RESPONSE OF RUSSET BURBANK SEED TUBERS CONTAINING GLYPHOSATE AND DICAMBA RESIDUES

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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 introduction of dicamba-tolerant soybean will increase the risk of potato injury to dicamba. The objective was to determine the effects of ‘Russet Burbank’ potato seed tuber emergence and yield that were exposed to dicamba and glyphosate the previous year. Field experiments were conducted in 2016 and 2017 to evaluate seed tubers from mother plants that were treated the previous year with glyphosate (8, 40 and 197 g ae ha^{-1}), dicamba (4, 20 and 99 g ai ha^{-1}) and glyphosate plus dicamba. The highest rates of dicamba (99 g ha^{-1}), glyphosate (197 g ha^{-1}) and the combination of rates caused 17 to 72% reduction in emergence and 23 to 57% reduction in total yield when compared to the non-treated check. Total yield reduction, when glyphosate and dicamba were applied to mother plants, were attributed to a reduced stand. Dicamba and glyphosate can reduce emergence and total production when residue persists in seed potatoes.

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LIST OF ABBREVIATIONS

USDA	United States Department of Agriculture
NASS	National Agriculture Statistics Service
POST	postemergence
PRE	preemergence
pKa	negative base-10 logarithm of the Ka
Koc	sorption coefficient
pH	potential hydrogenii (potential hydrogen)
CEC	cation exchange capacity
OM	organic matter
DAP	days after planting
WAP	weeks after planting
RCBD	randomized complete block design
GR	glyphosate-resistant

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INTRODUCTION

Dicamba-tolerant soybean has resulted in the increased use of dicamba. In North Dakota, soybean acres often exist adjacent to dicamba-susceptible crops, such as dry bean, field pea, sugarbeet, sunflower and potato. Susceptible plants can inadvertently be exposed to herbicides from particle drift, volatilization, contamination of spraying equipment, inversions, contaminated carrier water, mislabeled herbicide containers or misapplication. The potential for glyphosate and dicamba exposure to susceptible crops has increased with the introduction of glyphosate- and dicamba-tolerant soybean. Herbicide injury can result in reduced yield, quality and profits for potato growers (Hatterman-Valenti 2014; Hutchinson et al. 2014; Wall 1994; Coluqhoun et al. 2017; Eberlein et al. 1997)

Potato plants exposed to glyphosate or dicamba the previous year, contained these herbicide residues in the tubers until the following planting season (Hatterman-Valenti 2014; Hutchinson et al. 2014; Wall 1994; Coluqhoun et al 2017). As a result of exposure to dicamba or glyphosate, seed pieces had a delayed emergence or reduced stand and in some cases a yield loss (Hatterman-Valenti 2014; Hutchinson et al. 2014; Coluqhoun et al. 2017). Hatterman-Valenti (2014) reported that the cultivar ‘Russet Burbank’ had a 30 to 59% yield loss when seed tubers were planted back that had received 35 to 71 g ha^{-1} glyphosate (6 to 13% of field use rate) the previous growing season. Colquhoun et al. (2017) studied the effect of low dose rates of thirteen different herbicide treatments on potato seed tubers that were planted the following growing season. The treatment of 6 g ha^{-1} dicamba, 9 and 19 g ha^{-1} glyphosate did not reduce emergence or yield on the daughter tubers that were planted the following year. Glyphosate at 38 g ha^{-1} reduced emergence and overall yield when compared to the non-treated in one of the two years of the study (Coquhoun et al. 2017). Wall (1994) reported that the cultivar ‘Norland’ treated with dicamba at 2.8, 5.6 and 11.1 g ha^{-1} produced only minor injury to potatoes planted the following year, because treatment timing was at 2 weeks after emergence and rates were low. These symptoms were described as slight twisting of the stem and leaf cupping. Less is known about the effect of potato seed tubers contaminated with glyphosate plus dicamba on emergence, growth and yield when planted the following growing season.

The objective of this research was to determine the effects on emergence and yield of planting cultivar Russet Burbank potato seed tubers that were exposed to dicamba and glyphosate the previous year. Results of this study will benefit potato producers, crop consultants, agronomists and research institutions to better understand the adverse effects of glyphosate and dicamba residues in the cultivar Russet Burbank potato seed tubers.

CHAPTER 1. LITERATURE REVIEW

Glyphosate

Glyphosate is a nonselective, postemergence (POST) herbicide used to control annual and perennial weeds in reduced tillage cropping systems, non-crop areas, the home and garden market, crop pre-plant or preemergence burn-down, late-season weed control, or weeds in herbicide-tolerant crops (Anonymous 2012). The development of herbicide-tolerant crops in the 1990s changed glyphosate use in agriculture from a burn-down to an postemergence treatment. Since the introduction of glyphosate resistant (GR) crops in 1996, glyphosate has become the most widely used herbicide in the United States (Gianessi 2004). Glyphosate resistant technology was first introduced with soybean (*Glycine max* L.), but has since expanded to canola (*Brassica napus* L.), cotton (*Gossypium hirsutum* L.), corn (*Zea mays* L.), alfalfa (*Medicago sativa* L.), and sugar beet (*Beta vulgaris* L.). In the United States in 2016, GR soybean and corn represented 94% of soybean and 89% of corn hectares (NASS 2016).

Action and Fate

The primary mode of action for glyphosate is inhibition of the shikimate acid pathway (Sprankle et al. 1975). The shikimate pathway occurs only in plants, fungi and bacteria, and therefore has low animal toxicity (Carlisle and Trevors 1988). Glyphosate works by interfering with aromatic amino acid synthesis (phenylalanine, tryptophan and tyrosine) by binding to and inhibiting 5-enolpyruvyl-shikimate-3-phosphate synthase (Devine et al. 1993). The inhibition of the 5-enolpyruvyl-shikimate-3-phosphate synthase enzyme leads to the disruption of the shikimate acid pathway, which inhibits aromatic amino acid production (Senseman 2007). This process inhibits cell growth and causes plant death.

Although glyphosate successfully inhibits cell growth, absorption is slow and limited in most plant species due to high water solubility (Zollinger et al. 2017). Absorption of glyphosate is affected by ambient temperatures above 25 °C (Masiunas and Weller 1988). Glyphosate was absorbed faster during the first two days and at a greater amount above 20 °C versus 10 °C (Smid and Hiller 1981). When glyphosate contacts plant leaves it must pass through the plant cuticle by diffusion. Thereafter, it is translocated to the phloem where the glyphosate is transported, in a similar manner to plant nutrients, to the meristematic regions of the roots and shoots (Devine et al. 1993). Accumulation of glyphosate is highest at 48 hours after treatment in actively growing young roots and shoots (Sprankle et al. 1975; Bingham et al. 1980). The amount of glyphosate translocated within the plant is based on the amount that contacts the plant and is absorbed, as well as the environmental conditions (Masiunas and Weller 1988).

Glyphosate is a foliar applied herbicide with little to no soil activity because of high adsorption (Schuette 1998). It is bound tightly to soil particles making it unavailable for root uptake. This provides minimum exposure or risk of damage to rotational crops (Duke et al. 2012). Glyphosate is primarily broken down in the soil by microbes to aminomethylphosphonic acid and N-methylglycine metabolites (Torstensson 1985). Glyphosate is then degraded to naturally occurring substances such as carbon dioxide and phosphate (Sviridov et al. 2015).

Under normal environments, glyphosate has a half-life of 47 days, but can vary from 22 to 96 days depending on amount of water applied to the system (Rueppel et al. 1977). Glyphosate is a weak acid herbicide with a pKa value (a quantitative measure of the strength of an acid in solution) of 2.27 for monoanion, 5.58 for the dianion and 10.25 for trianion. Weak acids are compounds that release H+ ions and partially dissociated when mixed in water.

Glyphosate has a high Koc (sorption coefficient) value of 24,000 ml/g and therefore is rapidly adsorbed to soil particles and organic matter.

Injury Symptoms

The first observable symptom of glyphosate is chlorosis in the youngest plant tissue (Devine et al. 1993). The meristematic tissue will become chlorotic and thereafter necrotic. As demonstrated, Sawchuk (2006) observed that dry bean exposure to low doses of glyphosate resulted in chlorosis of the leaves, stunting and delaying the maturity of the plant. Non-lethal glyphosate injury can reduce potato leaf size and internode length (Eberlein et al. 1997) causing damage to the foliage and/or tubers of potatoes depending on the growth stage of the crop (Hutchinson et al. 2014; Crook 2016). Injury severity of potato vines of the cultivar Ranger Russet from least to greatest was 10-cm plants < tuber bulking < tuber initiation < tuber hooking (Felix et al. 2011). In addition to foliar damage, the severity of malformed tubers has also been determined to increase with higher doses of glyphosate (Felix et al. 2011). Potato foliage may have slight to unnoticeable injury or appear to recover from herbicide injury when plants are exposed to low rates of glyphosate (Felix et al. 2011). These low rates can lead to malformed tubers and yield reductions, reducing the value of the crop (Eberlein and Guttieri 1994; Hutchinson et al. 2007).

Previous research reports various effects glyphosate has on tuber recovery. These differences in results are because of treatment timing, cultivar sensitivity and environment. A study that evaluated sub-lethal glyphosate doses on ‘Ranger Russet’ found that plants exposed to glyphosate before tuber initiation recovered better than later application timings when treated with 107 g ha^{-1} glyphosate (Hutchinson et al. 2014). Hutchinson et al. (2014) stated that it is possible that a potato grower could maintain the crop if a small amount of glyphosate was encountered prior to tuber initiation (Hutchinson et al. 2014).

Glyphosate Resistant Weeds

Glyphosate-resistant soybean allows POST treatment of glyphosate, offering farmers broad-spectrum weed control and flexible treatment timing. Due to ease of use and economic benefits, GR crops were widely adopted. There are currently 38 glyphosate-resistant weeds that have been confirmed throughout the world (Heap 2017). Four glyphosate-resistant weeds have been confirmed in North Dakota: common ragweed (*Ambrosia artemisiifolia* L.) in 2007, tall waterhemp (*Amaranthus tuberculatus*) in 2010, kochia (*Kochia scoparia* L.) in 2012 and horseweed (*Conyza canadensis*) in 2015 (Heap 2017; Zollinger et al. 2017). Soybean growers use effective weed management practices to control glyphosate-resistant weeds with current POST herbicides. Soybean growers are encouraged to use preemergence herbicides to help control glyphosate-resistant weeds, but as of 2012 only 8% of growers had adopted this practice in North Dakota (Zollinger et al. 2014).

