MOTHER AND DAUGHTER CHIPPING POTATO CULTIVAR RESPONSES TO SUBLETHAL RATES OF GLYPHOSATE AND DICAMBA

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The Supervisory Committee certifies that this disquisition complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

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ABSTRACT

The effects of sublethal drift rates and carryover of glyphosate and dicamba into the next generation of seed potato cultivars Atlantic and Dakota Pearl are unknown. The objective of this research is to determine the impact of sublethal glyphosate and dicamba rates on mother and daughter chipping potato plants. Field studies were conducted in 2018 and 2019 in Oakes, ND. Herbicides were sprayed at the tuber initiation stage and consisted of dicamba (0, 20, and 99 g ae ha^{-1}) and glyphosate (0, 40, and 197% g ae ha^{-1}). During the year of application (2018), the combination of glyphosate at 197 g ha^{-1} and dicamba at 99 g ha^{-1} resulted in a 40% yield reduction compared to the non-treated in both cultivars. In 2019, the daughter tubers from mother tubers that were treated with glyphosate (23%) experienced a 16% reduction in marketable yield in both cultivars.

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LIST OF ABBREVIATIONS

USDA...United States Department of Agriculture

NASS ....National Agriculture Statistics Service

NRCS...Natural Resources Conservation Service

EPA ....Environmental Protection Agency

EU ....Experimental Unit

POST...postemergence

PRE ....preemergence

pKa..negative base-10 logarithm of the Ka

Koc..sorption coefficient

pH..potential hydrogenii (potential hydrogen)

DAP..days after planting

WAP...weeks after planting

RCBD...randomized complete block design

DT ....dicamba-tolerant

GT ....glyphosate-tolerant

INTRODUCTION

Potato (*Solanum Tuberosum L.)* was first domesticated by the Incas, in the Andean mountain range of South America around 500 B.C (NPC 2019). Since the Columbian Exchange era, the potato has traveled around world to become the fifth most important crop after wheat, corn, rice, and sugar cane and has been effective in feeding many people because of its high nutrient content. A 100 g of potato contains 110 calories, 2.05 g of protein, 17.49 g of carbohydrates, 12 mg of calcium, and 425 mg of potassium, along with a host of other essential nutrients (USDA 2018).

In 2017, the United States produced a total of 60 million metric tons of potatoes, 6% of which were used for seed production (USDA NASS 2018a). North Dakota is a unique agricultural state, growing a diverse variety of crops; from wheat, corn, and soybean to sugar beet, sunflower, and potato. In 2017, North Dakota harvested over 1.2 million metric tons of potatoes, ranking the state fourth in the nation for potato production. Of the potatoes harvested, over 76,000 metric tons were certified seed potatoes. However, soybean was the top crop in North Dakota by hectares, with 2 million hectares planted in 2017 and an estimated value of $2.1 billion (USDA-NASS 2018b). The introduction of dicamba-tolerant (DT) soybean in 2017 provided growers with an option to control glyphosate-tolerant weeds. Soybean acres often exist adjacent to other broadleaf crops, such as potatoes, which can be sensitive to dicamba vapor, drift, or spray-tank contamination (Hartzler 2017b).

New formulations of dicamba alone or combined with glyphosate have been developed with the goal of reducing dicamba drift and volatilization. In 2017, dicamba damage was so prevalent that the North Dakota Department of Agriculture implemented new dicamba application restrictions (NDDA 2018). For many parts of North Dakota, especially for counties in the southern half of the state, where potato planting often occurs by mid-April, it is likely that herbicide drift, vapor drift, or spray tank contamination will cause subsequent injury will affect potato production. Currently, there are no specific protocols for testing dicamba or glyphosate tuber residues for certified seed potato growers (NDSSD 2008). In addition, research has shown cultivar injury differences to sublethal glyphosate and dicamba rates for russet-skinned and red-skinned cultivars, but research has not evaluated white-skinned cultivars (Colquhoun 2017; Crook 2016; Geary 2019; Hatterman-Valenti et. al 2017; Hutchinson et. al. 2014; Robinson 2013; Wall 1994).

The objective of this research was to determine the impact of sublethal glyphosate and dicamba drift on the cultivars Atlantic and Dakota Pearl mother and daughter tubers. This research will benefit potato growers, potato processors, agronomists, and research institutions by demonstrating the effect of dicamba and glyphosate on white-skinned potato seed tubers.

CHAPTER 1. LITERATURE REVIEW

Dicamba

Dicamba is part of the site of action group 4, growth regulator, T1R1 auxin receptors (synthetic auxin), under the chemical family benzoic acid, that was discovered in the early 1940s (Hartzler 2017a). In 1962, dicamba was first approved for use in the US under a company called Velsicol. This herbicide is a common POST emergence herbicide used to control broadleaf weeds in grain crops, grasslands, and more recently soybean (Anonymous 2010). The chemical structure of the herbicide dicamba and aspirin, are very similar to each other (Figure 1).

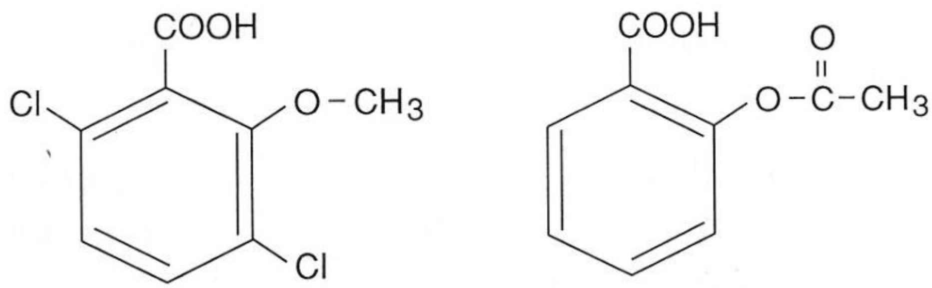

Figure 1. Chemical structure of dicamba (A) and aspirin (B) (Zimdahl 1999).

Dicamba acts similar to 2,4-D, and other common plant growth regulator herbicides, but there are key differences (Zimdahl 1999). Dicamba is often more effective on perennials at lower rates than 2,4-D, which requires higher rates to be effective. Dicamba can often be used in combination with other herbicides for weed control in turfgrass, corn, soybean and small grains. It is effective on weeds in the Polygonaceae family and can persists in soil for up to 60 days making it an effective herbicide.

Growers have been using dicamba for over 50 years on corn, which is often grown adjacent to soybean (Hartzler 2017b). However, it was not until the summer of 2016, when DT soybean were released, that non-DT soybean growers started to see an increase in off-target injury from dicamba. The main explanations for the increased volatilization or drift of dicamba are as follows; Firstly, postemergence application in soybean occurs in mid-June, whereas postemergence corn application of dicamba is in mid-May. This later application of dicamba can increase the potential for volatilization because of the higher temperatures at soybean application than corn. Secondly, corn has less canopy and foliage development than soybean at application, which leaves soil more exposed and more dicamba is absorbed into the soil. With more foliage intercepting the herbicide when applied to soybean, less dicamba is absorbed into the soil and more likely to move off target to other fields. The third reason is non-DT soybean are more susceptible to yield impacts later in the season when dicamba is applied postemergence than in corn. Other factors that could cause off-target injury from dicamba are using a much higher usage rate of dicamba, spraying in poor conditions, not using the correct sprayer setup, etc.

In October of 2017, the EPA introduced new regulations and changes to the dicamba label to combat the risk of volatilization (EPA 2017). These changes are as follows: 1) in order to apply dicamba, applicators must be certified; 2) applicators working under the supervision of a certified applicator cannot make dicamba applications unless they take a dicamba certification class; 3) applications of dicamba are only allowed between one hour after sunrise to one hour before sunset; 4) new tank mixing and clean-out instructions have been added to the improved label; 5) application of dicamba is prohibited on soybean 45 days after planting or after R1 stage, whichever comes first.

Fate and Action

Despite the prevalent use of dicamba around the world, the complete metabolic pathway has not been completely understood. It is clear that dicamba and other auxin herbicides disrupt the natural auxin indole-3-acetic acid pathways/signals which leading to abnormal growth (Sterling and Hall 1997). Once dicamba is absorbed into the plant, it moves through the phloem and xylem to areas of high metabolic activity (Gleason 2011). In general, auxin herbicides cause a rapid increase in ethylene and abscisic acid (ABA) biosynthesis production within the plant (Kraft et al. 2007). When abundant ABA is produced within the plant, it triggers the closing of the stomata. The result is limited carbon dioxide uptake and an increase in hydrogen peroxide, which could lead to cell death (Kraft et. al. 2007). The plant response to a synthetic auxin and typical response from dicamba is leaf epinasty and reduced growth in roots and shoots (Grossmann 2010).

Injury Symptoms

Dicamba has the ability to move to off-target crops and incur damage (Behrens et al. 1979; Johnson et al. 2012; Robinson et al. 2013). Susceptible crops can be inadvertently exposed to dicamba through physical drift, volatility, inversions, or tank contamination. Typical characteristics of sublethal rates of dicamba includes abnormal growth including leaf cupping, petiole epinasty, necrosis at growing points, and tissue swelling in the leaves and stems (Grossman 2010; Hatterman-Valenti et al. 2017; Seefeldt 2014). A study conducted by Wall (1994) showed that the response of potatoes to sublethal doses of dicamba included twisted stems and leaf cupping, from low doses of dicamba. These characteristics are commonly associated with synthetic auxin herbicides (Wall 1994).

Studies have shown that soybean and cotton are particularly sensitive to dicamba drift (Auch and Arnold 1978; Marple et al. 2008; Robinson et al. 2013). Dicamba, when applied to soybean at the vegetative stage (prior to pod production), can cause abnormal morphology, and nearly a 4% reduction in yield (Egan et al. 2014). However, if dicamba was applied to soybean at the reproductive stage or pod production, yield would be reduced. Dicamba drift on soybean caused yield loss at the V5 and R2 growth stage as compared to the V2 growth stage where little yield loss was detected (Robinson et al. 2013). These studies conclude that timing of dicamba drift on soybean will affect yields. The North Dakota Department of Agriculture has placed a cut off restriction at the summer solstice because after this date soybean enter the reproductive stage which will make them more vulnerable to dicamba drift.

