PREDICTING POTATO YIELD LOSS DUE TO METRIBUZIN SENSITIVITY IN NORTH DAKOTA

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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

A linear-log model to predict yield loss due to metribuzin injury was established by Love et. al. in 1993. Two experiments were conducted in 2016 and 2017 to evaluate and improve this model for application in North Dakota (ND). Metribuzin was applied (1.12 a.i./ha) when potato plants were 20-30 cm tall at Inkster, ND. The model did not accurately predict yield loss in 2016 but performed better in 2017. Foliar injury was more correlated with yield reduction than relative plant height. Results also indicated that new models that used foliar injury at 21 days after treatment (DAT) data and at 7 DAT data, most accurately predicted total yield loss and marketable yield loss, respectively. The new model performed similar to the previous model, but unlike previous model it can predict yield loss very early in growing season (21 DAT).

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DEDICATION

To my mother, Rokeya Begum

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INTRODUCTION

Potatoes were grown on 30,351 ha of land in North Dakota (ND), and total production was 1,200,000 Mt in 2017, up 16 percent from 2016 (USDA NASS 2018a). North Dakota ranks fourth for potato production in the US (USDA NASS 2018b). Approximately 60% of potatoes grown in North Dakota and Minnesota are for processing (French fries, chips, and other frozen), with the remainder used for table stock and certified seed (Thompson et al. 2015).

Weeds compete with potatoes for light, water, and nutrients, and can cause harvest interference (Hutchinson 2010). In addition, weeds may host other pests, such as insects, nematodes, and common potato pathogens. Weed control practices in potatoes include cultivation and herbicides, and a combination of the two is often more effective than either alone. However, herbicide may take less time to apply than to cultivate, and can often be applied in a single application versus multiple cultivations necessary for moderate to heavy infestations (Hutchinson 2010).

Among all the herbicides, metribuzin is the most widely used herbicide on potatoes (USDA NASS 2018c). It is used to control broadleaf weeds and annual grasses in most potato production areas in North America (Freeman 1982). However, potato cultivars often show differences in tolerance to metribuzin (Graff and Ogg 1976; Arsenault and Ivany 1996). It causes foliar injury and reduces plant height and yield in sensitive genotypes. As new cultivars are released, it is important for growers to know the cultivar's response to metribuzin to avoid injury and yield loss (Love et al. 1993).

Researchers at the University of Idaho established a regression model [Yield Loss= 1.142 + 0.176{log(height of injured plants/height of uninjured plants)} - 0.00796(foliar injury)] to predict yield loss due to metribuzin injury (foliar injury and plant height) without the necessity of destructively harvesting the potato plant -at the end of the season (Love et al. 1993). According to Love et al. (1993), this model can help scientists quickly evaluate a large number of breeding lines for metribuzin sensitivity and may help growers with weed control decisions for the cultivars they have planted. This model may save time, labor and capital resources needed to screen new cultivars for metribuzin sensitivity. It may also be used by growers to collect data for herbicide injury reimbursement claims.

The model was constructed based on the growing environment in southeastern Idaho. It is unknown if this model is equally applicable in the Northern Plains or other parts of the US. This study evaluated the predictive model's efficiency for potato production in the Northern Plains. Moreover, other regression models were evaluated to identify the best model to predict potato yield loss in the Northern Plains due to metribuzin injury. Several objectives were evaluated throughout this study by addressing the following questions. Does the model predict yield loss accurately? Is it applicable for the potato growing areas of North Dakota.? Does the model need any modification based on the environmental conditions in North Dakota? Can we predict potato yield loss due to metribuzin sensitivity early in the season? This investigation also evaluated some advanced NDSU potato breeding selections for metribuzin sensitivity and provided important agronomic information useful in the development of cultivar specific management profiles.

REVIEW OF LITERATURE

Potato

Description

Potato *(Solanum tuberosum* L.*)* is an herbaceous, dicotyledonous, and annual plant of the Solanaceae family, that grows to 0.4-1.4 m tall, and may range from erect to fully prostrate (Cutter 1992). Although it is classified as an annual, it can persist in the field vegetatively (as tubers) from one season to the next (Spooner 2010). Stems range from nearly hairless to heavily pubescent, round to angular in cross section, and may be green or pigmented due to anthocyanins (Cutter 1992). Potato leaves are compound and arranged spirally on the stem (Huaman 1986). Leaves consist of a midrib petiole), terminal leaflet, and several pairs of primary leaflets which are scattered with secondary and tertiary leaflets (De Jong et al. 2011). The part of the midrib below the lowest pair of primary leaflets is called a petiole (Huaman 1986).