To address this problem companies are developing soybean plants that are tolerant to additional herbicide chemistries such as dicamba, 2,4-D and hydroxyphenylpyruvate dioxygenase inhibitors. Synthetic-auxin herbicides have been widely used for weed control in corn and cereals for more than 50 years. In cropping systems where weeds have developed resistance to glyphosate, synthetic-auxins could provide another weed management tool.

Dicamba

Dicamba is a selective, synthetic-auxin herbicide which mimics the auxin, indole-3-acetic acid naturally found in most plants (Grossman 2010). Dicamba was registered for commercial use in 1967 (Senseman 2007). It is generally used as a POST treatment to control broadleaf weeds in small grains, corn, and grasses. It is also applied as an early pre-plant or preemergence treatment in corn. Dicamba is currently limited to an early pre-plant application with a 14 to 28 day waiting period depending on formulation and rate in non-dicamba-tolerant soybean (Anonymous 2010).

Action and Fate

Dicamba is a systemic herbicide that moves into the plant from the site of contact and translocates throughout the plant. Dicamba can enter the plant through the leaves, shoots or roots. After absorption, it moves in both the xylem and phloem to areas of high metabolic activity (Gleason 2011) and will accumulate in meristematic tissue of the plant (Stacewicz-Sapuncakis et al. 1973; Chang et al. 1971). Although a complete understanding of auxin herbicide mode of action has not been reached, dicamba mimics auxin hormones and causes abnormal growth by affecting cell division and causing production of ethylene (Devine et al. 1993).

Dicamba has a pKa value of 1.87, therefore, dicamba is in conjugate base form in most soils (Senseman 2007). Dicamba has a Koc value of 2 ml g^{-1} and is weakly adsorbed to the soil and is rapidly degraded (normal half-life of 4.4 days), giving it a low or medium leaching potential (Burnside and Lavy 1966). Dicamba movement in the soil can occur if the degradation rate is reduced in low soil temperatures (Fogarty and Tuovinen 1995). Degradation of dicamba results in the non-herbicidal metabolite 3, 6-dichlorosalicylic acid, that can be readily bound to soils at a pH range of 5.0 to 7.6 (Burnside and Lavy 1966).

Injury Symptoms

Dicamba can move off-target and damage to susceptible plant species (Behrens et al. 1979; Johnson et al. 2012; Robinson et al. 2013). Physical drift, volatility, tank contamination and inversions are some methods plants can be unintentionally exposed to dicamba. Characteristic foliar symptoms of dicamba are epinasty, leaf cupping, strapped veins, and calloused stems or leaves (Grossman 2010). These symptoms are common for most synthetic auxin herbicides. Studies involving non-lethal dicamba doses to off-target soybean and cotton have determined that crop injury is due to susceptibility of these crops to synthetic auxin herbicides (Behrens et al. 1979; Auch and Arnold 1978; Marple et al. 2008). Furthermore, there are millions of hectares planted to dicamba-susceptible crops each year across the United States, compounding the risk of economic loss due to dicamba drift (NASS 2016).

Soybean exposure to dicamba can have a negative effect on growth (Hartzler 2001; Auch and Arnold 1978; Robinson et al. 2013). Injury from dicamba can vary depending upon growth stage of soybean and rate (Auch and Arnold 1978). Soybean plants exposed to dicamba can become malformed and have their morphology altered (Robinson et al. 2013). Auch and Arnold (1978) found that dicamba treatments during vegetative growth affected the new leaf development by causing leaf cupping but did not affect pod and seed production of soybean. Dicamba treatments during flowering or early-pod production caused abnormal pod formation and reduced yield (Auch and Arnold 1978; Robinson et al. 2013). Yield can be affected based on growth stage at time of exposure, rate of dicamba intercepting the plant, and weather conditions (Robinson et al. 2013). Auch and Arnold (1978) concluded that dicamba drift to soybean during the early flowering growth stage resulted in greater reduction in yield than drift during any of the vegetative stages. Robinson et al. (2013) found that less plant injury resulted in a greater yield loss with treatments made at the V5 and R2 stages, compared to treatments at the V2 growth stage. This can be attributed to the movement of dicamba to the growth points and reproductive areas of soybean plants.

There are other examples of dicamba injury to other crops. A previous study evaluated cotton injury and yield as affected by low rates of 2,4-D and dicamba (Marple et al. 2008). Dicamba caused slight stem and petiole epinasty with leaf cupping and general chlorosis of developed leaves at the time of treatment. Cotton growth after dicamba treatment exhibited shoot and petiole epinasty, as well as leaf cupping and stunting (Marple et al. 2008). Marple et al. (2008) revealed that cotton is most susceptible to dicamba exposure at early growth stages. Another study conducted dose-response studies for two tomato (*Solanum lycopersicum* L.) cultivars exposed to glyphosate or dicamba at either the vegetative or early flowering growth stages (Kruger et al. 2011). The tomato cultivars were more susceptible to dicamba than to glyphosate. Exposure to these herbicides at the early flowering stage was more damaging than earlier exposure at a vegetative stage. Research has also been conducted on dicamba exposure to potato (Colquhoun et al. 2017; Wall 1994). Wall (1994) reported that 22 g ha^{-1} of dicamba reduced potato yield by 18% when applied at tuber initiation causing tuber malformations. Colquhoun et al. (2017) reported that 6 g ha^{-1} dicamba did not affect crop injury or yield when compared to the non-treated check.

Herbicide Exposure to Non-Target Crops

Glyphosate and dicamba are used widely to control weeds in production systems. Several GR crops including dicamba-tolerant crops are registered (NASS 2016). The increasing number of fields planted with glyphosate and dicamba tolerant crops will potentially lead to a greater use of dicamba, increasing the risk of exposing susceptible crops. Herbicide injury can cause reduction in yield and profitability, especially in potato (Hatterman-Valenti 2014; Leino and Haderlie 1985). This concern is amplified when growing certified potato seed. Potato can be exposed to glyphosate and dicamba in a variety of ways including herbicide drift, volatility, tank contamination, misapplications, inversions and spot treatments in the field (Robinson and Hatterman-Valenti 2013).

Particle Drift

Particle drift occurs when wind causes spray droplets to be displaced from their intended flight path. Particle drift can occur with any herbicide; however, the risk of damage to non-target plants varies among herbicides. Particle drift is based on the droplet size and selecting the correct nozzle (Peters et al. 2017). Drift can accumulate on the downwind side of a field or in a portion of an adjacent field. Downwind herbicide drift concentrations can vary from 1 to 16% of the target dose (Al-Khatib et al. 2003; Maybank et al. 1978). Environmental conditions other than wind can have an effect on particle drift. Low relative humidity and/or high temperature will cause rapid evaporation which creates smaller spray droplets and increases the chance of drift to occur by decreasing the speed that the droplets are falling (Anderson 1996). Spray particles from areas treated with herbicides can drift with air currents to susceptible, non-target crops.

The amount of drift that occurs can be attributed to wind speed and direction, presence of an air temperature inversion (cold air over warm air), application method, fluid properties, and droplet size. Droplet size is a function of spray volume, nozzle size, and spray pressure (Anderson 1996). Drift can be reduced by increasing droplet size. Spray applicators should choose a nozzle design, orifice size, and operating pressure combination that gives the largest droplet size while still providing adequate coverage. A spray droplet with the diameter size of 5 microns produces a fog-like droplet that can take 66 minutes to fall 3 meters. Comparatively, a larger droplet diameter size of 1,000 microns, similar to rain-like droplets, falls 3 meters in 1 second (ASAE 2009). The American Society of Agricultural Engineers classifies droplet size according to six categories based on size of the droplet (Table 1). The lowest boom height for adequate coverage should be used. Lower vehicle speeds generally reduce drift (Dexter 1993). Treatments should be made when wind speeds are below 16 km h^{-1} (unless label recommends lower), wind direction is away from sensitive crops, inversion conditions are absent and air temperature is below 30 °C (Anonymous 2016a; Anonymous 2016b).

Table 1. Droplet classification based on diameter size of water droplet.

Classification	Approximate VMD microns
Very fine	<100
Fine	100-190
Medium	190-285
Coarse	285-375
Very coarse	375-460
Extremely coarse	>460

Note- Adopted from ANSI/ASAE S572.1 (ASAE 2009).

Vapor Drift

Vapor drift is the movement of pesticides as vapor from the area of treatment after the spray droplets have landed on the target (Behrens and Lueschen 1979). Vapor pressure is the primary predictor of an herbicide’s volatility, and vapor pressure is directly related to temperature (Behrens and Lueschen 1979). Results of studies have shown dicamba volatilization occurring 1 to 3 days after treatment (Auch and Arnold 1978; Wall 1994). Two low-volatile formulations of dicamba were registered in 2017 (Anonymous 2016a; Anonymous 2016b).

Dicamba-BAPMA salt and dicamba-DGA salt plus an anion scavenger, are low volatile formulations registered for dicamba-tolerant crops. These new formulations still pose a risk for off-target movement causing injury to susceptible crops.

Volatility is related to vapor pressure, which is defined as the pressure exerted by a vapor in equilibrium with its liquid or solid phase. The higher the vapor pressure at a given temperature, the more of the material in the vapor phase. Little has been published concerning dicamba's vapor pressure. The *Herbicide Handbook* lists dicamba acid's vapor pressure as $4.5x10^{-3}$ at 25 °C (Senseman 2007). Vapor pressures of dimethylamine (DMA) salt and diglycolamine (DGA) are not published. Behrens and Lueschen (1979) observed DMA salt of dicamba was more volatile than the DGA salt of dicamba. Egan and Mortensen (2012) found that the DGA salt of dicamba is eight times less volatile than the DMA salt of dicamba. Glyphosate has a very low vapor pressure of $2.45x10^{-8}$ at 45 °C (Senseman 2007) and does not volatilize.

Spray applicators can limit the amount of volatility by monitoring environmental conditions and spraying when conditions do not favor volatility. These adverse conditions include: air temperature above 30 °C, conditions of high humidity and fog (Anonymous 2016). Temperatures below 30 °C decrease vapor pressure (Grover 1975). Behrens and Lueschen (1979) found that injury to soybean exposed to dicamba treated corn in closed chambers increased when temperature was raised from 15 to 30 °C, therefore neighboring crops pose a greater risk of volatility drift when spraying or a couple days after spraying, the temperature exceeds 30 °C.

Tank Contamination

Tank contamination is another source of crop injury from herbicides. Growers use the same sprayer to spray multiple crops with varying herbicides. Spray residues can be found throughout the spray system. Clean tank and hoses are required before spraying a susceptible crop or damage may occur to crops that are sprayed following herbicide treatments (Peters 2016). Herbicides, formulates and tank-mixed fertilizers, and adjuvants can remove auxin herbicide residue from the spray system (VanGessel 2008; Steckel et al. 2005).