Glyphosate

Glyphosate is part of the site of action group two, amino acid (EPSP) synthesis inhibitor under the chemical family organophosphorus (see figure 2). This molecule was first synthesized by Henri Martin as a potential pharmaceutical in 1950 (Franz et al 1997). However, it was never used for pharmaceutical applications. In 1974, Dr. John Franze of Monsanto Co, found use for glyphosate as an herbicide within agriculture (Duke and Powles 2008).

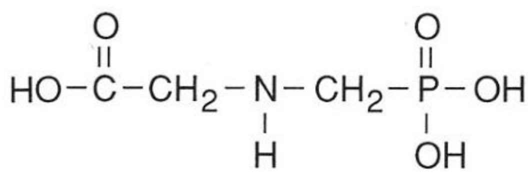

Figure 2. Chemical structure of glyphosate (Zimdahl 1999)

Glyphosate was released a year later to the market as a POST emergence non-selective herbicide used to control annual and perennial weeds. Growers, with the introduction of herbicide-tolerant crops, viewed herbicides as a silver bullet to control all weeds. The expiration of Monsanto's patent, and the subsequent availability of generic versions further increased glyphosate use in the United States (Fernandez C et al. 2014; USDA 2012). Today, glyphosate is one of the most widely used herbicide within the United States (Fernandez Cornejo and Osteen 2015). Glyphosate was used more (1 billion metric tons of a.i.) than the second leading herbicide atrazine in 2012 (34 million metric tons a.i.) (EPA 2012).

Fate and Action

When a new plant cell is formed, the necessary information for development is transported in genes by DNA and expressed in proteins. All plant information flows in one direction from the nucleic acids to proteins where it can be expressed. Disruption of important parts of this pathway will lead to growth inhibition or cell death (Zimdahl 1999). All proteins follow a basic blueprint that they are polymers of nitrogen containing molecules know as amino acids (Chaffey 2013). Disruption of gene expression can lead to growth inhibition or cell death. From the 21 different amino acids, herbicides have three sites of action for amino acid biosynthesis that can affect three different enzyme systems (Duke 1990). These sites of amino acid biosynthesis include 5-enoplyruvyl-shikimate 3-phosphate synthase (EPSPS), acetolactate synthase (ALS) or glutamine synthetase (GS). By blocking any one of these biosynthesis pathways, the plant will not synthesize essential amino acids, which will kill the plant.

Glyphosate specifically targets the enzyme EPSPS of the shikimate pathway (Duke et al 2008). The shikimate pathway is only found in plants and microorganisms (Hermann 1995). This enzymatic pathway is a biosynthetic route to the aromatic amino acids phenylalanine, tyrosine, and tryptophan (Srinivasan et al. 1956). Plants utilize these amino acids to produce pigments or compounds to defend against insects and herbivores (Dixon and Paiva 1995), protectants against UV light, and lignin (Bentley 1990; Singh et al. 1991; Whetten and Sederoff, 1995). By disrupting this pathway, aromatic amino acids are no longer synthesized, which reduces protein synthesis and growth, eventually leading to cell death (Duke 1988). Furthermore, at least 20% of the carbon fixed by plants flows through the shikimate pathway (Haslam, 1993). When this pathway is blocked, more carbon flows to the shikimate-3-phosphate, which is converted into high levels of shikimate acid (Duke 1988). Shikimate acid is found in the plant tissues at high levels after glyphosate is applied.

The active ingredient of Roundup PowerMAX® is glyphosate, N-(phosphonomethyl) glycine (Anonymous 2012). After foliar application, glyphosate is translocated into the plant and follows the pathway of nutrients into a sink site and can be found systemically in the plant (Ross and Childs 1996). These sink sites, including tubers, seeds and root and shoot meristems, are places of metabolic activity in which glyphosate will accumulate. In potatoes, glyphosate moves from the foliage to the eyes of tubers where high metabolic activity occurs (Smid and Hiller 1981).

Injury Symptoms

Potato plants can come into contact with glyphosate in a number of different ways. The most common way is through spray drift or tank contamination (Robinson and Hatterman-Valenti 2013). If potato plants come in contact with a sublethal rate of glyphosate, growers can expect damages to the leaves and tubers resulting in reduced yields and less marketable potatoes. This occurs because glyphosate is translocated to the growing points below and aboveground. There have been numerous studies on quack grass (*agropyron repens* (L.) Beauv), cotton (*Glossypium hirsutum* L), Canada thistle (*Cirsium arvense* (L.) Scop), and soybean (*Glycine max* (L.) Merr.) that concluded that glyphosate can translocate and accumulate in meristematic regions of the plants (Claus 1976; Gottrup et al. 1976; Haderlie et al. 1978; Wills 1978). These meristematic regions would include foliage, roots, rhizomes, or tubers. Common symptoms of foliage injury are yellowing or necrosis and overall stunting to the plant (Hatterman-Valenti et al. 2017; Smid and Hiller 1981). The damage from glyphosate will first appear on the newest plant tissue with new leaves along the growing point becoming chlorotic or necrotic.

Tuber symptoms include cracking of the skin, tissue death, malformed tubers, and smaller overall tubers (Crook 2016, Robinson and Hatterman-Valenti 2013). If tuber tissues die, the chances of secondary infection will increase. An application of glyphosate at 200 g ae ha^{-1} can leave enough residue in the tubers to can cause sprout growth inhibition or formation of shoots around potato eyes that look like cauliflower. Moderate concentrations of glyphosate at 120 g ha^{-1} in mother plant tubers may cause erratic or delayed emergence from planted daughter tubers followed by enlarged shoots or multiple shoots emerging form an eye. A concentration of glyphosate at 40 g h^{-1} may cause twisting and yellowing of new leaves and erratic root growth. Additionally, daughter tubers produced for the chipping market may become unmarketable because of the irregular size and shape. However, since chipping tubers do not go to the fresh market these superficial cracks of skin may be acceptable in some cases.

Off-Target Herbicide Crop Injury

When applying herbicides, there are many environmental, chemical, and physical factors that determine herbicide effectiveness. If these factors have not been accurately considered, unintended consequences could occur in the form of off-target damage. For example, herbicide injury due to drift in potatoes can incur unexpected overhead costs for growers (Hatterman-Valenti 2014). Off-target damage can occur through physical particle drift, volatility, or tank contamination (Hartzler 2017a). In the summer of 2017, with the increase use of DT soybean, over 200 growers in North Dakota reported off-target damage due to dicamba which effected over 66,000 ha (NDDA 2017). Whether this off-target damage was due to drift, volatility, or tank contamination is still uncertain.

Particle Drift

Physical spray drift occurs when spray droplets miss their intended target and move airborne to another location. These airborne droplet concentrations can range from 1 to 16% of the field use rate depending on the conditions (Maybank et al. 1978). Physical drift is affected by wind speed, boom height, and droplet size. The optimum droplet size when applying an herbicide is between 500 microns (moderate rain) and 1000 micron (heavy rain) but can vary based on herbicide used (Zimdahl 1999). Although this size of droplet is ideal, it does not guarantee that drift will not occur. The characteristics of liquid particles once they leave the sprayer with regard to droplet size is illustrated in Table 1. This table shows that the smaller the droplet diameter the farther in distance it will travel from its intended target with a 5 km h^{-1} wind.

A way to manage droplet diameter is with nozzle tips, spray volume, or operating pressure (Anderson 1996). Nozzles can produce a range of different spray patterns and droplet sizes to help reduce drift potential. A nozzle that produces a very fine fog can produce up to 1.4 million drops per square centimeter and can be airborne for up to 3960 sec if the boom sprayer is three meters above the canopy (Hipkins, et al., 2019 and Zimdahl 1999). Moreover, 5 km h^{-1} wind, these very fine droplets can travel up to 4,828 m away from the intended target. In contrast, if a nozzle produces a coarse or extra coarse droplet, the droplets will be airborne for approximately one and a half seconds and produce one droplet per square centimeter.

Table 1. Droplet size and its relationship on drift potential (adapted from Hipkins et al., 2019 and Zimdahl 1999)

Droplet Diameter (microns)	[a]Droplet size	[b]Classification	Drops (no. cm.$^{-2}$)	Evaporating water		Time to fall 3m (sec)	Distance traveled falling 3m in 5km h^{-1} wind (m)
				Drop life (sec)	Fall distance (cm.)		
5	Fog	Very Fine	1,429,102	0.04	<3	3960	4,828
20	Wet Fog	Very Fine	22,320	0.7	<3	252	335.0
100	Misty rain	Fine	178	16	244	10	13.4
240	Light Rain	Medium	-	-	-	6	8.5
400	Mod. Rain	Coarse	-	-	-	2	2.5
500	Mod. Rain	Coarse	1.3	400	3,800	1.5	2.0
1,000	Heavy Rain	Ex. Coarse	<1	1,620	>38100	1	1.4

[a]Droplet size category is based on the British Crop Protection Council (BCPC)
[b]Droplet size category is based on the American Society of Agricultural and Biological Engineers (ASABE). Table modified by Matthew Brooke

When applying glyphosate or dicamba, it is important to have the proper sprayer set up to minimize drift. When selecting nozzles, it is recommended to use nozzles that produces extremely coarse (1,000 micron) droplets (Peters et al. 2017). Depending on the nozzle manufacturer, optimum operating pressure should be 276 to 414 kPa to obtain the desired droplet size (Anonymous 2010; Anonymous 2018). To reduce drift of dicamba, the minimum spray volume should be 346 L ha^{-1} while equipment ground speed should not exceed 24 km h^{-1}. Spray boom should be no higher than 61 cm above the canopy and herbicides should not be applied when wind speed is less than 5 km h^{-1} or greater 16 km h^{-1}. (Anonymous 2018).

Vapor Drift

Volatility is the propensity of a chemical to vaporize and move from a liquid form to a gas form (Zimdahl 1999). Vapor drift is the movement of airborne gases, while particle drift is the movement of airborne liquids. If an herbicide volatilizes, it can cause off-target damage and reduce the performance of the herbicide at the target site. Factors that affect an herbicide’s ability to volatize are vapor pressure and ambient temperature.