The potato plant produces stolons, which are basically lateral stems (Huaman 1986). Stolons originate from the buds on the underground part of stems. Tubers, spherical to ovoid in shape, are swellings at the end of each stolon. The tuber flesh and skin can vary in color depending on the cultivar. The skin texture may vary from smooth to russetted . On the surface of the tuber are axillary buds with scale leaf scars that are called eyes (Struik 2007). When tubers are planted, these eyes develop into one or more shoots to form the next vegetative generation.

The terminal inflorescences are cymose type that are 5-11 cm long and generally found on the upper portion of the plant (Struik 2007). The inflorescences are usually branched and may contain up to 25 flowers (Cutter 1992). Potato flowers are perfect and consists of the four essential parts of a flower: calyx, corolla, stamen, and pistil (Huaman 1986). The corolla may be a range of colors, including white, pink, lilac, blue, purple, and red-purple (Cutter 1992). Potato flowers have five (sometimes six) stamens that are composed of anther and filament and joined to the corolla tube (Huaman 1986). The pistil is composed of the ovary, style, and stigma.

Potato fruits are spherical to ovoid berries, about 1-4 cm in diameter (Huaman 1986). They are green, or green tinged with white or purple spots or bands, when ripe. The berries may lack seeds or contain up to several hundred. The seeds are flat and round to oval and vary from 1000 to 1500 seeds per gram (Huaman 1986). The berries are toxic, due to the presence of glycoalkaloids (Struik 2007).

Potato production in the Red River Valley

The Red River Valley is a beautiful stretch of land between the rolling plains of North Dakota and the lakes and forests of Minnesota (Turnquist 1965). It is a flat and fertile valley formed by the ancient glacial Lake Agassiz. The large, flat, open area, free from stones and with fertile soil, was found to be ideal for the production of high quality potatoes. Long days with bright sunshine and cool nights allow production of cultivars with high tuber solids.

There were approximately 48,966 ha of potatoes planted in 2017, in North Dakota and Minnesota (USDA NASS 2018a). Total hectares planted in North Dakota in 2016 were 32,374, but decreased to 30,351 in 2017. However, yield was increased from 1,209,600 tons in 2016, to 1,408,959 tons in 2017. Hectares planted in Minnesota increased from17400 in 2016, to 18600 in 2017 with 105,821 tons yield increase (USDA NASS 2018b).

Potatoes are an expensive crop to grow. Crop growth and production is affected by fertilization, cultivation, rainfall and/or irrigation, weeds, insects, and diseases (Patterson 2010). Thus, a significant expenditure for various inputs including seed, fertilizer, pesticides, labor, electricity and fuel are required. Just like other crops, weed control in potato is an important part of potato production. Total yield may be significantly decreased by weeds (Isik et al. 2015).

Effects of weeds in potato production

Weeds compete with potatoes for light, water, and nutrients, and may interfere with harvest (Hutchinson 2010). They also host other pests such as insects, nematodes, and common potato pathogens. Nelson and Thoreson (1981) found that weed competition reduced both the average tuber size and the number of tubers. When they allowed weeds to grow all season, the yield loss was 54% compared to weed-free plots. If weeds were allowed to grow for the first eight weeks after potatoes emerged, then were controlled for the remainder of the season, yield loss was only 19%. If weeds were allowed to grow until 10 weeks after potato emergence, the yield decrease ranged from 25% to 40%. Thus, weed control during the early part of potato foliar development is most critical for high yielding and good quality tubers. Nelson and Thoreson (1981) also found a yield loss if cultivation to control weeds went too long (i.e. before row closure) due to root pruning and damage to developing tubers. In addition to the yield and quality reduction, weeds also reduced harvest efficiency by slowing the harvesting operation, leaving tubers in the ground, and/or carrying them over the conveying chain (Nelson and Giles 1989).

Potato yield and quality are affected when potatoes are grown under weedy conditions. If weeds are not controlled properly, they can cause 20%-80% potato yield loss (Ivany 1986; Baziramakenga and Leroax 1994). Love et al. (1995) reported that cultivars Russet Burbank and Frontier Russet produced less vine biomass and total yield in weedy plots, compared to weed-free plots. Weedy conditions also reduced the number of US No. 1 grade tubers (43%-92%) and increased the number of small tubers, compared to weed-free conditions (Love et al. 1995).

Weeds can be a serious problem in potato production as many species interfere with potato growth, and reduce yield and quality (Boydston and Vaughn 2002). The major weeds in potatoes in the Red River Valley of North Dakota include hairy nightshade (*Solanum sarrachoides* L.*)*, eastern black nightshade (*Solanum nigrum* L.), common lambsquarters (*Chenopodium album* L.), waterhemp (*Amaranthus tuberculatus* L.), and kochia (*Bassia scoparia* L.), along with volunteer corn (*Zea mays* L.), canola (*Brassica napus* L.) and small grains (Dr. Asunta Thompson, personal communication). The direct and indirect costs of weeds during potato production were estimated to average $114/ha in 1969 in the United States (Dallyn 1971). On average, 8.3% of the 517.7 Mt of potato production were lost due to weeds on a worldwide basis (Oerke 2006).