Russet Burbank

The cultivar Russet Burbank was discovered in the 1870s by Luther Burbank. It developed from a first-generation seedling of an open-pollinated cultivar Early Rose in Massachusetts (Crop Watch 2017). ‘Russet Burbank’ was originally released in 1902 as May’s Netted Gem by L.L. May & Co. (St. Paul MN) (Bethke et al. 2014). The names Netted Gem and Russet Burbank were used synonymously for many decades. The ‘Russet Burbank’ has become the major cultivar grown in the United States. In 2015, ‘Russet Burbank’ accounted for 41% of potatoes grown in the United States (NASS 2015). ‘Russet Burbank’ was the top cultivar produced in 2016 at 39% of North Dakota and 64% of Minnesota potato production (NASS 2016). The two major uses for ‘Russet Burbank’ are french fries and fresh potatoes.

‘Russet Burbank’ is a long season cultivar. It has a long dormancy, five months at 7 °C (Stark and Love 2003). The success of this variety is based on its high culinary acceptance in the fresh market, its long storage life and its excellent quality for processed french fries. Plant characteristics are indeterminate growth habit, large and upright spreading vines, and medium tuber set. The tubers are long, with shallow eyes, russet-skin and white flesh (Bethke et al. 2014).

Growth of a potato plant occurs in many stages (Dwelle and Love 2003). Sprout development is the first stage that occurs after planting, where the eyes on the seed piece begin to develop into sprouts that will emerge from the soil to become the stems. The eyes that express apical dominance will be the first to sprout. Roots will begin to form at the base of the emerging sprouts (Dwelle and Love 2003). Once sprouts emerge, photosynthesis and vegetative growth begins, and the leaves and branches develop from above-ground nodes. Tuber initiation begins when tubers start to form at the ends of the developed stolons; this stage can be hastened by plant stress. In this stage, the tubers are present but are not enlarging. This stage is often coupled with early flowering in many cultivars but the relationship is not related. After tuber formation, tubers begin to bulk in size by an expansion of cells with the accumulation of water, nutrients and carbohydrates. The tubers become the dominant site of nutrient deposit. Nearing the end of the season, unless 'Russet Burbank' is overcome with disease or is limited by nutrients, it will only senesce if desiccated, shredded or frozen.

Dormancy is the final stage of tuber life serving to preserve tubers as organs of vegetative reproduction under unfavorable growing conditions. Dormancy length varies for potato cultivars from a few weeks to 130 days, depending on holding temperature in storage and genetic disposition (Kleinkopf 2003). Dormancy is the regulation of bud development on the tubers. Once dormancy is broken, the buds begin to sprout.

Seed Production

Commercial potato production is achieved through vegetative-propagated plant material to maintain cultivar purity. A potato tuber is used as the propagative unit, rather than a true seed typically used for most cultivated crops. Vegetative propagation is necessary because potato is a tetraploid. However, this makes the process of seed production challenging because the management of seed-borne diseases is necessary for each seed generation (Sieczka et al. 2010). Many pathogens present in the propagative material can easily be transmitted to the progeny and be present when the seed is planted the following growing season. Viruses and bacterial diseases can transfer from generation to generation; therefore, seed is only allowed to be used for a limited number of generations to reduce disease potential. Cutting seed can also spread diseases through contaminated knives or open wounds. When potato seed is cut, surfaces are open wounds that provide opening for pathogenic organisms from other tubers or external sources a route for infecting the seed piece. Suberization, or skin healing will prevent disease entry.

The potato industry of North America provides potato seed stocks that are relatively free of disease-causing organisms and have cultivar purity, through an elaborate seed potato certification system. Seed potato certification in North America was first discussed in 1914 during the first annual meeting of the Potato Association of America. Twelve states and all Canadian provinces were engaged in seed potato certification by 1920 (Seiczka et al. 2010). In the United States, seed potato certification is the responsibility of each state with legal authority to carry out certification given to the land-grant university within the state, the state department of agriculture or through grower associations. The certification agency is responsible for conducting all required field, storage and shipping-point inspections. This practice is implemented to protect the potato industry, seed and commercial, from disease epidemics.

The North Dakota State Seed Department is one example of effective seed certification and was established in 1931 to work in conjunction with a variety of affiliates within the state to certify potato seed (NDSSD 2008). North Dakota has the second largest seed potato production program in the United States, certifying and inspecting an average of 6,100 hectares of seed potato cultivars annually (NDSSD 2008). A seed potato grower is subjected to three inspections during the growing season, testing and strict certification tolerances prior to being an approved certified seed grower. Three inspections are conducted at various times during the growing season to maximize the opportunity to detect seed-borne disease and pest problems, which can affect the crop the following year. After each lot is found to meet field inspection tolerances and other applicable rules and regulations, the grower is permitted to harvest and store the crop for seed. Certified seed production programs in the United States have been successful in limiting cultivar mixing and disease problems (Seiczka et al. 2010). Currently there are no specific regulations when it comes to glyphosate and dicamba damage, however, seed inspectors look for chemical damage.

Effects of Herbicide Residue in Seed

Herbicide residues have been found to affect progeny of plants contaminated by off-target herbicides. Glyphosate caused a decrease in germination and emergence in potato, soybean and wheat exposed to the herbicide the previous year (Hatterman-Valenti 2014; Hutchinson et al. 2014; Hatterman-Valenti and Robinson 2013; Norsworthy 2004; Blackburn and Boutin 2003; Yenish and Young 2000). Growth stage when the crop is exposed to the off-target herbicide will cause varied results to the seed emergence and yield the following year (Hatterman-Valenti 2014; Hutchinson et al. 2014; Norsworthy 2004). Since herbicide accumulation follows the same path of nutrient source-to-sink translocation, crops exposed to off-target herbicides during tuber bulking or seed formation will have more severe effects the following year compared to plants in the vegetative stage that are exposed to herbicides (Smid and Hiller 1981).

The first glyphosate exposure to potato was recorded by Worthington in 1985. Worthington (1985) reported the effect of glyphosate on the viability of seed potato tubers and concluded that glyphosate treatments applied to potato five weeks before harvest, adversely affected the growth of the harvested tubers planted the following season. Worthington (1985) reported delayed emergence and plants with distorted leaves when the mother plant was treated with 180 g ha^{-1} glyphosate.

Research has reported the effects of glyphosate on potatoes grown for seed that were exposed to glyphosate in North Dakota as well as the Pacific Northwest. Hutchinson et al. (2014) studied the effects of glyphosate contact to various growth stages of cultivar Ranger Russet. The results of the study demonstrated that glyphosate treatments at the mid-bulking stage caused seed planted back the next year to have low vigor, foliar chlorosis and stunting damage compared to earlier treatments at vegetative or hooking stages that did not cause damage to seeds. As the glyphosate rate applied to the mother crop increased above 54 g ha^{-1}, daughter tuber U.S. No. 1 yields as a percentage of total tuber yield decreased compared to the non-treated (Hutchinson et al. 2014).

Hatterman-Valenti (2014) discovered that the cultivar Red LaSoda expressed sprout inhibition when exposed to sub-lethal rates of 71 to 282 g ha^{-1} glyphosate during the late bulking growth stage. The seed tubers from the mother plant's leaves exposed to at least 71 g ha^{-1} glyphosate were described as having numerous sprouts emerging from a single eye in a cauliflower-curd fashion. Seed tubers that had received 282 g ha^{-1} glyphosate did not have any sprout emergence throughout the growing season (Hatterman-Valenti 2014). Other symptoms were delayed emergence with distorted leaflets, but the symptoms varied widely and did not appear to be affiliated with a specific glyphosate dose. Compared to the non-treated control, yield was reduced by 48% when treated with 71 g ha^{-1} glyphosate the previous year and 58% when treated 282 g $ha^{-}1$ glyphosate the previous year (Hatterman-Valenti 2014). A reduction in yield was associated with smaller and fewer tubers.

Glyphosate contamination in wheat seed has proven to be an issue with decreased emergence when exposed to over 300 g ha^{-1} glyphosate the previous year (Yenish and Young 2000). ‘Alpowa’ had a reduction in germination by 46% compared to the non-treated check, when evaluated at 2 weeks after planting (Yenish and Young 2000). The study concluded that wheat seed following pre-harvest glyphosate treatments were most greatly influenced by crop maturity stage at time of treatment than by herbicide rate (Yenish and Young 2000).

Studies have been performed to determine the effects of glyphosate on soybean seed (Azlin and McWhorter 1981; Whigham and Stoller 1979). A study from 1975 to 1976 demonstrated that 1.7 and 3.4 kg ha^{-1} glyphosate treatment two weeks prior to harvest reduced seed germination by 20 to 35% when compared to the non-treated soybean seeds (Whigham and Stoller 1979). The study suggested that glyphosate should not be used as a desiccant if the seeds were to be used for planting future crops, hypothesizing that the herbicide remained in the seed (Whigham and Stoller 1979). Azlin and McWhorter (1981) found treatment timing and treatment rate determined what effect, if any, glyphosate had on the soybean plant and seeds. Soybean plants treated with 3.4 kg ha^{-1} applied three weeks before harvest reduced germination by 30% of the non-treated control when planted the following year.

Dicamba can negatively affect potato plants and daughter tubers planted the following year. Wall (1994) reported that the cultivar Norland treated with dicamba produced only minor injury to potatoes planted the following year. This was likely because treatment timing was at two weeks after emergence and rates were low (2.8, 5.6 and 11 g ha^{-1} dicamba). These symptoms were described as slight twisting of the stem and leaf cupping. In another study, Haderlie et al. (1986) reported reduced emergence, stunting and epinasty in plants from 'Russet Burbank' tubers when 22 and 44 g ha^{-1} dicamba treatments were applied to the soil the previous year.

Dicamba-tolerant soybeans have been planted since 2016 in the United States and adoption of this technology is expected to increase dicamba use to combat the increasing glyphosate-resistant weed problems. Dicamba can drift and cause crop injury from volatility and spray tank contamination (Behrens and Lueschen 1979; Calhoun et al. 2017). Glyphosate drift injury has occurred since the release of glyphosate-tolerant crops in the mid 1990s (Blackburn and Boutin 2003). Glyphosate drift can reduce crop yield and negatively affect progeny (Crook 2016; Hatterman-Valenti 2014; Hutchinson et al. 2014). The Environmental Protection Agency has set 20 ppm as the maximum residue level for glyphosate in potato (EPA 2017). Currently, there is no research that is published with effects of irrigated 'Russet Burbank' seed tubers that are contaminated with glyphosate and dicamba. There are two main questions that need to be investigated concerning glyphosate and dicamba herbicide residue in potato seed:

1) Dicamba contamination rates and associated yield reduction on the cultivar 'Russet Burbank' potatoes grown for seed.
2) The effect of glyphosate and dicamba tank mixtures on the cultivar 'Russet Burbank' potatoes grown for seed.