When dicamba was introduced to the market, growers and researchers observed that dicamba, as an unformulated acid, volatilized readily because it has a vapor pressure of 4.5 x 10^{-3} mm Hg at 25 °C (Richter 1972). Glyphosate isopropylamine salt has a vapor pressure of 1.58 x 10^{-8} mm Hg at 25 °C, which is considered a low vapor pressure (Senseman 2007). Furthermore, the molecular weight of dicamba acid is 211 g $mole^{-1}$ where dimethylamine (DMA) dicamba has a molecular weight of 266 g $mole^{-1}$. However, the DMA salt formulation was thought to have low volatility because the higher molecular weight (Richter 1972). A study done by Behrens and Lueschen (1979), examined, in soybean, the degree at which dicamba volatilizes. Various formulation of dicamba were used in this study: dimethylamine, diethanolamine (DEOA), an acid formulation, and N-tallow-N, N^1, N^{1} -trimethyl-1,2-diaminopropane (TA) salt formulation. This study found that as temperature increased the volatility of the DMA formulation of dicamba also increased in a closed system. Between 15 to 30 °C, dicamba showed 5 to 35% visible injury on soybean. It was noted that above 30 °C the injury to soybean decreased because the plants were thought to have undergone heat stress which interfered with the plants' ability to absorb dicamba. This study also found that by lowering the humidity, in a closed system, DMA and DEOA volatility increased.

More recently, dicamba N,N-Bis-(3-aminopropyl)methylamine (BAPMA salt) formulations with a vapor pressure of 3.41 x 10^{-5} are available for applicators to reduce dicamba volatility when applied to DT cotton and soybean (Anonymous 2016; Anonymous 2018; MDA 2018). These new formulations do not completely eliminate volatility but can limit it when applied under the right conditions. For example, dicamba should not be applied in temperatures that exceed 30 °C or during a temperature inversion to limit volatility.

Tank Contamination

Tank contamination can also contribute to dicamba injury to off-target crops. Growers often make several chemical applications to their crops every year; sometimes spraying multiple chemicals to different crops within 24 hours. Unfortunately, most growers do not have the luxury of owning multiple sprayers for each chemical. Cleaning tanks and hoses on spray equipment becomes important when switching to a different chemical. If tank residues are not properly cleaned out, leftover pesticide may cause injury to other crops (Peters 2016). As little as 0.75 g a.e. ha^{-1} can cause significant crop injury to non-DT soybean (Soltani et al 2016). To limit tank contamination all dicamba labels have implemented a new triple rinse procedure (Anonymous 2018). This detailed procedure includes recirculating clean water throughout the tank for 15 minutes and flushing hoses and nozzles for at least one minute.

New Dicamba Application Requirements

After the summer of 2017, the North Dakota Department of Agriculture (NDDA) and the Environmental Protection Agency (EPA) applied additional requirements to the dicamba label to help prevent drift (NDDA 2018). These requirements are as follows:

- Applications of dicamba cannot be sprayed after June 30th or after first bloom of soybean or if the air temperature exceeds 30 °C.
- Anyone applying dicamba is required to complete a dicamba specific training before applying.
- Dicamba can only be applied on hour after sunrise to one hour before sunset.
- Applicators must maintain a speed of 20 kph or less when spraying dicamba. Exceeding this speed could result in drift.

- While applying dicamba, the sprayer should be fitted with nozzles that are greater than 26 °C and a minimum of 346 L of spray solution per hectare.

These new regulations were imposed for the 2018 growing season to help stop the off-target drift of dicamba. In 2017 and 2018, the NDDA conducted a state-wide survey to quantify the herbicide damage due to dicamba drift from DT soybean in North Dakota. Table 2 below summarizes the findings from the volunteer survey. In 2017 there were 215 complaints due to dicamba, whereas in 2018 there were only 54. The sudden drop in dicamba complaints may be attributed to different environmental conditions, lack of reporting by growers, and a better understanding of the dicamba application to soybean and the importance of following the label directions. By taking these steps, North Dakota is trying to limit the number of off-target incidences caused by dicamba.

Table 2. Soybean survey results from 2017 and 2018 of dicamba damage conducted by the North Dakota Department of Agriculture (NDDA). Weather data was taken from the North Dakota Agricultural Weather Neatwork (NDAWN).

Dicamba Survey	**2017**	**2018**
Survey Response	215	54
Field Reported Damage	3,623	536
Reported Damage (ha)	66,322	9,667
Climate		
Average Temperature (°C) *	15	15
Average Bare Soil Temperature (°C) *	17	17
Total Spring Rain Fall (cm)*	20	21

*Measurements were taken from averaged across the months of April to July in North Dakota.

Potato (*Solanum tuberosum L.*) Cultivars

Dakota Pearl

'Dakota Pearl' was selected as a seedling in 1985 and was released in 1999 (NDSU 2018). It was originally crossed at North Dakota State University in 1984 between ND118-1 and ND 944-6 by Dr. Robert Johansen (Thompson et al. 2005). This cultivar is used for chipping and table stock. The potential yield of this cultivar 23 T ha^{-1} with a tuber set from 12 to 14. The tubers it produces are 6.18 cm long by 5.49 cm wide with smooth white skin and white flesh. There are typically eight to nine eyes that are shallowly distributed around the tuber. These tubers can be stored for 7 months at 5.5 °C. Specific gravity average is 1.090, which is similar to 'Norchip'. It produces white flowers and olive green to yellowish green foliage with vigorous upright vines. Primary leaflets are medium sized that take on a narrow ovate shape with a cordate base. Attributes of 'Dakota Pearl' include resistance to Colorado Potato Beetle and low tuber sugar accumulations in storage. This cultivar is, however, susceptible to late blight and bacterial ring rot.

Atlantic

'Atlantic' was a cross between 'Wauseon' and USDA B5141-6 ('Lenape') (Webb 1978). It was released in 1976 by the USDA breeding program at Beltsville, MD making it the oldest cultivar in this field trial. This cultivar is the largest grown public cultivar in North America with the potential for high yields (Anonymous 2019). Tubers are oval-shaped with a length of 7.91 cm with a width of 7.32 cm (Webb 1978). The skin is a medium scaly net and the flesh is white. Tubers have a specific gravity of 1.085 to 1.100, which is excellent for chipping (PAA 2018). Leaves are bright green with little pubescents and produce prolific white flowers with abundant pollen. 'Atlantic' is susceptible to late blight and early blight, blackleg, leaf roll, stem canker, soft rot, common scab, dry rot, pink rot, and black scurf.

Potato Seed Production

Commercial potato production is a unique system for U.S. agriculture because it relies on vegetative propagation and does not require the use of true seed. All potatoes that are produced for commercial production in the U.S. are tetraploids. This presents a challenge to the industry because a tetraploid potato does not produce consistent large quantities of viable true seed for production proposes. Instead, potato tubers are physically cut into small 70 g pieces to make seed potatoes (Bissonnette 1993). By doing this, growers can achieve uniformity of the cultivars throughout the growing process. However, vegetative propagation has its own unique challenges. For example, many viruses in potato are tuber-bore, which can be transmitted to the next generation of tubers so it is important to obtain a clean seed source.

Fortunately, potato seed certification programs were established in the U.S. with the goal to produce relatively disease-free seed potatoes. The first person to suggest a potato seed certification program was W. A. Orton of the USDA in 1904 (Maloy 1993). In 1914, the first potato seed certification meeting was held by the Potato Association of America (PAA) (Sieczka et al. 2010). The participants of this meeting included 12 states and representatives from Canada, Ireland, Germany, and the USDA. By 1920, a seed potato certification program was established in most states in the US. Representing a voluntary agreement between growers and states to produces clean seed. Each state has different requirements and regulations for seed certification, however, throughout the years it has become a more uniformed standard. In general, the responsibility of seed potato certification falls on the individual state to carry out certification with legal authority. Certification agencies conduct inspections in the field, storage, and during the shipping process to prevent disease epidemics.

The State of North Dakota established a potato seed certification program in 1931 (NDSSD 2008). Today North Dakota produces over 6,000 hectares of seed potatoes per year, making it the second-largest producer of certified seed potatoes in the United States. However, it is not an easy process to keep potatoes disease-free and growers undergo a rigorous integrated pest management system for their growing operation. For instance, all storage facilities and equipment must be disinfected annually and used only for specified hectares. Furthermore, field rotations are closely monitored, and all cull piles must be properly destroyed. All North Dakota potato seed producers are subjected to three field inspections throughout the growing season to determine presence of disease and varietal purity. During the inspections, an inspector accepts or rejects a field for certification. Other factors that lead to field rejection are excessive weeds, hail, and chemical damage. Currently, there are no specific protocols in-place for seed potatoes that are contaminated with dicamba or glyphosate.

Herbicide Accumulation in Tubers

In today's world, everyone wants to know what is in the food they eat: from calorie count to sugar, protein, and pesticide residues. This concern is putting pressure on growers and processors to be transparent and to produce more with less. Herbicide residues have been among the most popular subjects in food health. Between growers and homeowners, the United States applied over 113 million kg of glyphosate in 2013 (U.S. GS 2013). Currently, the EPA allows a maximum of 0.2 ppm of glyphosate within potato tubers and 0 ppm is allowed for dicamba because there is no specific tolerance for dicamba at this time (U.S. EPA 2019). For other auxin mimicking herbicides, like 2,4-D, the EPA allows a maximum of 0.05 ppm within a fresh potato. Glyphosates mode of action is to inhibit the synthesis of essential amino acids within plants. However, animals and humans do not have these amino acids synthesis pathways and are thought not to be at risk (Borggard and Gimging 2008).

Detecting herbicide residues will not only benefit consumers but also certified seed potato growers. Unfortunately, there are no specific regulations or seed tests for herbicide residues in North Dakota certified seed potatoes. The inspector can however reject a field if he or she suspects chemical damage to the seed potatoes. Robinson and Hatterman-Valenti (2013) found that tubers with glyphosate residue can cause delayed or slow emergence, reduction in yield, along with malformation or thickening of shoots around eyes of seed piece. Colquhoun et al (2017) found that daughter from mother tubers treated with dicamba at 6 g ae ha^{-1} had similar stand count and yield as the non-treated. However, visible foliar damage was still seen in tubers with dicamba residue 42 days after planting (DAP). Therefore, a herbicide detection method would be good to screen tubers for growers and consumers.