Use of herbicides in potato production

Growers utilize cultural, mechanical, and chemical methods to control weeds in potato production (Burke and Everman 2014). Cultivation is the most important and abundantly used method of weed control in potato production. Multiple cultivations are required for medium to heavily infested fields. However, due to strict tuber quality requirements, multiple cultivations are not possible (Hutchinson 2010). Moreover, cultivation compacts the soil and can spread diseases.

Herbicides reduce the amount of labor, machinery, and fuel used for mechanical weed control (Cornejo et al. 2014). Herbicides, insecticides and fungicides have substantially increased crop yield in the last 50 years; they also improve the potato quality by controlling weeds, insects, nematodes and plant pathogens. Cornejo et al. (2014) also reported that, 60% of U.S. potato hectares planted were treated with herbicide in 1965. By 2008, herbicide use had grown to 90% of potato hectares planted (Cornejo et al. 2014).

Methods of herbicide application vary from pre-plant soil incorporation (PPI), post-plant but pre-emergence to the potato crop (PRE), to post-emergence (POST) applications (Hutchinson 2010). Several herbicides are registered for weed control in potato. Post-emergence herbicides are used primarily to maintain a weed-free crop after crop canopy development. There are very few herbicide options to control emerged weeds (Burke and Everman 2014). Options include metribuzin, rimsulfuron, sethoxydim, and clethodim, with metribuzin as the most widely used herbicide among them.

Metribuzin

Uses

Metribuzin was launched in 1970 by Bayer, under the trade name Sencor™, and was also sold by DuPont, under the trade name Lexone™, for control of certain broadleaf weeds and grassy weed species (Heri et al. 2008). It was first introduced in Germany in 1971, as a new potato herbicide, but within a short time, its main use was in soybeans. There are approximately 86 metribuzin products registered (Heri et al. 2008). In the United States, metribuzin has a wide range of uses, including in vegetable and field crops (soybeans, potatoes, barley, winter wheat, asparagus, sugarcane, tomatoes, lentils, peas), turfgrasses (recreational areas), and on other noncrop areas. Metribuzin is sold in more than 75 countries, with the top five being the United States, Brazil, Canada, China, and Germany.

Metribuzin may be soil-incorporated, surface applied, foliar applied, broadcast, or banded with ground equipment (Anonymous 2018). It can be applied by ground or aerial equipment, or through sprinkler irrigation in potato production. In 2016, herbicides were applied to 94% of fall potato hectares (USDA NASS 2018c). Metribuzin was the most widely used herbicide, and second most widely used pesticide in potato production. The total amount of metribuzin applied to potatoes was 1,360,791 kg, covering 77% of planted hectares in the US (USDA NASS 2018c).

Action and metabolic pathways

There are four different structural classes of triazine herbicides: chlorotriazines, methylthiotriazines, methoxytriazines, and atypical or asymmetrical triazines (Simoneaux and Gould 2008). Metribuzin is a member of the atypical triazine group. It's chemical name is 4-amino-6-tert-butyl-4,5-dihydro-3-methylthio-1,2,4- triazin-5-one. Metribuzin, like other triazine herbicides, is classified as a photosynthesis inhibitor, or group 5 herbicide (Roberts 1998). It is absorbed mainly by roots, but also by leaves, and translocation is always upward through the xylem.

Metribuzin inhibits photosynthesis in a susceptible plant by interfering with photosystem II electron transport in plant chloroplasts (Dodge 1983). It binds to the D1 protein, and causes a chain of events. As a result, highly reactive free radicals are produced, which attack and oxidize plant lipids and proteins, causing chlorosis, plant cell death, and plant tissue disintegration (Hutchinson 2012).

The mechanism of tolerance of a species to metribuzin depends on its ability to detoxify free metribuzin (Gawronski et al. 1986). Metabolism of metribuzin may involve several pathways, including the nonconjugative pathway, conjugative pathway, and/or production of nonextractable residues (Simoneaux and Gould 2008). Nonconjugative metabolic processes produce deaminated metribuzin (DA), diketo metribuzin (DK), and deaminated diketo metribuzin (DADK) through deamination and dethiomethylation (Mangeot et al. 1979). However, nonconjugative pathways are minor in most plants. Far more rapid detoxification occurs via conjugative pathways (Frear et al. 1983). Gawronski et al. (1985) working with potato, demonstrated that the conjugative metabolic pathway is sufficient in determining the selectivity of the herbicide. They also reported that homoglutathione conjugation is the predominant detoxification pathway, with N-glucosylation being of secondary importance.