Literature Cited

Al-Khatib K, Claassen M, Stahlman P, Geier P, Regehr D, Duncan S, Heer W (2003) Grain sorghum response to simulated drift from glufosinate, glyphosate, imazethapyr, and sethoxydim. Weed Technol. 17:261-265

[ASAE] American Society of Agricultural Engineers (2009) Standard S572.1: Spray nozzle classification by droplet spectra. St. Joseph, MI: ASABE

Anderson, W (1996) Methods of weed control in Weed Science: Principles and Applications. West Publishing Company. Minneapolis/St. Paul. p. 39-66

Anonymous (2010) Clarity® herbicide label. Research Triangle Park, NC: BASF Agricultural Products

Anonymous (2016a) Engenia® herbicide label. Research Triangle Park, NC: BASF Agricultural Products

Anonymous (2012) Roundup PowerMax® label 63027KS-10. Monsanto Co. 800 North Lindburg Boulevard, St. Louis, MO 63167. p.26

Anonymous (2016b) Xtendimax with VaporGrip Technology® label. Monsanto Co. 800 North Lindburg Boulevard, St. Louis, MO

Auch D, Arnold W (1978) Dicamba use and injury on soybeans (*Glycine max*) in South Dakota. Weed Sci. 26:471-475

Azlin W, McWhorter C (1981) Preharvest effects of applying glyphosate to soybeans (*Glycine max*). Weed Sci. 29:123-127

Behrens R, Lueschen W (1979) Dicamba volatility. Weed Sci. 27:486-493

Bethke P, Nassar A, Kubow S et al. (2014) History and Origin of Russet Burbank (Netted Gem) a Sport of Burbank. Am. J. Potato Res. 91:594-609

Bingham S, Segura J, Foy C (1980) Susceptibility of several grasses to glyphosate. Weed Sci. 28:579-585

Blackburn L, Boutin C (2003) Subtle effects of herbicide use in the context of genetically modified crops: a case study with glyphosate. Ecotoxicology 12:271-285

Burnside O, Lavy T (1966) Dissipation of Dicamba. Weeds 14:211-214 doi:10.2307/4040915

Carlisle S, Trevors J (1988) Glyphosate in the environment. Water, Soil and Air Pollution 39:409-420

Chang F, Born W (1971) Translocation and metabolism of dicamba in Tartary Buckwheat. Weed Sci. 19:107-112

Colquhoun J, Heider D, Rittmeyer R (2017) Seed potato growth and yield as affected by mother plant exposure to herbicides. Weed Technol. 31:136-147

Crook A (2016) Simulated glyphosate drift effects on ‘Red Norland’ commercial and seed potato industries. North Dakota State University Thesis

Crop Watch (2017) Russet Burbank: Characteristics. Available at http://cropwatch.unl.edu/potato/russetburbank. Accessed 27 April 2017 University of Nebraska-Lincoln. Lincoln, NE

Devine M, Duke S, Fedtke C (1993) Physiology of Herbicide Action. Englewood Cliffs, NJ: Prentice-Hall, Inc. Chapter 13. 252-263

Dexter A (1993) Herbicide spray drift. North Dakota St. Univ. Ext. Serv. Rep. A-657

Duke S, Lydon J, Koskinen W, Moorman T, Chaney R, Hammerschmidt R (2012) Glyphosate effects on plant mineral nutrition, crop rhizosphere microbiota, and plant disease in glyphosate-resistant crops. J Agric. Food Chem. 60:10375-10397

Dwelle R, Love S (2003) Plant growth and development. p. 9-11. In Stark J and Love S. (eds) Potato Production Systems. University of Idaho. Agricultural Communications, Moscow, Idaho.

Eberlein C, Guttieri M (1994) Potato (*Solanum tuberosum*) response to simulated drift of imidazolinone herbicides. Weed Sci. 42:70-75

Eberlein C, Westra P, Haderlie L, Whitmore J, Guttieri M (1997) Herbicide drift and carryover injury in potatoes. Pacific Northwest Extension Publ. 498.

EPA (2017) Regulation of Pesticide Residues on Food. United States Environmental Protection Agency. https://www.epa.gov/pesticide-tolerances. Accessed 9 November 2017

Felix J, Boydston R, Burke I (2011) Potato response to simulated glyphosate drift. Weed Technol. 25:637-644

Fogarty A, Tuovinen O (1995) Microbiological degradation of the herbicide dicamba. Journal of Industrial Microbiology 14:365-370

Gianessi LP (2004) Economic and herbicide use impacts of GR crops. Pest Manag. Sci. 61:241-245

Gleason C, Foley R, Singh K (2011) Mutant analysis in *Arabidopsis* provides insight into the molecular mode of action of the auxinic herbicide dicamba. PloS One 6:172-180

Grossmann K (2010) Auxin herbicides: Current status of mechanism and mode of action. Pest Manag. Sci. 66:113-120

Grover R (1975) A method for determining the volatility of herbicides. Weed Sci. 23: 529-532

Haderlie L, Petersen P, Leino P (1986) Potato seed vigor and yield potential following herbicide drift or carryover. Res. Prog. Rep. West. Soc. Weed Sci. 324-327

Hatterman-Valenti H (2014) Simulated Glyphosate Drift to Potato Mother Plants and Effect on Daughter Tubers Used for Seed Production. Weed Technol. 28: 253-258

Heap I (2017) The International Survey of Herbicide Resistant Weeds. Available at http://www.weedscience.org. Accessed September 20, 2017

Hutchinson P, Felix J, Boydston R (2014) Glyphosate Carryover in Seed Potato: Effects on Mother Crop and Daughter Tubers. American Journal of Potato Research. 91: 394-403

Hutchinson P, Morishita D, Price W (2007) Season-long dose-response of potato to sulfometuron. Weed Sci. 55: 521-527

Johnson V, Fisher L, Jordan D, Edmisten K, Stewart A, York A (2012) Cotton, peanut, and soybean response to sublethal rates of dicamba, glufosinate, and 2.4-D. Weed Technol. 26: 195-206

Kleinkopf G, Oberg N, Olsen N (2003) Sprout inhibition in storage: Current status, new chemistries and natural compounds. American Journal of Potato Research 80:317-327

Leino P, Haderlie L (1985) Simulated Herbicide Drift Injury in Potatoes. Proc. West. Soc. Weed Sci. 38: 93-99

Marple M, Al-Khatib K, Peterson D (2008) Cotton injury and yield as affected by simulated drift of 2,4-D and dicamba. Weed Technol. 22:609-614

Masiunas J, Weller S (1988). Glyphosate activity in potato (*Solanum tuberosum*) under different temperature regimes and light levels. Weed Sci. 36:137-140

Maybank J, Yoshida K, Grover R (1978) Spray drift from agricultural pesticide applications. J. Air Pollution. 28:1009-1014

[NASS] National Agricultural Statistics Service (2016) Acreage. Available at http://usda.mannlib.cornell.edu/usda/current/Acre/Acre-06-30-2016.pdf. Accessed 17 Nov. 2016

[NASS] National Agricultural Statistics Service (2016) Fall Potato Varieties Planted. Available at http://usda.mannlib.cornell.edu/usda/nass/cropprod//2010s/2016/cropprod-12-09-2016.pdf. Accessed 27 April 2017

[NASS] National Agricultural Statistics Service (2015) Fall Potato Acreage by Variety. Available at https://nass.usda.gov/statistics_by_state/Idaho/publications/crops_press_releases/2015/PT_VAR_12_01.pdf. Accessed 27 April 2017

[NDSSD] North Dakota State Seed Department (2008) Potato Program. Available at http://www.nd.gov/seed/potato/index.aspx. Accessed 21 June 2017 Fargo, ND

Norsworthy J (2004) Conventional soybean plant and progeny response to glyphosate. Weed Tech. 18:527-531

[PAA] The Potato Association of America (2017) Russet Burbank (*Solanum tuberosum*). Available at http://potatoassociation.org/industry/varieties/russet-potato-varieties/russet-burbank-solanum-tuberosum. Accessed 27 April 2017

Peters T (2016) Sprayer Cleanout: Avoiding Crop Injury due to Contamination. North Dakota State Univ. Ext. Serv., Fargo

Peters T, Thostenson A, Nowatzki J, Hofman V, Wilson J (2017) Selecting Spray Nozzles to Reduce Particle Drift. Bull. AE1246. North Dakota State Univ. Ext. Serv., Fargo

Robinson A, Hatterman-Valenti (2013) Effect of glyphosate on potatoes. Bull. A1642. North Dakota State Univ. Ext. Serv., Fargo

Robinson A, Simpson D, Johnson W (2013) Response of glyphosate-tolerant soybean yield components to dicamba exposure. Weed Sci. 61:526-536

Rueppel M, Brightwell B, Schaefer J, Marvel J (1977) Metabolism and degradation of glyphosate in soil and water. J. Agric. Food Chem. 25:517-528

Sawchuk J, Van Acker R, Friesen L (2006) Influence of a Range of Dosages of MCPA, Glyphosate, and Thifensulfuron: Tribenuron (2:1) on Conventional Canola (*Brassica napus*) and White Bean (*Phaseolus vulgaris*) Growth and Yield. Weed Technol. 20: 184-197

Senseman S (2007) Herbicide Handbook. Lawrence, KS: Weed Science Society of America

Schuette J (1998) Environmental fate of glyphosate. Environmental Monitoring & Pest Management Department of Pesticide Regulation

Sieczka J, Thornton B, McMorran J, Mosley A (2010) Early generation seed potato production and certification. Commercial potato production in North America. Potato Association of America

Smid D, Hiller L (1981) Phytotoxicity and translocation of glyphosate in the potato (*Solanum tuberosum*) prior to tuber initiation. Weed Sci. 29:218-223

Sprankle P, Meggitt W, Penner D (1975) Absorption, action, and translocation of glyphosate. Weed Sci. 23:235-240

Stacewicz-Sapuncakis M, Vengris J, Marsh H, Jennings P, Robinson T (1973) Response of common purslane to dicamba. Weed Sci. 21:385-389