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CHAPTER 2. 'ATLANTIC' AND 'DAKOTA PEARL' SEED POTATOES RESPONSES TO GLYPHOSATE AND DICAMBA SIMULATED DRIFT

Abstract

The effects of sublethal drift rates of glyphosate and dicamba on seed potato cultivars Atlantic and Dakota Pearl are unknown. This research explores the effects of glyphosate and dicamba measured through visible injury, as well as tuber yield, and quality reduction. Herbicides were applied at the potato tuber initiation stage and consisted of dicamba rates of 0, 20, and 99 g ae ha^{-1} and glyphosate rates of 0, 40, and 197 g ae ha^{-1}. At 7 days after treatment (DAT), the spray combination of glyphosate (197 g ae ha^{-1}) and dicamba (99 g ae ha^{-1}) resulted in the most plant damage, at 28% based on visible ratings from 0% (no injury) to 100% (plant death). Plant injury from glyphosate (40 g ae ha^{-1}) and dicamba (20 g ae ha^{-1}) was similar to the non-treated. At 21 DAT, visible injury increased to 40% for the combination of glyphosate (197 g ae ha^{-1}) and dicamba (99 g ae ha^{-1}) treatment. Tuber specific gravity was lower for plants sprayed with any herbicide treatment that included dicamba. Results from the two field trials suggest that sublethal combinations of glyphosate (197 g ae ha^{-1}) and dicamba (99 g ae ha^{-1}) decreased potato yields and tuber specific gravity.

Introduction

North Dakota is a unique agricultural state growing a diverse number of crops: from wheat, corn, and soybean to sugar beet, sunflower, and potato. In 2017, North Dakota harvested over 1.2 million metric tons of potatoes with an estimated value of $207 million. (USDA-NASS 2017). Of the potatoes harvested, over 76,000 metric tons were certified seed potatoes. Ranking the state fourth in the nation for potato production and seed production. However, soybean was the most planted crop in North Dakota, with 2 million hectares planted in 2017 at an estimated value of $2.1 billion (USDA-NASS 2018). The introduction of dicamba-tolerant soybean in 2017 provided growers with an option to control glyphosate-tolerant weeds. Soybean are often planted adjacent to other broadleaf crops, such as potato, that can be sensitive to dicamba.

New formulations of dicamba, have been developed with the goal of reducing dicamba volatilization. Even so, dicamba off-target movement caused sufficient damage in 2017 that the North Dakota Department of Agriculture implemented new dicamba application restrictions (NDAA 2017). For many parts of North Dakota, especially for counties in the southern half of the state where potato planting often occurs by mid-April, it is likely that instances of dicamba drift, vapor drift, or spray tank contamination, and the subsequent injury, will affect potato hectares. Currently, there are no protocols for testing glyphosate or dicamba tuber residue for certified seed potatoes (NDSSD 2008). In addition, research has shown cultivar injury differences to sublethal glyphosate and dicamba rates for russet-skinned and red-skinned cultivars, but research has not evaluated white-skinned cultivars (Crook 2016; Geary 2019).

Potatoes are unique because glyphosate and dicamba drift can cause direct yield losses to the daughter tubers from damaged mother plants and may be severely inhibited if plants are grown for seed production (Hatterman-Valenti et al. 2017). In addition, the russet skinned cultivar 'Russet Burbank' has shown almost 40% visible injury and two-fold total yield variation to the same sublethal glyphosate and dicamba rate. No research has examined the response of white-skinned chipping potatoes to sublethal (simulated spray drift) rates of dicamba or glyphosate.

The objective of this research was to determine the effect of glyphosate and dicamba on 'Atlantic' and 'Dakota Pearl' chipping potatoes grown for commercial production. This research will benefit commercial and seed potato growers, potato processors, agronomists, and research institutions to understand the effect of dicamba and glyphosate on white-skinned chipping potatoes.

Materials and Methods

A field experiment was conducted in 2018 at a North Dakota State University (NDSU) Irrigated Research Site, located five kilometers south of Oakes, North Dakota (46.07 N, -98.09 W; elevation 392 m). The experiments were set up as a randomized complete block design (RCBD), two-factor arrangement (herbicide x cultivar), with two cultivars, four replicates, five treatments, and two locations. Tuber initiation (TI) was selected on the importance of developing of daughter tubers (Stark and Love 2003). According to Stark and Love this growth stage is also where plant injury can have the greatest influence on harvest yield. Furthermore, this growth stage is present for the regulation of dicamba imposed by the North Dakota Department of Agriculture.

The treatments consisted of a non-treated control, dicamba (Clarity®, BASF Corporation, Research Triangle Park, NC, 27709), and glyphosate (PowerMax®, Monsanto Company, St. Louis, MO, 63167). Dicamba treatments were 20 and 99 g ae ha^{-1}, or 2 and 9% of the field use rate of 1121 g ae ha^{-1} within soybean (Jenks 2019). Glyphosate treatments were 40 and 197 g ae ha^{-1}, or 2 and 12% of the field use rate of 1680 g ae ha^{-1} within soybean (Table 3). These rates represent spray drift quantities or tank contamination that a grower might encounter in a North Dakota growing season.

Table 3. Glyphosate and dicamba simulated spray drift treatments applied at tuber initiation growth stage to 'Atlantic' and 'Dakota Pearl' potatoes on June 26th, 2018 at Oakes, ND.

Treatment	Herbicide rate	
	—— g ae ha^{-1} ——	—— % of field use rate ——
Non-treated	0	0
Glyphosate +	197	12
Dicamba	99	9
Glyphosate +	40	2
Dicamba	20	2
Dicamba	99	9
Glyphosate	197	12

Two field locations were used in Oakes, ND. Location one was planted on the north end of the research farm and location two was planted at the south end of the research farm. The soil type found in location one is a Embden fine sandy loam (USDA-NRCS, 2017). The soil type found location two is a mixture of half Embden fine sandy loam and half Glyndon loam. The typical soil profile of Embden fine sandy loam is a fine sandy loam from 0 to 203 cm down in depth. The typical soil profile of a Glyndon loam is loam though the first 0 to 28 cm, followed by silt loam from 29 to 183 cm and loam from 184 to 203 cm down in depth. Different crop rotations were used in both locations. In location one previous crop, in 2017, was corn and in location two the previous crop was soybean. Seed pieces for both locations were planted on May 7, 2018.

Certified 'Atlantic' and 'Dakota Pearl' seed potatoes were cut into 70g ± 5 g seed pieces, ensuring that every seed piece had at least two or more eyes/seed. After the seed pieces were cut, they were stored for two weeks at 10 °C and 95% relative humidity (RH) to induce suberization and seed conditioning prior to planting. Each experimental unit (EU) contained two rows with 20 seed pieces planted in each row (40 total seed pieces/EU). All seed pieces were planted 31 cm within-row with a 91 cm row spacing at 35,880 seed pieces ha^{-1}. The row length was 6.1 m long with a seed depth of 10 cm. A 1.5 m gap of five ‘Red Norland’ potato plants separated each treatment with in a row. Furthermore, two border rows of ‘Russet Burbank’ plants were planted between each treatment rows to separated and reduce contamination between treatments at application. North Dakota Extension potato recommendations were performed throughout the growing season (Bissonnette 1993).

Treatments of glyphosate and dicamba were applied with a CO_2 backpack sprayer equipped with a 1.8 m boom and four XR11002 flat fan nozzles (TEEJET Spraying Systems Company, Wheaton, IL 60189) at 45cm nozzle spacing, 138 kPa pressure, and an output of 346 L ha^{-1}. Herbicides at both locations were applied progressing from lowest to highest rate starting with glyphosate treatments first to mitigate cross-contamination of experimental units (EU). The temperature at the start and end of spray applications was 21 and 23 °C, respectively. The treatments were applied at TI on June 26th at both locations. Visible foliar injury was recorded 7 and 21 days after treatment (DAT). Typical foliar injury from dicamba and glyphosate was leaf cupping, malformation of new leaf growth, and yellowing or chlorosis at the growing points, respectively (Bissonnette 1993; Wall 1994). Rating was based on a 0 to 100% visible injury scale where 0% equates to no foliar damage and 100% equates to complete death of the potato vine. Location one was harvested September 5th and location two was harvested September 6th using a single row, mechanical harvester in 2018. Two weeks after harvest, tubers from both locations were graded and separated into four weight categories; <113, 133-169, 170-182, and >282 g. After grading a representative sample of 50 or more tubers, from each EU, were stored at 2.2 °C with 90 to 95% RH for seven months. Two months into storage, random samples of 10 tubers were taken from each EU. To obtain specific gravity measurements, the weight of tubers in air were measured followed by the weight of tubers in water. From there specific gravity equals the weight of tubers in air divided by the weight of tubers in air minus the weight of tubers in water.

Data Analysis

Data from both location one and two were combined, after testing homogeneity of variance using a folded F-test method were combined and subjected to analysis of variance using PROC GLIMMIX procedure using Statistical Analysis Software (SAS version 9.4. SAS Institute Inc., 100 SAS Campus Dr., Cary, NC 27513). Locations were repeated in space and considered a random effect while cultivar and treatments were considered fixed effects. LS means ($\alpha = 0.05$) was used to separate treatment means.

Results and Discussion

Foliar Injury

At 7 and 21 DAT, herbicide treatments influenced plant injury symptoms (Table 4). At 7 DAT, the combination of glyphosate at 197 g ae ha^{-1} and dicamba at 99 g ae ha^{-1} caused 29% visible foliar injury when compared to the non-treated plants. Foliar injury increased to 40% at 21 DAT, which was a higher injury rating than all other treatments. Plants that were treated with dicamba at 99 g ha^{-1} alone or the combination of glyphosate at 40 g ha^{-1} and dicamba at 20 g ha^{-1} were not different 7 DAT when compared to the non-treated plants. However, 21 DAT, plant foliage treated with dicamba at 99 g ha^{-1} alone or the combination of glyphosate at 40 g ha^{-1} and dicamba at 20 g ha^{-1} experienced an increase in foliar injury by 8 to 16%, which was different from the non-treated plants. Furthermore, glyphosate at 197 g ha^{-1} exhibited 15% foliar injury 7 DAT and decreased to 12% foliar injury at 21 DAT. All plants, 21 DAT, had more visible injury than the non-treated plants, which displayed no signs of herbicide injury. Among cultivars, there were no significant differences in foliar injury at either 7 or 21 DAT.