The half-life of metribuzin in soil is 1.5-4.0 months (Roberts 1998). However, in optimum degradation conditions (warm temperature and high soil moisture), the metribuzin half-life is reduced to 14 to 28 days. Metribuzin adsorption is higher in high organic matter soils, and lower in sandy or sandy-loam soils (Hutchinson 2012).

Injury symptoms

Metribuzin can damage potato plants if rates are too high, if applied at the wrong time, or if used on sensitive cultivars (Graff and Ogg 1976). Metribuzin injury to potato plants may cause several symptoms: general chlorosis, chlorosis of the leaf margins, interveinal chlorosis, necrosis of the leaf tips, and necrosis of the leaf margins. As time and dose of application increases, most potato cultivars show visible symptoms, such as necrosis of leaf margins, total leaf necrosis, stunted growth, and in some cases, death.

Renner and Powell (1998) reported that injury to Russet Burbank from metribuzin was less common than with many cultivars; however, metribuzin damage is possible if Russet Burbank plants experience three consecutive days of cloud cover prior to metribuzin application. Gawronski et al. (1985) used a nutrient solution that included metribuzin labelled with ^{14}C to determine that Russet Burbank accumulated 13% and 39% metribuzin in petioles and stems after four days of treatment, respectively. Conversely, at the same time Chipbelle only accumulated 6% and 13% metribuzin in petioles and stems, respectively. Eight days after treatment, Russet Burbank had accumulated 30% of metribuzin in leaf blades, while Chipbelle had accumulated 68% in leaf blades (Gawronski et al. 1985). They concluded that Chipbelle was more susceptible to phytotoxicity because photosystem II inhibiting herbicides acted directly on the chloroplasts in the leaves. Many other white and red skinned cultivars are also sensitive to metribuzin (Gawronski et al. 1986).

Figure 1. Metribuzin injury symptoms at 7 days after treatment

Regardless of variety, if the crop is stressed, or plant growth is slowed for reasons such as cool cloudy weather for several days prior to application, herbicide metabolism within the plant may be slowed, resulting in prolonged exposure, and leading to injury or death (Hutchinson 2012). If the cultivar is tolerant, foliar injury may disappear due to rapid metabolism, when environmental conditions improve.

Effect of metribuzin on weed control

Metribuzin provides excellent control of many broadleaf weeds. Ivany (1979) found that metribuzin completely controlled lambsquarters (*Chenopodium album* L.), lady's-thumb (*Persicaria maculosa* L.*)*, and hempnettle (*Galeopsis tetrahit* L.), regardless of time of application and rate. He also reported that control of perennial sowthistle (*Sonchus oleraceus* L.) was generally good and was improved as the rate of application was increased. Metribuzin at 1 kg a.i. ha^{-1} POST application provided 98% control of the perennial sowthistle. However, satisfactory control of wild buckwheat (*Fallopia convolvulus* L. var. *convolvulus)* was not achieved with metribuzin applications. Only 57% of the wild buckwheat was controlled with a 1 kg a.i. ha^{-1} POST application of metribuzin (Ivany 1979).

Metribuzin provides better weed control when it is tank mixed with other post emergence herbicide. Robinson et al. (1996) found that when metribuzin was applied PRE at 280 g ha^{-1}, followed by POST 280 g ha^{-1}, it provided commercially acceptable control (greater than 90%) of smooth pigweed (*Amaranthus hybridus* L.), redroot pigweed (*Amaranthus retroflexus* L.) and common lambsquarters. A single application of 280 g ha^{-1} metribuzin PRE or POST also controlled these weeds. However, none of these treatments controlled jimsonweed (*Datura stramonium* L.), large crabgrass (*Digitaria sanguinalis* L.), or fall panicum (*Panicum dichotomiflorum* L.). For these weeds, 35 and 280 g ha^{-1} rimsulfuron and metribuzin, respectively, were required when applied PRE or POST.

In another experiment, Renner and Powell (1998) found that metribuzin at 140 g ha^{-1} POST controlled redroot pigweed and common lambsquarters, and at 210 g ha^{-1} controlled barnyardgrass (*Echinochloa crus-galli* L.) and wild buckwheat. When they used rimsulfuron and metribuzin in combination, commercial (greater than 90%) weed control was achieved with reduced rates, compared with higher rates of either herbicide applied alone. Tank mixtures of 18 g ha^{-1} rimsulfuron, plus 140 g ha^{-1} metribuzin POST, provided at least 96% control of all weeds.