Stark J, Love S et al. (2003) Potato Production Systems. University of Idaho. Agricultural Communications, Moscow, Idaho

Steckel L, Chism C, Thompson A (2005) Cleaning plant growth regulator (PGR) herbicides out of field sprayers. University of Tennessee Extension. 05-0167 W071. Accessed 9 November 2017

Sviridov A, Shushkova T, Ermakova I, Ivanova E, Epiktetov D, Leontievsky A (2015) Microbial Degradation of Glyphosate Herbicides (Review). Applied Biochemistry and Microbiology. 51: 188-195

Thompson L, Egli D (1973) Evaluation of seedling progeny of soybeans treated with 2,4-D, 2,4-DB and dicamba. Weed Sci. 21:141-144

Torstensson L (1985) Behavior of glyphosate in soils and its degradation. In E. Grossbard & D. Atkinson (Eds.), The herbicide glyphosate (137-150). London, U.K.: Butterworh & Co., Ltd

[USDA] U.S. Dep. Agriculture. 2012. Pesticide use and market. Economic Research Service. Available at http://www.ers.usda.gov/topics/farm-practices-management/chemical-inputs/pesticide-use-markets.aspx. Accessed Nov. 5, 2016

VanGessel M (2008) Sprayer clean-out guidelines: reducing crop injury due to herbicide contamination. University of Delaware Cooperative Extension. WF-8-01/08

Wall D (1994) Potato (*Solanum tuberosum*) response to simulated drift of dicamba, clopyralid, and tribenuron. Weed Sci. 42:110-114

Whigham D, Stoller E (1979) Soybean desiccation by Paraquat, Glyphosate, and Ametryn to accelerate harvest. Agronomy J. 71:630-633

Worthington T (1985) The effect of glyphosate on the viability of seed potato tubers. Potato Res 28:109-112

Yenish J, Young F (2000) Effect of preharvest glyphosate application on seed and seedling quality of spring wheat (*Triticum aestivum*) Weed Tech. 14:212-217

Zollinger R, Christoffers M, Dalley C, Endres G, Gramig G, Howatt K, Jenks B, Lym R, Ostlie M, Peters T, Robinson A, Thostenson A, Valenti HH (2017) North Dakota Weed Control Guide. North Dakota State Univ Ext Serv Publ W-253. p.71

Zollinger R, Markell S, Knodel J, Gray J, Jantzi D, Hagemeister K, Kilpatrick P (2014) Pesticide use and pest management practices in North Dakota, 2012. Bull. W1711. North Dakota State Univ. Ext. Serv., Fargo

CHAPTER 2. EVALUATION OF RUSSET BURBANK SEED EXPOSED THE PREVIOUS GROWING SEASON TO LOW RATES OF GLYPHOSATE AND DICAMBA

Abstract

Dicamba use in dicamba-tolerant soybean may increase the risk of potato seed tubers affected by glyphosate or dicamba if mother plants are exposed to glyphosate or dicamba. The objective of this study was to determine the effects of planting ‘Russet Burbank’ potato seed tubers from mother plants that were exposed to dicamba (4 to 99 g ae ha^{-1}), glyphosate (8 to 197 g ae ha^{-1}) and the combination of dicamba and glyphosate during tuber initiation the previous growing season. Daughter tubers were planted back near Oakes and Inkster, North Dakota in 2016 and 2017, at the same research farm they were grown the previous year. The highest rates of dicamba (99 g ha^{-1}), glyphosate (197 g ha^{-1}) and the combination caused 17 to 72% reduction in emergence and 23 to 57% reduction in total yield when compared to the non-treated check. Dicamba applied at 20 g ha^{-1} (2% of the recommended field use rate), reduced yield 11 to 33%. Total yield reduction, when glyphosate and dicamba were applied to mother plants, were attributed to a delayed and reduced stand. Dicamba and glyphosate can reduce emergence and total production when residues are carried over in seed potatoes. ‘Russet Burbank’ was more susceptible to dicamba than glyphosate.

Introduction

Injury to parent plants from glyphosate and dicamba have caused a decrease in germination and emergence in potato, soybean, dry bean and wheat (Hatterman-Valenti 2014; Hutchinson et al. 2014; Hatterman-Valenti and Robinson 2013; Norsworthy 2004; Blackburn and Boutin 2003; Yenish and Young 2000). Dicamba-tolerant cultivars of soybean and cotton will allow dicamba and glyphosate to be applied during the cropping season to control hard-to-kill broadleaf weeds and glyphosate-resistant weeds. The potential contact of susceptible crops to these chemicals increases as applications will be allowed through the R1 soybean growth stage. For example, in 2016 and 2017 there have been several thousands of acres of crops injured or destroyed by dicamba (Bradley 2017; Barber et al. 2017). Minor crop producers and USDA have expressed concern that off-target movement through volatility, particle drift or spray tank contamination could result in crop injury, yield reduction and pesticide residue issues (Anonymous 2016a; Anonymous 2016b; USDA-ARS 2015).

Potato production in 2015 totaled 22.4 million metric tons in the United States valued at \$3.7 billion on about 404,000 ha (USDA-NASS 2017). North Dakota ranked fourth in overall potato production, which totaled 1.1 million metric tons and the crop valued at \$222 million (National Potato Council 2017). This value is dependent on consistent successful commercial potato production, which begins with the availability of high-quality seed. North Dakota has the second largest seed potato production program in the United States, certifying and inspecting an average of 6,100 ha of seed potato cultivars annually (NDSSD 2008). ‘Russet Burbank’ is the most widely grown potato for seed in the United States (National Potato Council 2017).

A number of studies report the effects of glyphosate on potato when treated during the growing season (Colquhoun et al. 2014; Hatterman-Valenti et al. 2017; Hatterman-Valenti 2014; Hutchinson et al. 2014; Worthington 1985; Wall 1994). Worthington (1985) reported the effect of glyphosate on the viability of seed potato tubers and concluded that glyphosate treatments applied to a growing crop of potatoes adversely affected the growth of the harvested tubers planted the following season by germination inhibition. Hatterman-Valenti (2014) reported that the cultivar Red LaSoda expressed more than 80% sprout inhibition when exposed to 71 to 282 g ha^{-1} glyphosate during the late bulking growth stage. Hutchinson et al. (2014) evaluated the effect of glyphosate treatments (8.5, 54, 107, 215 and 423 g ha^{-1}) applied to the cultivar Ranger Russet at 10- to 15-cm plant height, stolon hooking, tuber initiation and mid-bulking. Glyphosate treatments at mid-bulking caused the least foliar injury, but reduced daughter tuber emergence the most among treatment timings. ‘Ranger Russet’ exposed to 107 to 423 g ha^{-1} glyphosate at tuber initiation had a 40 to 55% decrease in yield when compared to the untreated plants. However, Colquhoun et al. (2017) found that treatments at tuber initiation of 9 to 38 g ha^{-1} glyphosate on ‘Russet Burbank’ mother plants when planted back caused up to 30% foliar injury, but no total yield loss.

The effects of dicamba on mother plants and subsequent tuber seed pieces has shown dicamba can carryover in potato tubers. Wall (1994) reported that treatments of 2.8, 5.6 and 11.1 g ha^{-1} dicamba at 2 weeks after emergence on the cultivar Norland produced 6% visual foliar injury to potatoes when daughter tubers were planted the following year. These symptoms were described as slight twisting of the stem and leaf cupping but did not affect yield (Wall 1994). Colquhoun et al. (2017) found that a treatment of 6 g ha^{-1} dicamba on mother plants when planted back did not reduce stand density or yield in either year of the study.

Differing results from herbicide injury studies on potato could be explained by environmental conditions. Masiunas and Weller (1988) reported that plants grown at 25/13 °C temperature regimes showed more phytotoxicity from glyphosate treatments than plants grown at 13/4 °C temperature regimes. Smid and Hiller (1981) observed similar symptoms to Masiunas and Weller (1988) when potato was exposed to glyphosate and reported that translocation patterns were symplastic. Multiple low dose herbicide studies suggest that differing environments during time of treatment may cause differences in susceptibility to sub-lethal doses applied to non-target crops (Al-Khatib and Tamhane 1999; Hatterman-Valenti 2014; Hatterman-Valenti et al. 2017).

Successful commercial potato production begins with the availability of high-quality seed. Glyphosate residue within seed tubers has been shown to decrease emergence and crop quality for russet-skinned potato cultivars grown in irrigated and dryland conditions (Hatterman-Valenti, 2014; Hutchinson et al. 2014). However, there is less known of the effects of dicamba and dicamba plus glyphosate on 'Russet Burbank' seed tubers when the mother plant is exposed to these herbicides. The objective of this study was to determine the effects of dicamba, glyphosate and the combination of dicamba and glyphosate residues in seed tubers on emergence and yield.

Materials and Methods

Field experiments were conducted at the NDSU Oakes Irrigation Research Site near Oakes, North Dakota (46.07 N, -98.09 W; elevation 392 m) and at the Northern Plains Potato Growers Association Irrigation site near Inkster, North Dakota (48.16 N, -97.43 W; elevation 314 m). Soil type at Oakes was an Embden coarse-loamy, mixed, superactive, frigid Pachic Hapludolls (14% clay, 70% sand, 16% silt). Soil at Inkster was an Inkster coarse-loamy, mixed, superactive, frigid Pachic Hapludolls (15% clay, 66% sand, 19% silt) (USDA-NRCS 2017). Studies were conducted from 2015 to 2016 and from 2016 to 2017. In the first year of the study, mother plants (experimental generation 1) were grown and treatments were applied at tuber initiation. In the second year, progeny from mother plants (experimental generation 2) were planted at the same research farm, but in a different location to ensure a four-year potato rotation.

The experimental methods used for experimental generation 1 in 2015 was described by Hatterman-Valenti et al. (2017). A similar experimental method was used in 2016 for the experimental generation 1. The experiment was set up as a randomized complete block design with four replicates and ten treatments consisting of a non-treated check, dicamba (Clarity®, BASF Corporation, Research Triangle Park, NC, 27709) and glyphosate (PowerMax®, Monsanto Company, St. Louis, MO, 63167) (Table 2).

Table 2. Glyphosate and dicamba treatments applied to Russet Burbank potatoes in Oakes and Inkster, ND.