All potato plants that were treated with sublethal rates of glyphosate or dicamba displayed damage in the top 15 to 20 cm of the canopy. Previous research has shown that ‘Russet Burbank’ visible injury from the same sublethal dicamba rate varied by almost 40% and caused nearly a two-fold difference in the total yield loss (Hatterman-Valenti et al. 2017). It was concluded that the less responsive plants (lower visible injury and less total yield reduction) were stressed from higher air temperatures. Hutchinson (2014) showed that 20 to 50% visible injury to ‘Russet Burbank’ from glyphosate (107 and 215 g ha^{-1}) spray drift 7 and 21 DAT, but did not test for a second cultivar. Results suggest that chipping potato cultivars may respond similarly to sublethal glyphosate and/ or dicamba as long as environmental conditions are not stressful when the off-target injury occurs.

Table 4. Visible plant injury ratings 7 and 21 days after treatments (DAT) during tuber initiation growth stage for regionally grown chipping potato cultivars in July 2018 at Oakes ND.

Cultivar		Visible Plant Injury[a]	
		7 DAT	21 DAT
		——— Injury (%) ———	
Atlantic		9	13
Dakota Pearl		11	17
Herbicide			
Glyphosate	Dicamba	7 DAT	21 DAT
—— g ae ha^{-1} ——		——— Injury (%) ———	
0	0	0 c	0 d
197	99	29 a	40 a
40	20	1 c	8 c
0	99	6 c	16 b
197	0	15 b	12 bc
P-value			
Cultivar		0.4603	0.2167
Herbicide		0.0031	0.0003
Cultivar x Herbicide		0.6761	0.4734

[a]Numbers followed by the same letter in a column are not significantly different according to LS Mean separation comparison at α=0.05. No significant differences within a column were observed when no letters are included.

Tuber Measurements

Total Yield

The main effects of herbicide influenced the total yield of ‘Atlantic’ and ‘Dakota Pearl’ (Table 5). There was no interaction among total yield so cultivars were not analyzed separated. Non-treated plants and those treated with a combination of glyphosate at 40 g ha^{-1} and dicamba at 20 g ha^{-1} had higher total yields, at 46 T ha^{-1} and 42 T ha^{-1}, compared to other treatments. Plants treated with glyphosate at 197 g ha^{-1} and dicamba at 99 g ha^{-1} had the lowest total yield at 28 T ha^{-1}, compared other treatments. This was a 42% yields reduction compared to the non-treated. Across cultivars, plants treated with glyphosate at 197 g ha^{-1} or dicamba at 99 g ha^{-1} alone had similar total yields at 34 and 35 T ha^{-1}. However, this resulted in a total yield reduction of 21 and 23%, respectively, when compared to the non-treated.

Graded Tubers

At the tuber weight category >282 g only herbicide treatments influenced tuber yield (Table 5). However, at the tuber weight category <113, 133-169, and 170-182 g the interaction of cultivar and herbicide treatments influenced plant tuber size. The first interaction at <113 g weight category, was significant due to the differences in magnitude. The response from both cultivars were similar, but across treatments ‘Atlantic’ had fewer T ha^{-1} for tubers that weighed <113 g. The results also suggested that ‘Dakota Pearl’ was more sensitive to glyphosate at 197 g ha^{-1} than ‘Atlantic’ because ‘Dakota Pearl’ treated with glyphosate alone produced more <133 g tubers than all other treatments. ‘Dakota Pearl’ greater sensitivity to glyphosate was reinforced when plants with the combination of glyphosate at 197 g ha^{-1} and dicamba at 99 g ha^{-1} produced the more < 133 g tubers, at 12 T ha^{-1}, than all other treatments except glyphosate at 197 g ha^{-1}. The increase in tubers <113 g, when plants were treated with glyphosate, suggests that the herbicide slowed tuber bulking, but not tuber set, therefore the plants produced more smaller tubers.

The second interaction, at 113 to 169 g weight category, suggested that ‘Dakota Pearl’ was more sensitive to glyphosate than ‘Atlantic’. ‘Dakota Pearl’ plants treated with glyphosate at 197 g ha^{-1} produced 8 T ha^{-1}, while ‘Atlantic’ plants treated with glyphosate at 197 g ha^{-1} produced 16 T ha^{-1}. Inversely, ‘Dakota Pearl’ produced 15 T ha^{-1} when treated with dicamba at 99 g ha^{-1} alone while ‘Atlantic’ produced 12 T ha^{-1}. The combination of glyphosate at 197 g ha^{-1} and dicamba at 99 g ha^{-1} did reduce tuber yield by 34 and 41% for both cultivars. Finally, ‘Atlantic’ and ‘Dakota Pearl’ treated with the combination of glyphosate at 40 g ha^{-1} and dicamba at 20 g ha^{-1} were not different from the non-treated.

The third interaction, at the 170 to 282 g weight, category was similar to the previous interaction. ‘Dakota Pearl’ plants treated with glyphosate at 197 g ha^{-1} produced 2 T ha^{-1}, while ‘Atlantic’ plants treated with glyphosate at 197 g ha^{-1} produced 7 T ha^{-1}. Finally, at the >283 g weight category, non-treated plants outperformed all other treatments producing 13 T ha^{-1}. Plants treated the combination of glyphosate at 197 g ha^{-1} and dicamba at 99 g ha^{-1} had the largest yield reduction when compared to the non-treated at 85%, but this response was similar to plants treated with glyphosate at 197 g ha^{-1} or dicamba 99 g ha^{-1} with a reduction of 62 to 77%, respectively, compared to the non-treated.

All plants that were treated experienced smaller misshapen tubers that would not make it past inspection certification. Typical symptoms were growth cracks near the bud end of tubers and elephant hide skin. Crook (2016) reported that ‘Red Norland’ potato yield was negatively affected when glyphosate rates were applied at tuber initiation rather than early bulking or late bulking. She concluded that as glyphosate rate increased, yield per plant decreased. Colquhoun el al. (2014) reported that ‘Russet Burbank’, when treated with sublethal rates of dicamba, at 1.4, 4.2, and 7.0 g ha^{-1}, did not affect the total yield. He reported fewer larger tuber but an increase in tubers <133 g within the dicamba treatments. Data from this experiment would suggest that ‘Dakota Pearl’ is more sensitive to glyphosate than ‘Atlantic’ causing the interaction within the various tuber grades.

Table 5. Tuber measurements of ‘Atlantic’ and ‘Dakota Pearl’ after treated with sublethal rates of glyphosate and dicamba during tuber initiation growth stage in 2018.

Cultivar			Potato Tuber Yield[a]				
			<113 g	113-169 g	170-282 g	>282 g	Total Yield
			—T ha^{-1}—				
Atlantic			7	15	7	8	37
Dakota Pearl			12	14	6	5	37
Herbicide							
	Glyphosate	Dicamba	<113	113-169	170-282	>282	Total Yield
	—g ae ha^{-1}—		—T ha^{-1}—				
	0	0	6 d	17 a	9 a	13 a	46 a
	197	99	12 b	11 b	3 c	2 c	28 c
	40	20	7 cd	17 a	8 a	8 b	42 a
	0	99	9 c	14 b	6 b	5 bc	34 b
	197	0	16 a	12 b	4 c	3 c	35 b
Cultivar x Herbicide							
	Glyphosate	Dicamba	<113	113-169	170-282	>282	Total Yield
	—g ae ha^{-1}—		—T ha^{-1}—				
Atlantic	0	0	5 f	17 a	9 a	17	48
	197	99	9 cde	10 c	4 de	3	26
	40	20	6 ef	18 a	8 ab	9	41
	0	99	8 cdef	12 bc	5 cd	7	32
	197	0	10 cd	16 a	7 bc	5	38
Dakota Pearl	0	0	7 def	17 a	9 a	11	44
	197	99	15 b	11 bc	2 e	1	29
	40	20	9 cde	17 a	8 ab	8	42
	0	99	11 c	15 ab	7 bc	4	37
	197	0	21 a	8 c	2 e	1	32
P-value							
Cultivar			0.0673	0.5654	0.1794	0.1264	0.9608
Herbicide			0.0017	0.0110	0.0010	0.0119	0.0036
Cultivar x Herbicide			0.0372	0.0369	0.0192	0.3371	0.1877

[a]Numbers followed by the same letter in a column are not significantly different according to LS Mean separation comparison at α=0.05. No significant differences within a column were observed when no letters are included

Specific Gravity

Herbicide treatments were influenced tuber specific gravity (Table 6). Plants treated with the combination of glyphosate at 197 g ha^{-1} and dicamba at 99 g ha^{-1} had tubers with lower specific gravity than tubers from non-treated plants or tubers from plants treated with the herbicide combination of glyphosate at 40 g ha^{-1} and dicamba at 20 g ha^{-1}. Plants treated with glyphosate at 197 g ha^{-1} or dicamba at 99 g ha^{-1} had tubers with specific gravities of 1.0924 to 1.0948 kg m^{-3}, which was less than the tuber specific gravity from non-treated plants. Even though treating plants with glyphosate, dicamba, or the herbicide combination reduced the tuber specific gravity all values are within the USDA standard for chip processing, which is above 1.080 kg/m^3 (Raiz 2016). Obtaining a high specific gravity can limit the cook time and oil absorbed into the tuber during processing (Stark and Love 2003). Tuber size can affect tuber specific gravity. Large tubers tend to have a higher specific gravity vs smaller tuber. This could explain why plants, that were treated with herbicides produced more small tubers, had a reduction in specific gravity. Even though all treatments are above 1.080 kg/m^3 there could be a hidden cost in processing with the reduction of specific gravity.

Colquhoun (2014) reported no change in tuber specific gravity (1.070 to 1.080 kg/m^3) from ‘Russet Burbank’ tubers that were sprayed at tuber initiation with glyphosate at 7 g ha^{-1} or dicamba at 1.4, 4.2 or 7.0 g ha^{-1}. These findings suggest that russeting-skinned potatoes can respond differently than chipping type potatoes to sublethal glyphosate and/or dicamba rates.