Hutchinson et al. (2006) reported that sulfentrazone provided 84% more broadleaf weed control when tank-mixed with metribuzin, compared to sulfentrazone applied alone. Sulfentrazone at 53 g ha^{-1} tank-mixed with metribuzin at 420 g ha^{-1} controlled 90% of hairy nightshade (*Solanum sarrachoides* L.*)*, 94% of redroot pigweed, 95% of common lambsquarters, and 93% of kochia (*Bassia scoparia* L.). Similar results were previously found by Hutchinson et al. (2004) when they included metribuzin in the tank mixture with rimsulfuron. Metribuzin at a rate of 280 g ha^{-1} combined with rimsulfuron at 26 g ha^{-1} controlled 99% of common lambsquarters, 98% of hairy nightshade, and 100% of both redroot pigweed and kochia.

Effect of metribuzin on growth and yield of potatoes

Many investigations have evaluated the effect of herbicides on the yield of potato, mainly because yield is the ultimate goal (Graff and Ogg 1976; Friesen and Wall 1984; Arsenault and Ivany 1996). However, the results may vary drastically due to varying conditions of weather, soil, and/or cultivar. Previous studies have found that effects of metribuzin depend on cultivar, treatment rate, time of application, and the method of application (Graff and Ogg 1976; Friesen and Wall 1984; Arsenault and Ivany 1996).

The effect of metribuzin varies among cultivars and the rate of application. Hatterman-Valenti et al. (1994) reported reduced yields for the cultivars Atlantic and Norchip due to metribuzin sensitivity. Metribuzin applied POST at 0.56 kg ha^{-1} reduced the total and A sized tubers by 9% compared to the untreated control. However, lowering the metribuzin rate to 0.28 kg ha^{-1} resulted in an 8% increased total yield in the case of Atlantic. Yield reduction also occurred when metribuzin was applied POST at 0.42 kg ha^{-1}. Arsenault and Ivany (1996) also studied the effect of metribuzin on three potato cultivars including AC Novachip, AC Belmont, and Russet Norkotah. They reported that metribuzin resulted in no yield reduction for Belmont. However, the total yield of Russet Norkotah and AC Novachip were reduced when metribuzin was applied post-emergence at 1 kg a.i. ha^{-1}.

Ackley et al. (1996) found that potatoes treated with metribuzin at 28 g ha^{-1} POST, or metribuzin + rimsulfuron at 28 + 35 g ha^{-1} POST, produced higher total yields, and a greater percentage of A-size tubers than untreated plots. Robinson et al. (1996) reported that metribuzin at 0.42 kg ha^{-1} with rimsulfuron decreased total and U.S. No. 1 yield by 3 and 6%, respectively.

Hutchinson et al. (2004) conducted an experiment using the Russet Burbank cultivar with post-emergence rimsulfuron at 26 g ha^{-1} plus metribuzin at 0, 140, or 280 g ha^{-1} in all possible combinations with three adjuvants: a nonionic surfactant, a crop oil concentrate, and methylated seed oil. They found that compared to the weedy control, all metribuzin rates and adjuvant combinations resulted in increased U.S. No. 2, U.S. No. 1, and total tuber yields, and reduced undersized tuber yields. However, all metribuzin rates and adjuvant combinations produced similar amounts of U.S. No. 2, U.S. No. 1, and total tuber yields compared to the weed-free control.

The injurious effect of metribuzin to potato has been shown to depend on the method of metribuzin application. Friesen and Wall (1984) evaluated the response of 22 potato cultivars to soil-incorporated and foliar applications of metribuzin. They found that the cultivars Alaska Red and Shepody had significantly reduced yields in the case of both soil-applied and foliar-applied metribuzin at a rate of 1 kg ha^{-1}. However, none of the cultivars were affected when metribuzin was applied to the soil at the same rate, except Rhine Red. Potato genotypes Caribe, F72117, and ND146-4R had significantly reduced yields due to1 kg ha^{-1} of metribuzin applied POST. Friesen and Wall (1984) also reported that there were no consistent or significant differences in average tuber size, specific gravity of tubers, or plant stands for all the genotypes evaluated.

The effect of metribuzin on potato yield may also be influenced by the time of application. Ivany (1979) conducted an experiment to determine the response of potato cultivars Irish Cobbler, Sebago, Netted Gem, and Kennebec to metribuzin application time and rate. Significant differences were not found for yields between pre-emergence and early post-emergence treatments. However, when metribuzin application was delayed until late post-emergence (25-30 cm plant height), Irish Cobbler and Sebago produced significantly lower marketable yield, compared to pre-emergence and early post-emergence treatments. The timing of metribuzin application had mixed results in research trials conducted by Arsenault and Ivany (1996). They reported that metribuzin application timing affected tuber yield in some years, but not in others.