#	Treatment	Herbicide rate
		g ae ha^{-1}
1	Non-treated	0
2	Glyphosate	8
3	Glyphosate	40
4	Glyphosate	197
5	Dicamba	4
6	Dicamba	20
7	Dicamba	99
8	Glyphosate	8
	Dicamba	4
9	Glyphosate	40
	Dicamba	20
10	Glyphosate	197
	Dicamba	99

Experimental Generation 1

Seed pieces were planted on June 10, 2015 and May 18, 2016 at Inkster, ND; and on May 22, 2015 and May 5, 2016 at Oakes, ND. Treatments occurred at tuber initiation and were applied in progression from lowest to highest dose to the two middle rows of the experimental plots. The glyphosate and dicamba rates were selected to represent the ratio for the proposed dicamba plus glyphosate if tank mixed at different concentrations that could be plausible for drift or tank contamination. The glyphosate doses represented 1, 5 and 23% of the field use rate of 846 g ae ha $^{-1}$ (Table 2). The dicamba doses represented 0.3, 2 and 9% of the field use rate of 1120 g ae ha^{-1}. All treatments were applied to the center of the plots with a 1.8-m-wide boom equipped with XR11002 flat fan nozzles (TeeJet Spraying Systems Company, Wheaton, IL 60189) in 140 L ha^{-1} carrier volume using a CO_2-pressurized backpack sprayer at 138 kPa. In 2015, the treatments were applied on July 30, at Inkster and July 7, at Oakes. In 2016, they were applied on July 6, at Inkster and on June 28, at Oakes. An average daily maximum temperature of 28 °C and minimum temperature of 15 °C occurred at Inkster 2015 and Oakes 2016 on the day of application of the treatments. Conversely, an average daily maximum temperature of 24 °C and minimum temperature of 10 °C occurred at Oakes 2015 and Inkster 2016 on treatment dates. The two center rows in every plot were harvested with a custom built, single-row mechanical harvester. Following grading, tubers from each experimental plot were stored as individual plot samples over the winter, in a 2.2 °C potato seed storage with 90-95% relative humidity.

Experimental Generation 2

Seed pieces were planted in a randomized complete block design with four replications. In the second year, stored tubers from experimental generation 1 were warmed to 10 °C at 90-95% relative humidity. Fifty seed tubers were arbitrarily selected from each stored plot sample and cut into 70 g ± 5 g seed pieces. Each seed piece was cut from a different tuber to expand variability among seed pieces. Seed were planted at 30 cm spacing within-row and 90 cm between rows with a seed depth of 12 cm. Plots were planted in a different location on the research farm to ensure a four-year potato rotation to reduce potential problems with soil-borne diseases. In 2016, seed was planted on May 5, in Oakes, ND and on May 18, at Inkster, ND. In 2017, planting occurred on May 12, in Oakes, ND and June 2, in Inkster, ND. The plots were maintained according to North Dakota State University recommended potato production standards (Bissonnette et al. 1993).

Emergence and plant height data were collected at five and eight weeks after planting (WAP). Visual injury data was not reported because previous work has indicated that visual injury estimates does not accurately estimate yield loss (Colquhoun et al. 2017). All plots were desiccated with diquat (Reglone®, Syngenta Crop Protection, LLC, Greensboro, NC 27419) at two and three weeks before harvest. Oakes was harvested on September 13 in 2016 and 2017. Inkster was harvested on September 30, 2016 and October 6, 2017. The two center rows of each experimental plot were harvested with a custom built single-row mechanical harvester. Thereafter, tuber yield and quality were determined according to USDA grading standards (Anonymous 1991; USDA 2011). One row was weighted and discarded and the other row was graded for size and quantity, and separated into <113, 113-170, 171-283, 284-397, >397 g tuber categories. The percentage of tubers in each size class was adjusted to represent the total yield from the harvested rows. Total marketable yield was calculated as a summation of tubers >113 g.

Data Analysis

The data collected met the assumptions of normally and equally distributed data by the Shapiro-Wilk test and were subjected to analysis of variance using PROC MIXED procedure using SAS 9.4 (Statistical Analysis Software, version 9.4. SAS Institute Inc., 100 SAS Campus

Dr., Cary, NC 27513). Year and location combinations were considered an environment sampled at random, as suggested by Carmer et al. (1989) and Blouin et al. (2011). Because temperature differences when treated, there was an environment by treatment interaction and data were pooled according to the two varying environments as was done by Solomon and Bradley (2014) and Blouin et al. (2011). The Inkster 2016 data was combined with the Oakes 2017 data (Environment 1), while Oakes 2016 data was combined with Inkster 2017 data (Environment 2). A test of homogeneity of variance between the sites in Environment 1 indicated that the environments could be combined; the same was performed between sites in Environment 2. Environments and replicates were considered random and treatments fixed. Tukey's pairwise comparisons ($P=0.05$) were used to separate treatment means.

Results and Discussion

Emergence

Potato tubers planted back the following season as seed from the mother plants that were exposed to dicamba and glyphosate exhibited herbicide injury symptoms. At 5 and 8 weeks after planting (WAP) there were differences in emergence for Environment 1 ($P < 0.0001$ at 5 WAP; $P < 0.0001$ at 8 WAP) and Environment 2 ($P < 0.0001$ at 5 WAP; $P < 0.0001$ at 8 WAP) (Table 3). At 5 and 8 WAP the 99 g ha^{-1} dicamba, 197 g ha^{-1} glyphosate and 99 g ha^{-1} dicamba plus 197 g ha^{-1} glyphosate caused 17 to 72% reduction in emergence when compared to the non-treated check. The seed pieces that did not emerge by 8 WAP often remained in the soil the entire growing season with short 1 to 3 cm multiple sprouts. This observation was also noted by Hatterman-Valenti (2014) who found that seed pieces with 71 to 282 g ha^{-1} glyphosate applied the previous year to mother plants remained intact with a proliferation of small sprouts. A treatment of 2% of the field use rate (20 g ha^{-1}) of dicamba to the mother plant was enough to reduce emergence 15 to 17% across timings and environments when compared to the non-treated check. The lowest rate of dicamba (4 g ha^{-1}) and glyphosate (8 g ha^{-1}) had no effect on emergence compared to the non-treated check, except for dicamba (4 g ha^{-1}) in Environment 2 at 5 WAP which had a stand reduction of 8%. Coluqhoun et al. (2017) did not report a reduction in stand when the mother plant was treated with 6 g ha^{-1} dicamba the previous year, similar to our results of 4 g ha^{-1} dicamba.

Table 3. Emergence of plants (percent) grown from seed tubers from mother plants that were treated with glyphosate and dicamba the previous growing season and evaluated at 5 and 8 weeks after planting (WAP). Environment 1 (Inkster, ND, 2016 and Oakes, ND, 2017), and Environment 2 (Oakes, ND, 2016 and Inkster, ND, 2017).

			Environment 1				Environment 2			
Treatment	Glyphosate	Dicamba	5 WAP		8 WAP		5 WAP		8 WAP	
	g ae ha^{-1}		Plant emergence (%)							
1	0	0	88	ab[a]	95	a	90	a	97	a
2	8	0	85	b	96	a	85	ab	90	ab
3	40	0	80	bc	86	ab	85	ab	90	ab
4	197	0	25	f	49	d	53	e	68	c
5	0	4	93	a	94	a	83	b	95	a
6	0	20	76	cd	89	ab	77	bc	83	b
7	0	99	40	e	79	bc	70	d	78	bc
8	8	4	91	ab	95	a	86	ab	95	a
9	40	20	73	d	83	b	78	b	90	ab
10	197	99	25	f	67	c	65	d	80	b

[a] Numbers followed by the same letter in a column are not significantly different according to Tukey pair-wise comparison at P = 0.05

Foliar injury of experimental generation 2 plants, was especially evident when the mother plants were treated with 99 g ha^{-1} dicamba, 197 g ha^{-1} glyphosate and 99 g ha^{-1} dicamba + 197 g ha^{-1} glyphosate as foliar chlorosis, stunting, and twisted leaves and stems, as if glyphosate and dicamba had been applied directly to the plants rather than the mother crop (Figure 1). Similarly, Hatterman-Valenti (2014) reported some plants from seed with glyphosate residues, had delayed emergence, distorted leaflets with random puckers on the leaf surface and leaf strapping. These symptoms are also similar to what would be expected from a synthetic auxin herbicide activity on potato (Thornton et al. 2013). Symptom severity varied widely, and did not appear to be associated with a specific glyphosate and/or dicamba rate applied to the mother plants, as reported by Hatterman-Valenti (2014). Differences observed in individual plant responses were attributed to variability in the amount of herbicide entering a daughter tuber due to source-to-sink differences for tubers within an individual mother plant treated with a sub-lethal herbicide dose (Hatterman-Valenti 2014).

During the tuber initiation growth stage the tuber becomes a major sink for photosynthate deposition. This causes exogenous chemicals, such as glyphosate and dicamba to be translocated to the tuber at the time of exposure (Smid and Hiller 1981). It may not be equally distributed among each of the tubers on a single plant, as was shown by Crook (2016). Our work adds to the body of research that shows herbicide carryover in seed varies between each seed piece (Colquhoun et al. 2017; Crook 2016; Hatterman-Valenti 2014). Residue analysis is a poor predictor of plant health and the yield potential for plants that have been exposed to harmful herbicides (Crook 2016). Future work with spectral imaging could possibly be used in winter grow outs to detect herbicide injury.

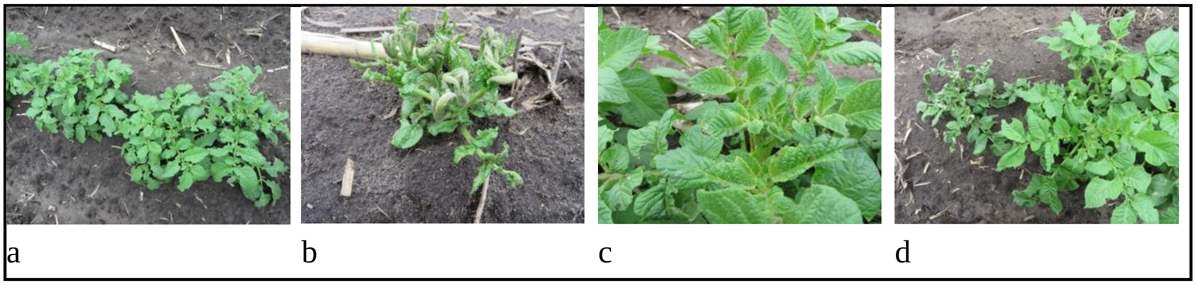

Figure 1. Visual symptoms of daughter tubers from mother plants that were treated with dicamba and glyphosate the previous growing season at 5 weeks after planting at Inkster, ND in 2017. (a) Non-treated plants exhibiting normal emergence and growth, (b) tubers planted from mother plants exposed to dicamba ≥20 g ha^{-1} expressed symptoms of twisted stems and leaves, (c) tubers planted from mother plants exposed to glyphosate ≥40 g ha^{-1} had symptoms of chlorosis in newest leaves, (d) tubers planted from mother plants exposed to dicamba ≥ 20 + glyphosate ≥40 g ha^{-1} expressed symptoms of stunting sporadically and stem twisting.