Table 6. Specific gravity of 'Atlantic' and 'Dakota Pearl' two months after being in storage at 2.2°C with 90-95% relative humidity in 2018.

Cultivar		Specific Gravity[a]
		——kg/m^3——
Atlantic		1.0998
Dakota Pearl		1.0905
Herbicide		
Glyphosate	Dicamba	
—— g ae ha^{-1} ——		——kg/m^3——
0	0	1.1054a
197	99	1.0876c
40	20	1.0999ab
0	99	1.0900bc
197	0	1.0927bc
P value		
Cultivar		0.1664
Herbicide		0.0440
Cultivar x Herbicide		0.5000

[a]Numbers followed by the same letter in a column are not significantly different according to LS Mean separation comparison at α=0.05. No significant differences within a column were observed when no letters are included

Conclusion

Since 2016, the EPA has taken off-target moment of dicamba very seriously by implementing stricter regulations on the herbicide. Some of these regulations are mandatory applicator training and label changes. This has seemed to help mitigate the risk of off-target movement of dicamba but does not completely prevent the problem from occurring in the future.

This is the first study to investigate the impact of sublethal glyphosate and dicamba rates on two white skinned chipping potatoes. This research indicates, that the cultivars Atlantic and Dakota Pearl, when treated with glyphosate at 197 g ha^{-1}, dicamba at 99 g ha^{-1}, or the combination of both herbicides could result in a reduction of total yield, tuber specific gravity. Furthermore, 'Dakota Pearl', when treated with glyphosate at 197 g ha^{-1}, produced more tubers at the lowest weight category (<113g) and fewer tubers at all other tuber weight categories (133 to >282) when compared to 'Atlantic'. Based on these results 'Dakota Pearl' seem more sensitive to glyphosate at 197 g ha^{-1} than 'Atlantic'. Growers that are in close proximity to chipping potato growers should always take precautions when spraying glyphosate and/or dicamba and know the impacts if there is off-target movement.

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CHAPTER 3. RESPONSE OF 'ATLANTIC' AND 'DAKOTA PEARL' DAUGHTER TUBERS FROM MOTHER PLANTS EXPOSED TO SUBLETHAL GLYPHOSATE AND DICAMBA

Abstract

The increased use of glyphosate and dicamba tolerant soybean can result in off-target exposure and damages to seed potato tubers. For certified seed potato growers, this would affect yields in the current season as well as plant emergence the following growing season. The objective of this study was to determine the effects of 'Atlantic' and 'Dakota Pearl' potato (*Solanum tuberosum* L.) tubers, used for seed from mother plants that were exposed to glyphosate at 40 and 197 g ae ha^{-1}, dicamba at 20 to 99 g ae ha^{-1}, or the combination of glyphosate and dicamba the previous year at the tuber initiation stage. At 8 weeks after planting (WAP), daughter tubers from mother plants receiving glyphosate at 197 g ha^{-1}, or the combination of glyphosate and dicamba, had reduced emergence by 17 and 24% when compared to the non-treated respectively. Furthermore, at 7 WAP, daughter tubers from mother plants receiving the combination of dicamba at 99 g ha^{-1} and glyphosate at 197 g ha^{-1} or glyphosate at 197 g ha^{-1} had reduced plant height by 16 and 20%, respectively, compared to the non-treated. Daughter plants from the mother plants that received the combination of glyphosate at 197 g ha^{-1} and dicamba at 99 g ha^{-1} had a 21% total yield reduction and canopy reduction when compared to the non-treated. Results from the two field trials suggest that the combination of glyphosate at 197 g ha^{-1} and dicamba at 99 g ha^{-1}, carried over from mother plants to daughter tubers for both cultivars, the following growing season, to affect total yield from the daughter plant injury. Further research needs to evaluate the influence of environmental stresses on the potato response to sublethal amounts of glyphosate and/or dicamba.

Introduction

In the early 2000s, weeds in glyphosate tolerant (GT) crop fields were becoming increasingly resistant to the herbicide glyphosate. To combat this problem in soybean, dicamba tolerant soybean were released in 2016, with no spray restrictions for the herbicide. In 2017, many growers, throughout the United States reported a record number of pesticide misuse associated with off-target dicamba applications (Hartzler 2017b). It was determined that the off-target damage of dicamba was associated with spray drift, volatility, and tank contamination. Numerous researchers have shown that glyphosate and dicamba injury to parent potato, wheat, dry beans, and soybean can cause a decrease in vigor, emergence, and germination the following year (Blackburn and Boutin 2003; Hatterman-Valenti and Robinson 2013; Hatterman-Valenti 2014; Hutchinson et al. 2014; Norsworthy 2004; Yenish and Young 2000).

A vital part of North Dakota agriculture is the production of certified and clean seed potatoes for growers. In 2018, North Dakota produced 76,000 metric tons of certified potato seed, which ranked the state fourth in the nation for seed potato production (USDA-NASS 2019). Producing potato seed for commercial use is unique among agricultural crops because *Solanum tuberosum* L. is a tetraploid that does not produce dependable viable true seed (Jansky 2016). The current production method used by growers to achieve uniformed commercial potato production is though asexual vegetative propagation of tubers. These propagation tubers are known as seed pieces and can be manually cut into 70 g pieces or small whole tubers can be used from which stems emerge after planting. Although resources are shifting to make potatoes into a diploid to produce true seed, tetraploid potatoes still command the largest source of potato seed. Seed pieces are successful for most growers, but challenges may occur in terms of seed residues, seed-borne diseases, and cultivar purity (Sieczka et al. 2003).

Unfortunately, there are no specific regulations or seed tests for herbicide residues in North Dakota certified potato seed production. The inspector can however reject a field if they suspect chemical damage to the seed potatoes. Currently, the EPA allows a maximum of 0.2 ppm of glyphosate within potato tubers but no specific tolerance for dicamba (U.S. EPA 2019). For other auxin mimicking herbicides, like 2-4D, the EPA allows a maximum of 0.05 ppm within a potato tuber. Robinson and Hatterman-Valenti (2013) showed that tubers with glyphosate residue have delayed or slow emergence along with malformation or thickening of shoots around eyes of the seed piece.

The objective of this research was to determine the response of daughter tubers when the mother plants have received a sublethal rate of glyphosate, dicamba, or a combination of both herbicides the previous growing season for the chipping potato cultivars of Atlantic and Dakota Pearl. This research will benefit potato growers, potato processors, agronomists, and research institutions by demonstrating the effects of dicamba, glyphosate, or the combination of both herbicides on white-skinned potato seed tubers.

Materials and Methods

A field experiment was conducted in 2019 at the North Dakota State University (NDSU) Irrigated Research Site, located five kilometers south of Oakes, North Dakota (46.07 N, -98.09 W; elevation 392 m). The experiments were arranged as a two-factor randomized complete block design, with two cultivars, four replicates, five treatments, and two locations near Oakes, ND. Mother plants of the two cultivars (Atlantic and Dakota Pearl) were treated with sublethal glyphosate, dicamba, or the combination of both herbicides at the tuber initiation growth stage the previous year. Randomly selected tubers of each experimental unit (EU) for all both cultivars were stored over the winter and planted the following spring.

Treatments that were applied to mother plants in 2018 consisted of a non-treated, dicamba (Clarity®, BASF Corporation, Research Triangle Park, NC, 27709), and/or glyphosate (PowerMax®, Monsanto Company, St. Louis, MO, 63167) (Table 8). Dicamba treatments were 20 and 99 g ae ha^{1}, or 2 and 9% of the field use rate of 1121 g ae ha^{-1} (Jenks 2019). Glyphosate treatments were 40 and 197 g ae ha^{-1}, 2 and 12% of the field use rate of 1680 g ae ha^{-1}. (Table 7). These rates were chosen to represent low and high spray drift quantities or tank contamination that a grower might encounter in a North Dakota growing season.

In 2018, herbicide treatments were applied the previous year with a CO_2 backpack sprayer equipped with a 1.8 m boom and four XR11002 flat fan nozzles (TEEJET Spraying Systems Company, Wheaton, IL 60189) 45 cm apart at 138 kPa and an output of 346 L ha^{-1}. Herbicide treatments at both locations were applied on June 26, 2018 in progression of lowest to highest rates starting with glyphosate treatments first to mitigate cross contamination of EU's and complied with the new 2017 North Dakota rules for dicamba application. The temperature at the start and end of application was 21 and 23 °C respectfully.

Table 7. Glyphosate and dicamba simulated spray drift treatments applied at the tuber initiation growth stage in 2018 to 'Atlantic' and 'Dakota Pearl' mother plants near Oakes, ND.

Treatment	Herbicide rate	
	—— g ae ha^{-1} ——	——% of field use rate——
Non-treated	0	0
Glyphosate Dicamba	197 99	23 9
Glyphosate Dicamba	40 20	5 2
Dicamba	99	9
Glyphosate	197	23

Two field locations were used in Oakes, ND. The soil type found in location one is a Gardena loam. The soil type found location two is a Swenoda fine sandy loam (USDA-NRCS, 2017). The typical soil profile of Gardena loam is a fine sandy loam from 0 to 20 cm and silt loam 21 to 203 cm down in depth. The typical soil profile of a Swenoda fine sandy loam is loam though the first 0 to 83 cm, followed by loam from 83 to 203 cm down in depth. Different crop rotations were used in both locations. In location one previous crop was corn and in location two the previous crop was soybean in 2018.

In the spring of 2019, ‘Atlantic’ and ‘Dakota Pearl’ seed potatoes were taken out of storage and cut into 70 g seed pieces, ensuring that every seed piece had two or more eyes. After the tubers were cut, they were stored for two weeks at 10 °C at 95% relative humidity to induce suberization and seed conditioning prior to planting. Seed pieces, for both locations, were planted on May 13, 2019. In location 1 the previous crop, in 2018, was soybean and in location two the previous crop was corn. Each EU contained two rows with 20 seed pieces planted in each row (40 total seed pieces/EU). All seed pieces were planted 31 cm apart with a 91 cm spacing between each row at 35,880 seed pieces ha^{-1}. The row length was 6.1 m long with a seed depth of 10 cm. A 1.5 m gap of five ‘Red Norland’ potato plants separated each treatment with in a row. Furthermore, two border rows of “Russet Burbank” plants were planted between each treatment rows to separated and reduce drift at application. Throughout the growing season, each location received standard North Dakota potato production practices (Bissonnette 1993).