Metribuzin also affects plant growth. Graff and Ogg (1976) reported that plant height of all potato cultivars, except Norgold Russet, were reduced significantly at 14 days after treatment when metribuzin was applied at the 1.12 kg a.i. ha^{-1}. Plant vigor and dry weight of all cultivars were also reduced significantly at 1.12 kg a.i. ha^{-1}. However, cultivars showed varying tolerances with differing rates of metribuzin. Therefore, metribuzin may increase, decrease, or have no effect at all on yield and growth of potato.

Predictive model

As it is not possible to collect and analyze data from the future, people collect current data and often past data to predict the future (Davenport 2018). This is called predictive modeling. Predictive modeling is performed to either predict future observations or understand relationships between predictors and an outcome of interest. Multiple variables are utilized to understand their relationship with the outcome of interest (Dohoo et al. 2003). Regression analysis and its various forms are the primary tools for predictive analysis (Davenport 2018). In regression analysis we assume that the value of one variable is caused or influenced by (or we wish to predict it by) the value or state of another variable. The outcome variable is called the dependent variable, whereas the 'causal' or 'predictor' variables are called the independent or predictor variables (Dohoo et al. 2003). Before performing a regression analysis, a researcher hypothesizes that a set of independent variables are statistically correlated with the dependent variable (Davenport 2018). Love and Haderlie (1989) found that metribuzin injury(foliar damage and plant height reduction) had a strong correlation with potato yield reduction.

Love and Haderlie (1989) reported that foliar injury one week after metribuzin application was moderately and negatively correlated with relative yield (treated/untreated), with correlation coefficient (r) values ranging from -0.48 to -0.86 ($p<0.05$). The correlation strengthened as the time between application and injury evaluation increased. Correlation coefficients ranged from -0.64 to -0.92 three weeks after metribuzin application. Relative plant height (treated/untreated) was also highly correlated with relative yield; correlation coefficients ranged from 0.80 to 0.85. On the other hand, relative vine maturity (treated/untreated) showed low and erratic correlation with relative yield.

Based on their experimental results, Love et al. (1993) developed a model to predict potato yield loss due to metribuzin injury. They used two explanatory variables, plant height proportion (PHR) at harvest, defined as injured/uninjured, and percent foliar injury at 21 days after metribuzin application, to predict yield loss. Three multiple regression models, including linear, quadratic and linear log, were considered and evaluated. Inspection of the residual plots for each model revealed that the best residual pattern and structure was present with the linear log model, with a coefficient of determination (R^2) value of 0.78. They proposed a prediction model: $YL = 1.142 + 0.176 (\log PHR) - 0.00796 (FI)$, where YL = predicted proportion of uninjured crop yield expressed by the injured crop, PHR = height of injured plants/height of uninjured plants, and FI = percent foliar injury. Love et al. (1993) indicated that the model is not applicable to all application methods and conditions. Hence, it is necessary to evaluate this model for use in North Dakota and the Northern Plains.

MATERIALS AND METHOD

Experimental design and preparation

Field trials were conducted during the 2016 and 2017 growing seasons at the Northern Plains Potato Growers Association (NPPGA) irrigated research site near Inkster, ND (48° 09′ 57.3″ N, 097° 43′ 12.9″ W; 313 m above mean sea level). The soil type at the research site is an Inkster sandy loam (coarse loamy, mixed, superactive, frigid Pachic Hapludolls). The previous crops were soybean (*Glycine max* L.) and corn (*Zea mays* L.) in 2016 and 2017, respectively. Twenty-six potato genotypes (cultivars and advancing breeding selections) were evaluated in 2016 and twenty-four genotypes (cultivars and advancing breeding selections) were evaluated in 2017 (Table 1). Russet Norkotah and Shepody served as the resistant and susceptible check, respectively (Love et. al. 1993).

A randomized complete block design with split-plot arrangement was used. Hand cut potato seed pieces, weighing between 60-80g, were planted in single rows with a 30 cm within row spacing and 90 cm between rows, at a seed depth of 10 cm, using 10 seed pieces per experimental unit. Each experimental unit was separated in the row by a blank space of 150 cm for easy identification and treatment application. Planting was completed on May 19, 2016 and May 24, 2017.

Standard North Dakota potato production practices were applied throughout the growing season. Prior to planting, the experimental site was fertilized and cultivated. In-furrow insecticide was applied during the planting procedure. Granular nitrogen was broadcasted prior to sprout emergence, and incorporated with the hilling procedure.

Table 1. Potato genotypes and their parents screened for metribuzin sensitivity in 2016 and 2017.