Plant Height

At 5 and 8 WAP there were differences in Environment 1 ($P < 0.0001$ at 5 WAP; $P < 0.0001$ at 8 WAP) and Environment 2 ($P < 0.0001$ at 5 WAP; $P < 0.0001$ at 8 WAP) in plant height (Table 4). At 5 and 8 WAP, 99 g ha^{-1} dicamba, 197 g ha^{-1} glyphosate and 99 g ha^{-1} dicamba + 197 g ha^{-1} glyphosate caused 17 to 77% reduction in plant height when compared to the non-treated check. The treatment 20 g ha^{-1} dicamba (2 % of recommended field use rate) caused 30% reduction in plant height when compared to the non-treated at 5 WAP in Environment 1 and caused 17% reduction in plant height when compared to the non-treated at 5 WAP in Environment 2.

Crook (2016) reported similar findings when 105 and 210 g ha^{-1} glyphosate was applied to the mother plants the previous growing season, reduced plant heights of 53 to 57% when compared to the non-treated check. Crook (2016) reported 53 g ha^{-1} glyphosate resulted in plants that were 38% shorter when compared to the non-treated, whereas our study only had 5 to 12% height reduction when compared to the non-treated at 40 g ha^{-1} glyphosate treated to the mother plants the previous year. Crook (2016) may have seen more injury from glyphosate contaminated seed tubers because the cultivar Red Norland was used and in our study, we planted the cultivar Russet Burbank. Red-skinned potatoes have expressed greater injury symptoms to glyphosate than 'Russet Burbank' (Hatterman-Valenti 2014).

Table 4. Plant height measured at 5 and 8 weeks after planting (WAP) from seed tubers from mother plants that were exposed to glyphosate and dicamba the previous growing season. Environment 1 (Inkster, ND, 2016 and Oakes, ND, 2017), and Environment 2 (Oakes, ND, 2016 and Inkster, ND, 2017).

			Environment 1				Environment 2			
Trt[b]	Glyphosate	Dicamba	5 WAP		8 WAP		5 WAP		8 WAP	
	—— g ae ha^{-1} ——		—— Plant height (cm) ——							
1	0	0	17	a[a]	50	ab	36	a	65	a
2	8	0	17	a	54	a	36	a	65	a
3	40	0	14	ab	52	ab	36	a	62	ab
4	197	0	5	d	34	d	21	c	50	c
5	0	4	16	a	51	ab	34	a	63	ab
6	0	20	12	b	48	bc	31	b	61	ab
7	0	99	8	c	44	c	30	b	57	b
8	8	4	17	a	54	a	34	a	62	ab
9	40	20	12	b	49	abc	30	b	58	b
10	197	99	4	d	40	dc	30	b	56	b

[a] Numbers followed by the same letter in a column are not significantly different according to Tukey pair-wise comparison at P=0.05.

[b] Abbreviation: trt, treatment

Yield

Differences in treatments existed for total yield ($P < 0.0001$) and total marketable yield ($P < 0.0001$) of potato tubers grown from seed tubers that were from mother plants treated the previous season with glyphosate and dicamba in each Environment (Table 5). The rates of 99 g ha^{-1} dicamba, 197 g ha^{-1} glyphosate and 99 g ha^{-1} dicamba + 197 g ha^{-1} glyphosate caused 23 to 52% reduction in total yield and 33 to 57% reduction in total marketable yield when compared to the non-treated check. In some cases, 40 g ha^{-1} glyphosate or 20 g ha^{-1} dicamba reduced yield or total marketable yield; however, the combination of 40 g ha^{-1} glyphosate + 20 g ha^{-1} dicamba caused 15 to 25% total yield and 15 to 27% total marketable yield reduction when compared to the non-treated check.

Foliar plant development is vital for the production of tubers and there was a similar pattern for emergence and yield. As expected, the higher the herbicide rate, the greater the yield loss, as which reinforces similar research (Hatterman-Valenti 2014; Hutchinson et al. 2014; Crook 2016). While harvesting and grading the experimental generation 2 tubers there were no external defects observed on any of the treatments, as were noted by Hatterman-Valenti (2014) and Hutchinson et al. (2014).

Table 5. Total yield and total marketable yield (TMY) of potatoes grown from potato tuber seed from mother plants that were treated the previous season with glyphosate and dicamba. Environment 1 (Inkster, ND, 2016 and Oakes, ND, 2017), and Environment 2 (Oakes, ND, 2016 and Inkster, ND, 2017).

			Environment 1				Environment 2			
Trt[c]	Glyphosate	Dicamba	Total yield		TMY[b]		Total yield		TMY	
	—— g ae ha^{-1} ——		—— T ha^{-1} ——							
1	0	0	53	a[a]	49	a	61	a	53	a
2	8	0	54	a	49	a	56	ab	48	ab
3	40	0	51	a	46	a	54	c	47	b
4	197	0	27	c	21	c	39	e	31	d
5	0	4	56	a	52	a	60	ab	53	a
6	0	20	38	b	33	b	55	bc	49	ab
7	0	99	26	c	22	c	47	d	41	c
8	8	4	55	a	50	a	60	ab	52	a
9	40	20	40	b	36	b	52	cd	45	c
10	197	99	26	c	23	c	38	e	33	d

[a] Numbers followed by the same letter in a column are not significantly different according to Tukey pair-wise comparison at P=0.05.
[b] TYM, Total marketable yield includes U.S. No. 1 and U.S. No. 2 tubers > 4 oz.
[c] Abbreviation: trt, treatment

Differences in treatments existed for tuber size distribution for all tuber weight categories ($P < 0.0001$) of potato tubers grown from seed tubers that were from mother plants treated the previous season with glyphosate and dicamba in Environment 1 (Table 6). Seed from the mother plants exposed to 197 g ha^{-1} glyphosate, 99 g ha^{-1} dicamba and 197 g ha^{-1} glyphosate + 99 g ha^{-1} dicamba the previous year, caused 20 to 40% reduction in tuber yield in the 113 to 169 g weight category and 53 to 59% reduction in tuber yield in the 170 to 282 g weight category when compared to the non-treated check. Seed from plants treated with 20 g ha^{-1} dicamba and 20 g ha^{-1} dicamba + 40 g ha^{-1} glyphosate caused 18 to 50% reduction in tuber yield in the 170 to 397 weight categories.

Table 6. Experimental generation 2 yield and grade when plants were treated with glyphosate and dicamba during the tuber initiation growth stage in 2015 and 2016 and daughter tubers planted as seed pieces in 2016 and 2017 in Environment 1 (Inkster, ND, 2016 and Oakes, ND, 2017).

			Tuber weight category (g)				
Trt[b]	Glyphosate	Dicamba	<113	113-169	170-282	283-397	>397
	g ae ha^{-1}		T ha^{-1}				
1	0	0	3 b[a]	5 b	17 ab	13 a	14 a
2	8	0	4 a	7 ab	17 ab	15 a	11 b
3	40	0	4 a	7 ab	16 b	12 b	12 ab
4	197	0	4 a	5 b	7 d	5 d	4 c
5	0	4	4 a	6 ab	19 a	16 a	12 ab
6	0	20	4 a	5 b	13 c	9 c	8 c
7	0	99	2 c	3 c	7 d	5 d	7 c
8	8	4	4 a	8 a	19 a	13 a	11 b
9	40	20	4 a	6 b	14 c	10 c	7 c
10	197	99	2 c	4 c	8 d	5 d	6 c

[a] Numbers followed by the same letter in a column are not significantly different according to Tukey pair-wise comparison at P=0.05.

[b] Abbreviations: trt, treatment

Differences in treatments existed for tuber size distribution for all tuber weight categories ($P < 0.0001$) of potato tubers grown from seed tubers that were from mother plants treated the previous season with glyphosate and dicamba in Environment 2 (Table 7). Seed from the mother plants exposed to 197 g ha^{-1} glyphosate, 99 g ha^{-1} dicamba and 197 g ha^{-1} glyphosate + 99 g ha^{-1} dicamba the previous year, caused 22 to 30% reduction in tuber yield in the 113 to 169 g weight category and 24 to 44% reduction in tuber yield in the 170 to 282 g weight category when compared to the non-treated check. However, 20 and 99 g ha^{-1} dicamba treatment to the mother plant the previous year did not reduce tuber yield in the 383 to 397 g tuber weight category when compared to the non-treated check in Environment 2. Similar results of the weight category 340 to 397 g were found by Hatterman-Valenti (2014) when 'Russet Burbank' seed was contaminated by at least 35 g ha^{-1} glyphosate. Coluqhoun et al. (2017) graded the daughter tubers from mother plants treated with 6 g ha^{-1} dicamba, 9, 19 and 38 g ha^{-1} but did not find any reductions in yield and this was likely because of the low rate of dicamba used the previous year.

Table 7. Experimental generation 2 yield and grade when plants were treated with glyphosate and dicamba during the tuber initiation growth stage in 2015 and 2016 and daughter tubers planted as seed pieces in 2016 and 2017 in Environment 2 (Oakes, ND, 2016 and Inkster, ND, 2017).

			Tuber weight category (g)									
Trt[b]	Glyphosate	Dicamba	<113		113-169		170-282		283-397		>397	
	g ae ha^{-1}		T ha^{-1}									
1	0	0	8	a[a]	11	a	22	a	13	a	9	a
2	8	0	7	ab	11	a	21	ab	12	a	6	c
3	40	0	7	ab	11	a	19	bc	11	ab	5	d
4	197	0	8	a	8	c	12	d	6	c	5	d
5	0	4	7	ab	10	ab	21	a	12	a	10	a
6	0	20	6	b	8	c	18	c	13	a	10	a
7	0	99	6	b	8	c	16	c	11	ab	7	bc
8	8	4	8	a	11	a	22	a	13	a	6	c
9	40	20	7	ab	10	ab	19	bc	10	b	6	d
10	197	99	6	b	8	c	13	d	7	c	5	d

[a]Numbers followed by the same letter in a column are not significantly different according to Tukey pair-wise comparison at P=0.05.
[b]Abbreviation: trt, treatment

Our results indicate that ≥20 g ha^{-1} dicamba or ≥197 g ha^{-1} glyphosate, or the combination of these rates of glyphosate and dicamba to mother plants caused reduced emergence and yield when seed tubers from the mother plants were planted the following growing season. Total yield reduction, when glyphosate and/or dicamba were treated to the mother plants, were attributed to slower emergence or germination inhibition to the seed pieces. Hatterman-Valenti et al. (2017) demonstrated that potato stressed from higher air temperatures just prior and during the herbicide treatment resulted in yield differences among two locations, as was shown in our results for the seed tubers used from these mother plants. The differences in environments at treatment time to mother plants seems to be the most likely cause for differences in contaminated seed tuber growth and yield, as was reported by Hatterman-Valenti et al. (2017) and Hatterman-Valenti (2014).