Plant emergence and height measurements were recorded weekly for one month starting five after planting (WAP) with one additional plant height measurements recorded at nine WAP. Plants were measured from the base of the soil to the top of the growing point on the potato. Canopy development was also recorded at eight and nine WAP with Canopeo software (Version 2.0. Copyright © 2015 by the American Society of Agronomy, Inc., 5585 Guilford Road Madison, WI 53711-5801) Canopy cover was based on a 0-100% scale with 0% equates to no canopy development or grounded cover and 100% equates to complete vegetation cover. Location one was harvested September 12th and location two was harvested September 13th. Each EU was harvested with a custom, single row, mechanical harvester. One week following harvest, tubers from each EU were graded for total and marketable yields as well as weights for individual tuber size categories. These size categories ranged from <113, 113-169, 170-282, and >283 g.

Data Analysis

Data from both location one and two were combined, after testing homogeneity of variance using a folded F-test method were combined and subjected to analysis of variance using PROC GLIMMIX procedure using Statistical Analysis Software (SAS version 9.4. SAS Institute Inc., 100 SAS Campus Dr., Cary, NC 27513). Locations were repeated in space and considered random while cultivar and treatment considered fixed. LS means ($\alpha = 0.05$) was used to separate treatment means.

Results and Discussion

Emergence

‘Atlantic’ and ‘Dakota Pearl’ potato seed pieces planted from mother plants that were exposed to sublethal rates of glyphosate or dicamba exhibited herbicide injury symptoms but the degree of injury varied between cultivars (Table 8). At 5 WAP, the combination of glyphosate at 197 g ae ha^{-1} and dicamba at 99 g ae ha^{-1} to mother plants resulted in a 35% reduction in emergence for ‘Atlantic’ when compared to the non-treated. However, the treatment resulted in a 53% reduction in emergence for ‘Dakota Pearl’, which was lower when compared to ‘Atlantic’. Inversely, daughter tubers from mother plants treated with dicamba at 99 g ha^{-1} had a significant 29% reduction in emergence for ‘Atlantic’ when compared to the non-treated, while the same treatment with ‘Dakota pearl’ resulted in 91% plant emergence, which was similar to the 94% emergence for the non-treated.

Similarly, at 6 and 7 WAP, herbicide residues in daughter tubers from mother plants treated with dicamba at 99 g ha^{-1} resulted in 26 and 29% reduction in emergence for ‘Atlantic’ when compared to the non-treated, while the same treatment with ‘Dakota Pearl’ was not different from the non-treated. At 6 WAP, herbicide residues in daughter tubers from mother plants treated with the combination of glyphosate at 197 g ha^{-1} and dicamba at 99 g ha^{-1} resulted in a 21 and 35% reduction in emergence of ‘Atlantic’ and ‘Dakota Pearl’, respectively, when compared to the non-treated. More daughter tuber injury was observed when mother plants were treated with glyphosate at 197 g ha^{-1} than the combination of glyphosate at 197 g ha^{-1} and dicamba at 99 g ha^{-1}, with only 54% and 64% emergence for ‘Atlantic’ and ‘Dakota Pearl’, respectively. However, this delayed emergence was only different from the delayed emergence for ‘Atlantic’ daughter tubers with residues form the combination of glyphosate at 197 g ha^{-1} and dicamba at 99 g ha^{-1}.

Finally, at 8 WAP, there were no differences among herbicide injury between cultivars. Glyphosate at 197 g ha^{-1}, dicamba at 99 g ha^{-1} and the combination of glyphosate at 197 g ha^{-1} and dicamba at 99 g ha^{-1} caused roughly 13 to 24% decrease in emergence 8 WAP. The lowest treatment combination of glyphosate at 40 g ha^{-1} and dicamba at 20 g ha^{-1} had no effect on emergence though all four weeks of data collection. Tubers that did not emerge 8 WAP either did not produce any shoots or showed delayed emergence up to harvest.

These findings were similarly observed by Geary (2019) who observed a 17 to 30% decrease in emergence for ‘Russet Burbank’ plants eight WAP for daughter tubers from mother plants treated with glyphosate at 197 g ha^{-1}, dicamba at 99 g ha^{-1}, or the combination of glyphosate 197 g ha^{-1} and dicamba at 99 g ha^{-1} the year before. He also observed no significant difference in emergence for 'Russet Burbank' tubers that were treated the year before with a combination of glyphosate at 40 g ha^{-1} and dicamba at 20 g ha^{-1} 8 WAP. Furthermore, Hatterman-Valenti (2014) observed a 76 to 95% reduction in emergence of 'Red LaSoda' and 'Russet Burbank' seed pieces from mother plants that were treated with glyphosate (71, 141, and 282 g ha^{-1}) during late bulking (LB) the previous year suggesting that herbicide residue amounts in daughter tubers depends on several factors during the initial off-target exposure and the source sink relationship in the potato plant when the off-target injury occurred.

Table 8. Plant emergence (percent) from seed pieces from mother plants that were treated with sublethal rates of glyphosate and/or dicamba the previous growing season, and evaluated weekly starting at five weeks after planting (WAP) in 2019 near Oakes, ND.

Cultivar			Plant Emergences[a]			
			5 WAP	6 WAP	7 WAP	8 WAP
			Plant Emergence (%)			
Atlantic			69	78	83	84
Dakota Pearl			71	84	90	93
Herbicide						
	Glyphosate	Dicamba	5 WAP	6 WAP	7 WAP	8 WAP
	g ae ha^{-1}		Plant Emergence (%)			
	0	0	95 a	99 a	99 a	99 a
	197	99	50 b	71 cd	82 b	86 b
	40	20	80 a	90 ab	94 a	95 a
	0	99	80 a	83 bc	85 b	86 b
	197	0	45 b	59 d	69 c	75 c
Cultivar x Herbicide						
	Glyphosate	Dicamba	5 WAP	6 WAP	7 WAP	8 WAP
	g ae ha^{-1}		Plant Emergence (%)			
Atlantic	0	0	96 a	99 a	99 a	99
Atlantic	197	99	61 cde	78 bcd	85 bc	87
Atlantic	40	20	75 abc	84 abc	90 ab	91
Atlantic	0	99	67 bcd	70 cde	73 de	74
Atlantic	197	0	44 ef	54 e	63 e	68
Dakota Pearl	0	0	94 a	99 a	99 a	99
Dakota Pearl	197	99	41 f	64 de	78 cd	86
Dakota Pearl	40	20	88 ab	96 ab	98 a	99
Dakota Pearl	0	99	91 a	95 ab	97 ab	97
Dakota Pearl	197	0	45 def	64 de	74 cde	82
P value						
Cultivar			0.6344	0.2993	0.1700	0.1324
Herbicide			0.0066	0.0065	0.0029	0.0059
Cultivar x Herbicide			0.0265	0.0127	0.0388	0.0657

[a]Numbers followed by the same letter in a column are not significantly different according to LS Mean separation comparison at α=0.05. No significant differences within a column were observed when no letters are included

Plant Height

Cultivar did not influence plant height differences measured 5 to 9 WAP (Table 9). Daughter plants from mother plant treated with glyphosate at 197 g ha^{-1} or the combination of glyphosate at 197 g ha^{-1} and dicamba at 99 g ha^{-1} were consistently shorter every week measured when compared to the non-treated. Daughter plants from mother plants treated with dicamba at

99 g ha^{-1} or the lower combination rate of glyphosate at 40 g ha^{-1} and dicamba at 20 g ha^{-1} had similar plant heights as the non-treated every week measured.

Plant herbicide injury symptoms were observed at both locations in daughter plants from mother plants that were treated with glyphosate at 197 g ha^{-1}, dicamba at 99 g ha^{-1}, and the combination of glyphosate at 197 g ha^{-1} and dicamba at 99 g ha^{-1} the previous year. These symptoms were leaf epinasty, malformation at leaf tips, chlorosis, stunting, single stem emergence, thickening of stem and were similar to symptoms reported by Hatterman-Valenti (2014), Hutchinson (2014) Colquhoun (2017), and Geary (2019), reported a 20 to 30% plant height reduction for ‘Russet Burbank’ daughter plants from mother plants treated with glyphosate at 197 g ha^{-1} and the combination of glyphosate at 197 g ha^{-1} and dicamba at 99 g ha^{-1} the previous year. However, the severity of plant injury symptoms was not consistent throughout each treatment. According to Smid and Hill (1981), nutrient reserves within the seed pieces transferred throughout the plant up to the tuber initiation stage. They reported that when mother potato plants were exposed to glyphosate and dicamba at TI, the herbicides translocate from the foliage into the apical meristem of tuber tissue in a source to sink fashion. This suggests that potato plants with seed pieces containing glyphosate or dicamba residues, would transfer the herbicides throughout the plants. However, the herbicides do not always translocate and distribute evenly throughout the daughter tubers as reported by Crook (2014) and Geary (2019) and could explain the inconsistency of injury symptoms throughout the treatments.

Table 9. Daughter plant heights for seed pieces from mother plants that were treated with sublethal rates of glyphosate and/or dicamba the previous growing season, and measured weekly starting at five weeks after planting (WAP) in 2019 near Oakes, ND.

