off-target and onto mother plants in the bulking stage with daughter tubers as the main sink for resources. Plant injury symptomology may be transient or not visible and daughter tubers often do not have visible injury symptoms. However, glyphosate residues are in these tubers and plant emergence may be delayed or prevented the following spring. Currently, certified seed producers hope affected seed will be identified during field plantings in winter nurseries. However, herbicides rarely drift onto more than a small portion of a field, so if tubers from affected areas were not selected for the winter nursery testing, the seed producer may be unaware of problems that may occur in the spring. Current research at North Dakota State University (NDSU) is directed toward identifying the threshold residue level in a seed piece that does not inhibit sprout growth along with a more economical yet reliable method to determine glyphosate residues in seed tubers. Seed producers are also being proactive by talking with neighbors and posting signs about the danger of glyphosate drift to potatoes grown for seed. Potatoes are not as sensitive as cereal crops to glyphosate, but the potential consequences from glyphosate off-target movement to potato are very significant.

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