The results from this research indicate high seed potato susceptibility to glyphosate and dicamba. A lower percentage of the field use rate of dicamba (2%) was needed for similar reduction in emergence, height and yield than with glyphosate (5%). Glyphosate or dicamba residues in seed tubers can result in poor emergence causing an erratic plant stand that could increase weed problems (Eberlein et al. 1997). A poor crop canopy can also, increase soil temperature, causing a loss of soil moisture and inefficient use of nutrients (Van Delden 2001). Seed with low vigor generally produces a weaker plant, allowing for pathogens to invade and cause infection (Stead 1999). Increased weed and pathogen problems could lead to more herbicides and fungicides treatments, increasing the cost of production that may have a lower yield than desired.

The detection of glyphosate and dicamba residues within the seed can be positively confirmed by laboratory analysis. Further research is important in testing methods for potato growers to have a standard for testing glyphosate and dicamba residues in seed. Although services are available, it is not a mandatory requirement from the state seed department to test residue levels in seed. Previous research has suggested that different cultivars and different exposure timings cause varied responses to glyphosate (Hatterman-Valenti 2014; Hutchinson et al. 2014; Wall 1994). Further studies of commonly grown cultivars with dicamba plus glyphosate treatments would be beneficial to the industry as potatoes vary widely on their response to herbicide injury. This would be especially important for white-skinned potatoes, as there is little work reported on herbicide injury in these potato cultivars. The most effective management strategy is to prevent dicamba and glyphosate from contaminating fields that will be used for foundation or certified seed. Dedicating a sprayer for potato production could reduce spray tank contamination. Following label directions and applying herbicides under low drift conditions will reduce risk of exposure to seed potato fields.

Literature Cited

Al-Khatib K, Tamhane A (1999) Dry pea (*Pisum sativum* L.) response to low rates of selected foliar- and soil-applied sulfonylurea and growth regulator herbicides. Weed Technol. 13:753-758

Anonymous (2010) Clarity® herbicide label. Research Triangle Park, NC: BASF Agricultural Products

Anonymous (2016) Engenia® herbicide label. Research Triangle Park, NC: BASF Agricultural Products

Anonymous (2012) Roundup PowerMax® label 63027KS-10. Monsanto Co. 800 North Lindburg Boulevard, St. Louis, MO 63167

Anonymous (2017) Seed certification standards. North Dakota State Government. Available at http://www.legis.nd.gov/information/acdata/html/74-03.html. Accessed 30 August 2017 Fargo, ND

Anonymous (1991) United States standards for grades of potatoes. Washington DC: USDA Agricultural Marketing Service. p.1-6

Anonymous (2016) Xtendimax with VaporGrip Technology® label. Monsanto Co. 800 North Lindburg Boulevard, St. Louis, MO

Barber T, Norsworthy J, Scott B, Ross J, Hightower M (2017) Dicamba in Arkansas- Frequently Asked Questions. University of Arkansas Agriculture and Natural Resources. FSA2181

Bissonnette H, Preston D, Lamey H (1993) Potato production and pest management in North Dakota and Minnesota. North Dakota State Univ. Ext. Serv., Ext. Bul. Issue 26

Blackburn L, Boutin C (2003) Subtle effects of herbicide use in the context of genetically modified crops: a case study with glyphosate. Ecotoxicology 12:271-285

Blouin D, Webster E, Bond J (2011) On the analysis of combined experiments. Weed Technol. 25:165-169

Bradley K (2017) A Final Report on Dicamba-injured Soybean Acres. Integrated Pest Management, University of Missouri Ext. Serv. Published Oct. 30, 2017

Carmer S, Nyquist W, Walker W (1989) Least significant differences for combined analysis of experiments with two- or three-factor treatment designs. Agron. J. 81:665-672

Colquhoun J, Heider D, Rittmeyer R (2014) Relationship between visual injury from synthetic auxin and glyphosate herbicides and snap bean and potato yield. Weed Technol. 28:671-678

Colquhoun J, Heider D, Rittmeyer R (2017) Seed potato growth and yield as affected by mother plant exposure to herbicides. Weed Technol. 31:136-147

Eberlein C, Westra P, Haderlie L, Whitmore J, Guttieri M (1997) Herbicide drift and carryover injury in potatoes. Pacific Northwest Extension Publ. 498.

Everitt J, Keeling J (2009) Cotton growth and yield response to simulated 2,4-D and dicamba drift. Weed Technol. 23: 503-506

Haderlie L, Petersen P, Leino P (1986) Potato seed vigor and yield potential following herbicide drift or carryover. Res. Prog. Rep. West. Soc. Weed Sci 324-327

Hatterman-Valenti H, Endres G, Jenks B, Ostlie M, Reinhardt T, Robinson A, Stenger J, Zollinger R (2017) Defining glyphosate and dicamba drift injury to dry edible pea, dry edible bean, and potato. HortTech. 27:502-509

Hatterman-Valenti H (2014) Simulated glyphosate drift to potato mother plants and effect on daughter tubers used for seed production. Weed Technol. 28:253-258

Hutchinson P, Felix J, Boydston R (2014) Glyphosate carryover in seed potato: effects on mother crop and daughter tubers. Am. J. Potato Res. 91: 394-403

Johnson V, Fisher L, Jodan D, Edmisten E, Stewart A, York A (2012) Cotton, peanut, and soybean response to sublethal rates of dicamba, glufosinate, and 2,4-D. Weed Technol. 26:195-206

Lemoine R, Camera S, Atanassova R, Dedaldechamp F, Allario T, Pourtau N, Bonnemain J, Laloi M, Coutos-Thevenot P, Maurousset L, Faucher M, Girousse C, Lemonnier P, Parrilla J, Durand M (2013) Source-to-sink transport of sugar and regulation by environmental factors. Front Plant Sci. 4:272

Marple M, Al-Khatib K, Peterson D (2008) Cotton injury and yield as affected by simulated drift of 2,4-D and dicamba. Weed Technol. 22:609-614

Masiunas J, Weller S (1988). Glyphosate activity in potato (*Solanum tuberosum*) under different temperature regimes and light levels. Weed Sci. 36:137-140

National Potato Council (2017) Potato Statistical Yearbook 2017

[NDSSD] North Dakota State Seed Department (2008) Potato Program. Available at http://www.nd.gov/seed/potato/index.aspx. Accessed 30 August 2017 Fargo, ND

Norsworthy J (2004) Conventional soybean plant and progeny response to glyphosate. Weed Technol. 18:527-531

Robinson A, Hatterman-Valenti H (2013) Effect of glyphosate on potatoes. Bull. A1642. North Dakota State Univ. Ext. Serv., Fargo

Robinson A, Simpson D, Johnson W (2013) Response of glyphosate-tolerant soybean yield components to dicamba exposure. Weed Sci. 61:526-536

Smid D, Hiller L (1981) Phytotoxicity and translocation of glyphosate in the potato (*Solanum tuberosum*) prior to tuber initiation. Weed Sci. 29: 218-223

Solomon C, Bradley K (2014) Influence of application timings and sublethal rates of synthetic auxin herbicides on soybean. Weed Technol. 28:454-464

Stalikas C, Konidari C (2001) Analytical methods to determine phosphoric and amino acid group-containing pesticides. J. Chromatography 907:1-19

Stead D (1999) Bacterial diseases of potato: relevance to in vitro potato seed production. Potato Res. 42:449-456

Thornton M, Lee J, John R, Olsen N, Navarre D (2013) Influence of growth regulators on plant growth, yield, and skin color of specialty potatoes. Am. J. Potato Res. 90:271-283

[USDA] US Department of Agriculture (2011) United States Standards for Grades of Potatoes. Washington DC: U.S. Department of Agriculture p.1-6

[USDA-NASS] US Department of Agriculture, National Agricultural Statistics Service (2017) Potatoes 2016 Summary. http//usda.mannlib.cornell.edu/usda/current/Potat/Pota-09-14-2017.pdf. Accessed 9 November 2017

[USDA-NRCS] USDA-NRCS Soil Survey Division (2017) Official Soil Series Descriptions View by Name. Accessed June 14, 2017. https://soilseries.sc.egov.usda.gov/osdname.asp

[USDA-ARS] USDA-ARS Crop Protection and Management Research. https://www.ars.usda.gov/research/publications/publication/?seqNo115=307980. Accessed 9 November 2017

Van Delden A (2001) Yield and growth of potato and wheat under organic N-management. Agron. J. 93:1370-1385

Wall D (1994) Potato (*Solanum tuberosum*) response to simulated drift of dicamba, clopyralid, and tribenuron. Weed Sci. 42:110-114

Willkie P, Sorenson T, Noury J, Friday D, Murphy K, Gonzalez K, Richardson B (2012) Marketing U.S. Potatoes. Washington DC: U.S. Department of Agriculture p.1-10

Worthington T (1985) The effect of glyphosate on the viability of seed potato tubers. Potato Res. 28:109-112

Yenish J, Young F (2000) Effect of preharvest glyphosate application on seed and seedling quality of spring wheat (*Triticum aestivum*) Weed Technol. 14:212-217

APPENDIX

Table A1. Analysis of variance of emergence, plant height and yield treated with different rates of dicamba and glyphosate during tuber initiation to the mother plants the previous year at Inkster and Oakes, ND in 2016 and 2017.

Source	Environment	Treatment rate	Environment x treatment rate
	P value		
Emergence			
5 WAP	<0.0001	<0.0001	<0.0001
8 WAP	<0.0001	<0.0001	0.0003
Plant height			
5 WAP	<0.0001	<0.0001	<0.0001
8 WAP	<0.0001	<0.0001	<0.0001
Yield			
Total yield	<0.0001	<0.0001	0.0200
TMY	<0.0001	<0.0001	0.0047
<113 g	<0.0001	0.0096	0.6541
113-169 g	0.0485	<0.0001	0.8088
170-282 g	0.0023	<0.0001	0.0890
283-397 g	0.0002	<0.0001	0.4105
>397 g	0.0111	0.0007	0.6261