Clones	Parents	
	Female	Male
AND00272-1R	Minn. 17922	A92653-6R
AND97279-5Russ	A92001-2	Ranger Russet
ATND99331-2PintoY	Inka Gold	COA9419-5R
ND4659-5R	NorDonna	ND2842-3R
ND6002-1R	NorDonna	Bison
ND6961B-21PY	J138-A12	Winema
ND7132-1R	ND5002-3R	ND5438-1R
ND7519-1	ND3828-15	W1353
ND7799c-1	Dakota Pearl	NY115
ND7818-1Y	Morene	Marcy
ND7882b-7Russ	AND9552-4Russ	Russet Norkotah
ND7982-1R	Minn. 17572	ND5256-7R
ND8068-5Russ	ND2667-9Russ	ND4233-1Russ
ND8304-2 (used only in 2016)	ND860-2	ND7083-1
ND8305-1 (used only in 2016)	ND2471-8	White Pearl
ND091933ABCR-2Russ	PA99N2-1	ND049474ABC-1Russ
ND091933ABCR-7Russ	PA99N2-1	ND049474ABC-1Russ
ND091938BR-2Russ	PA99N82-4	Dakota Trailblazer
ND0920007R-2Russ	ND860-2	PA99N2-1
ND092355CR-2Russ	ND060475C-4Russ	PA99N2-1
Chieftain	La1354	Ia1027-18
Dakota Ruby	ND7188-4R	ND5256-7R
Dakota Russet	Marcy	AH66-4
Russet Norkotah	ND9526-4Russ	ND9787-5Russ
Dakota Pearl	ND1118-1	ND944-6
Shepody	Bake-King	F58050

Application of treatments

The treatments consisted of a single application of metribuzin at a rate of 1.12 kg a.i. ha^{-1} and a hand weeded control; treatments were replicated two times in 2016 and three times in 2017. Metribuzin (Sencor^{TM} 75 DF) was applied post-emergence when plants reached an average height of 20 cm. Application of metribuzin was completed with a CO_2 backpack sprayer equipped with a 1.8 m boom and four 8002 flat fan nozzles, spaced 45 cm apart, at 275 kPa and an output of 187 L ha^{-1}. Environmental conditions at the time of spraying are described in Table 2.

Table 2. Environmental conditions at the Northern Plains Potato Growers Association irrigated research site during metribuzin application in 2016 and 2017, Inkster, ND.

Environmental Condition	28th June, 2016	30th June, 2017
Soil moisture	Normal	Normal
Wind speed	11 km h^{-1}	13 km h^{-1}
Wind direction	South-west	North-west
Dew presence	No	No
Cloud cover	0%	100%
Air temperature	21.0^0 C	15.5^0 C
Humidity	60%	80%

Visual rating of foliar injury and plant height were recorded during the growing season following the method of Love et al. (1993). Visual assessment of foliar injury was recorded as an average percentage of foliage for each plant in the plot showing typical symptoms. Visible foliar injury were based on 0-100 scale where 0% = no injury and 100% = complete death of potato plants. Plant height was recorded from three randomly selected plants in each plot and then averaged before analysis. Height was determined by measuring from the soil surface to the uppermost meristematic tip. In 2016, foliar injury was recorded 21 days after treatment (DAT) and plant height was measured prior to harvest. In 2017, foliar injury and plant height were recorded at 7, 14, and 21DAT. An additional plant height measurement was also recorded prior to harvest in 2017.

Potatoes were harvested using a single-row harvester (Hasia-Redatron GmbH, Butzbach, Germany) on September 29, 2016 and October 2, 2017. After harvesting, tubers were stored at the NDSU Potato Research building. Tubers were graded using an electronic vegetable grader (Hagan Electronics Inc., United Circle Parks, NV, USA) following the USDA potato standards (USDA 2011), where the tubers were graded in four weight ranges of 0-113 g, 113-170 g, 170-283 g and >283 g. Culls and damaged tubers were separated and weighed prior grading of each plot to determine US No. 2 and Cull grades. Total tuber yield was calculated by summing up all grade weights and culls. Marketable tuber yield was the sum of 113-170 g, 170-283 g, and >283 g grade tuber weights.

Data analysis

Analysis of variance was completed for each year to determine if significant metribuzin, genotype, or metribuzin x genotype responses occurred. Yield reduction was calculated using the model developed by Love et al. (1993):

$$YL = 1.142 + 0.176(\log(PHI/PHU)) - 0.00796(FI)$$

Where, YL= yield loss, PHI= height of injured plants, PHU= height of uninjured plants, and FI= foliar injury. Yield reduction obtained using the model was compared with the actual yield reduction, in order to determine the validity of the model for environmental conditions in ND and the Northern Plains potato growing regions. Relative total tuber yield (RTTY), relative marketable yield, and relative plant height were calculated by dividing the value for each treated plot by the value for the untreated plot in each replicate. The relative yields were then correlated with foliar injury and relative plant height values for each experiment. Statistical analysis was carried out using SAS Statistical Software 9.4 (SAS Institute Inc., 100 SAS Campus Dr., Cary, NC 27513).