Cultivar		Plant Heights[a]				
		5 WAP	6 WAP	7 WAP	8 WAP	9 WAP
		Plant Height (mm)				
Atlantic		100	246	348	497	594
Dakota Pearl		102	226	343	483	585
Herbicide						
Glyphosate	Dicamba	5 WAP	6 WAP	7 WAP	8 WAP	9 WAP
g ae ha^{-1}		Plant Height (mm)				
0	0	135 a	289a	411a	563a	655a
197	99	65 b	181b	269b	416c	526c
40	20	114 ab	247a	377a	503ab	598ab
0	99	126 a	282a	378a	533a	618a
197	0	65 b	180b	292b	434bc	550bc
P value						
Cultivar		0.8110	0.4053	0.7712	0.4848	0.7498
Herbicide		0.0414	0.0089	0.0100	0.0174	0.0230
Cultivar x Herbicide		0.6067	0.1425	0.1606	0.7139	0.8774

[a]Numbers followed by the same letter in a column are not significantly different according to LS Mean separation comparison at α=0.05. No significant differences within a column were observed when no letters are included

Canopy Development

'Atlantic' and 'Dakota Pearl' potato seed pieces planted from mother plants that were exposed to sublethal rates of glyphosate or dicamba exhibited a reduction in canopy development but the degree of injury varied between cultivars at 8 WAP (Table 10). Residues in daughter tubers from mother plants treated with the combination of glyphosate at 97 g ha^{-1} and dicamba at 99 g ha^{-1} resulted in 43% reduction in canopy development for 'Dakota Pearl' when compared to the non-treated at 8 WAP. 'Atlantic' had a 25% reduction in canopy development for the same treatment. Residues in daughter tubers from mother plants treated with glyphosate alone resulted in a 32 to 34% reduction in canopy for both cultivars. At 9 WAP, neither cultivar or herbicide treatment from the previous year influenced plant canopy development, even though the percent cover varied by 19% between daughter plants from the non-treated and daughter plants from mother plants treated with glyphosate at 197 g ha^{-1}.

According to Oijen (1991) a plants ability to maximize canopy cover and light interception is linearly linked to tuber yield. Boyd et al. (2002) reported that canopy cover could explain 87% of total tuber yield in 'Russet Burbank'. These findings show how important canopy development is for potatoes. When daughter tubers, from mother tubers that were treated with glyphosate or dicamba, are grown the symptoms of delayed emergence, stunting of plants and malformed leaf's affect the canopy development and the plants ability to maximize light interception.

Table 10. Canopy measurements eight and nine weeks after planting (WAP), using Canopeo software, on regionally grown chipping potato "Atlantic' and 'Dakota Pearl' in 2019 at Oakes ND.

Cultivar			Canopy Cover[a]	
			8 WAP	9 WAP
			——— % Covered ———	
Atlantic			71	83
Dakota Pearl			73	85
Herbicide				
	Glyphosate	Dicamba	8 WAP	9 WAP
	—— g ae ha^{-1} ——		——— % Covered ———	
	0	0	87 a	93
	197	99	58 b	77
	40	20	77 a	89
	0	99	78 a	87
	197	0	58 b	74
Cultivar x Herbicide				
	Glyphosate	Dicamba	8 WAP	9 WAP
	—— g ae ha^{-1} ——		——— % Covered ———	
Atlantic	0	0	86 a	93
	197	99	66 bc	81
	40	20	73 ab	85
	0	99	72 ab	83
	197	0	56 cd	75
Dakota Pearl	0	0	88 a	94
	197	99	50 d	73
	40	20	84 a	93
	0	99	84 a	92
	197	0	59 bcd	75
P value				
Cultivar			0.6508	0.6947
Herbicide			0.0058	0.0681
Cultivar x Herbicide			0.0354	0.0967

[a]Numbers followed by the same letter in a column are not significantly different according to LS Mean separation comparison at α=0.05. No significant differences within a column were observed when no letters are included

Tuber Measurements

Yield

Daughter tuber total and marketable yield was influenced by the herbicide treatment to mother plants the previous year (Table 11). Daughter plants from mother plants treated with glyphosate at 197 g ha^{-1} and the combination of glyphosate at 197 g ha^{-1} and dicamba at 99 g ha^{-}

^{1}, had reduced 21 and 26% lower total yields, respectively, compared to daughter plants total yield from the non-treated.

Potato tubers grown for chips must fall under the categories, U.S. No. 1. and U.S. No. 2., to be considered marketable (USDA-AMS 1997). Tubers in the U.S. No. 2 category (minimum requirement for marketability) can be no less than 3.81 cm in diameter unless specified by the buyer. Preliminary measurements done before grading showed that tubers in the $<$113 g category was less than 3.81 cm diameter making this category unmarketable. Unmarketable tubers can be eliminated based on size or external and internal defects such as growth cracks or seriously misshapen tubers. The interaction of cultivar and herbicide treatments influenced plant marketable yield. Daughter plants from mother plants treated with glyphosate at 197 g ha^{-1} had 16% lower marketable yields compared to daughter plants from the non-treated. Daughter tubers form mother plants treated with dicamba at 99 g ha^{-1} or the two combinations of glyphosate and dicamba did not affect marketable yield.

Geary (2019) reported that daughter plants from mother plants treated with glyphosate at 197 g ha^{-1}, dicamba at 99 g ha^{-1}, or the combination of glyphosate 197g ha^{-1} and dicamba at 99 g ha^{-1} had marketable or total yields reduced by 33 to 57%. As concluded by Hatterman-Valenti (2014), Hutchinson (2014), and Crook (2016), greater herbicide residues in daughter tubers persist longer and result in greater yield reductions compared to non-treated. For instance, glyphosate can remain stable in tubers for 8 months (Ballingall 2011). The finds suggest that russet potatoes are more sensitive to dicamba and glyphosate, were chipping potatoes are more sensitive to glyphosate alone. Furthermore, seed potato pieces that did not sprout or break down where occasionally found during the harvest and grading process.

Table 11. Total yield and marketable yield, of 'Atlantic' and 'Dakota Pearl' from potatoes treated with glyphosate and dicamba in 2019 at Oakes, ND.

Cultivar		Potato Yield[a]	
		Total Yield	Marketable Yield
		——T ha^{-1}——	
Atlantic		38	30
Dakota Pearl		39	30
Herbicide			
Glyphosate	Dicamba	Total Yield	Marketable Yield
—— g ae ha^{-1} ——		——T ha^{-1}——	
0	0	43 a	31 ab
197	99	34 b	27 bc
40	20	42 a	34 a
0	99	42 a	33 a
197	0	32 b	26 c
P value			
Cultivar		0.5643	0.7705
Herbicide		0.0185	0.0419
Cultivar x Herbicide		0.2031	0.2815

[a]Numbers followed by the same letter in a column are not significantly different according to LS Mean separation comparison at α=0.05. No significant differences within a column were observed when no letters are included

Marketable yield includes U.S. No 1 and U.S No. 2 tubers > 4oz

Tubers Graded

Tubers from both cultivars were graded after harvest into one of four size categories: <133 g, 113-169 g, 170-282 g and >283 g (Table 12). Herbicide applied to mother plants the previous year affected daughter plant tuber production for the tuber weight categories <113 g and 113-169 g. In the category <133 g, the non-treated daughter plants produced more tubers than all other treatments. This result was attributed to the herbicide residues in the daughter tuber seed pieces that reduced the tuber set for the daughter tubers. In contrast, the non-treated daughter plants had greater tuber set on average (9 tubers/plant). Even though non-treated daughter plants were larger than daughter plants with herbicide residues, resources were not sufficient for the additional tubers/plant.

In the category 113-169 g, the daughter plants from mother plants that received glyphosate at 197 g ha^{-1} or the combination of glyphosate at 197 g ha^{-1} and dicamba at 99 g ha^{-1} had fewer tubers compared to the non-treated. In the categories 170-282 and >282 g there was no difference between herbicide treatments.

Table 12. Graded yield of 'Atlantic' and 'Dakota Pearl' after treated with dicamba and glyphosate during tuber initiation growth stage in 2019 at Oakes, ND.

Cultivar (C)		Tuber Weight Category (g)[a]			
		<113	113-169	170-282	>282
		——T ha^{-1}——			
Atlantic		8	15	7	9
Dakota Pearl		9	15	7	8
Herbicide (H)					
Glyphosate	Dicamba	<113	113-169	170-282	>282
—— g ae ha^{-1} ——		——T ha^{-1}——			
0	0	11 a[a]	18 a	7	6
197	99	7 bc	13 b	6	8
40	20	9 b	16 a	8	9
0	99	8 b	16 a	7	9
197	0	6 c	11 b	6	9
P-value					
Cultivar		0.1946	0.6933	0.5755	0.5754
Herbicide		0.0138	0.0135	0.0764	0.1583
Cultivar x Herbicide		0.1871	0.2070	0.2573	0.7631

[a]Numbers followed by the same letter in a column are not significantly different according to LS Mean separation comparison at α=0.05. No significant differences within a column were observed when no letters are included

Conclusion

Emergence and growth of daughter plants was influenced by herbicide applied to mother plant the previous year. For instance, growers that experience sublethal drift rates of glyphosate at 197g ha^{-1}, dicamba at 99 g ha^{-1}, or the combination of glyphosate at 197 g ha^{-1} and dicamba at 99 g ha^{-1} to mother tubers resulted in 20% fewer emerged daughter plants at 8 WAP. Equally noted, daughter plants experienced a 12 to 17% reduction in plant height and 20% reduction in canopy development at 9 WAP when mother plants were treated with glyphosate at 197 g ha^{-1} or the combination of glyphosate at 197 g ha^{-1} and dicamba at 99 g ha^{-1}. Growers could expect a

20% total yield reduction if daughter plants were from mother plants that were exposed to combination of glyphosate at 197 g ha^{-1} and dicamba at 99 g ha^{-1} or glyphosate at 197 g ha^{-1} alone. However, residues in daughter tubers from mother plants treated with only glyphosate at 197 g ha^{-1} resulted in a 16% reduction in marketable yield. Finally, growers who plant clean seed pieces with no herbicide residue may see more small tubers (< 133 g). One explanation for this could be that the non-treated plants produced more tubers, hence, had to allocate a limited amount of nutrients to more tubers. Whereas the daughter plants from mother tubers produced fewer tubers therefore marketable yields did not vary from the non-treated.

Future direction of this research should determine how much herbicide residue was present in the daughter tubers of Atlantic and Dakota Pearl using an ELISA test. Additional research should determine if the glyphosate and/or dicamba are distributed evenly throughout each daughter tuber. This process should help determine how to test a seed lot that may be contaminated with glyphosate and/or dicamba residues. Mother plants subjected to higher glyphosate and/or dicamba concentrations may have daughter tuber seed pieces with delayed emergence and shorter daughter plants, and lower marketable yields. Evaluating off-target damage from herbicides is a difficult situation for all involved. By following the labeled instructions, applicators can minimize off-target herbicide injury.

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