New model

Using data from the 2017 trial several new models were proposed. MATLAB was used to evaluate the predictive capability of all possible models using leave one out cross-validation. Each of the possible combinations of variables was fitted to each dataset (n=24) which were constructed by sequentially dropping one entry from the full data set. Regression was fitted using the 'regress' command of MATLAB. Using each constructed model, the left out genotype's yield reduction was predicted and compared with the observed yield reduction. The mean square error (MSE) of predictions within each model was computed to determine the average predictive capacity of each model as:

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(\hat{e}_i - e_i)^2$$

Where MSE is the mean square error of the n permutations of leave one out cross validation. $\hat{e}_i$ is the predicted yield proportion of the i^{th} accession using the model constructed from the n-1 remaining accessions for each of the i individuals. e_i is the observed yield reduction of the i^{th} individual. Those models having the lowest mean square error were considered the best predicting models. Statistical analysis was carried out using MATLAB R2016a (The MathWorks, Inc., Natick, MA).

RESULTS AND DISCUSSION

Analysis of variance

The homogeneity tests (F- test) were insignificant for the variables that were common in 2016 and 2017 growing seasons. Therefore, all the variables were analyzed on a yearly basis instead of combined across years. There was a significant ($P < 0.1$) interaction between genotypes and metribuzin treatment for foliar injury responses at 21 days after treatment (DAT) in 2016 (Table 3). This was expected since genotypes had different sensitivities to metribuzin. The main effect of genotype had a significant influence on marketable and total tuber yield as well as relative plant height before harvest during 2016 growing season. Metribuzin treatment also had a significant ($P < 0.1$) effect on marketable yield.

Table 3. Effect of metribuzin and genotype on total tuber yield, marketable yield, relative plant height, and foliar injury for 2016 growing season.

Sources of Variation	Total tuber yield	Marketable yield	Relative plant height (before harvest)	Foliar injury (21 DAT)
	----------------------------------P values-------------------------			
Metribuzin	0.2992^{ns}	0.0097^{***}	0.1684^{ns}	$<.0001^{***}$
Genotype	$<.0001^{***}$	$<.0001^{***}$	$<.0001^{***}$	0.0005^{***}
Metribuzin x Genotype	0.6117^{ns}	0.585^{ns}	0.7704^{ns}	0.0005^{***}

*** indicates significance at $P < 0.01$ level. ^{ns} indicates non significance.

The metribuzin treatment by genotype interaction was significant ($P < 0.1$) for marketable yield, relative plant height at 14 and 21 DAT, and foliar injury at 7, 14, and 21 DAT (Table 4). The main effects of metribuzin treatment and genotype had significant ($P < 0.1$) effect on total yield and relative plant height 7 DAT and just before harvest.

Table 4. Effect of metribuzin treatment and genotype on total tuber yield, marketable yield, relative plant height (at 7 DAT, 14 DAT, 21 DAT, before harvest), and foliar injury (at 7 DAT, 14 DAT, 21 DAT) for the 2017 growing season.

Sources of variation	Total tuber yield	Marketable yield	Relative plant height				Foliar injury		
			7 DAT	14 DAT	21 DAT	before harvest	7 DAT	14 DAT	21 DAT
	---P Values---								
Metribuzin	<.0001***	<.0001***	<.0001***	<.0001***	<.0001***	<.0001***	<.0001***	<.0001***	<.0001***
Genotype	<.0001***	<.0001***	<.0001***	<.0001***	<.0001***	<.0001***	<.0001***	<.0001***	<.0001***
Metribuzin x Genotype	0.0688^{ns}	0.0241**	0.48^{ns}	<.0001***	<.0001***	0.9128^{ns}	<.0001***	<.0001***	<.0001***

**, *** indicates significance at $P < 0.05$ and $P < 0.01$, respectively. ^{ns} indicates non significance.

Evaluation of previous model

The predictive model established by Love et al. (1993) did not accurately predict yield losses due to metribuzin sensitivity in 2016, for potatoes produced at Inkster, ND (Figure 2). The correlation between actual yield proportion (injured/uninjured) and predicted yield proportion (injured/uninjured using this model) was not significant ($P < 0.1$). The correlation of determination (r^2) between actual total tuber yield proportion and predicted total tuber yield proportion was only 0.160. In 2017, the model performed better with a correlation of determination of 0.424 that was highly significant ($P < 0.1$).

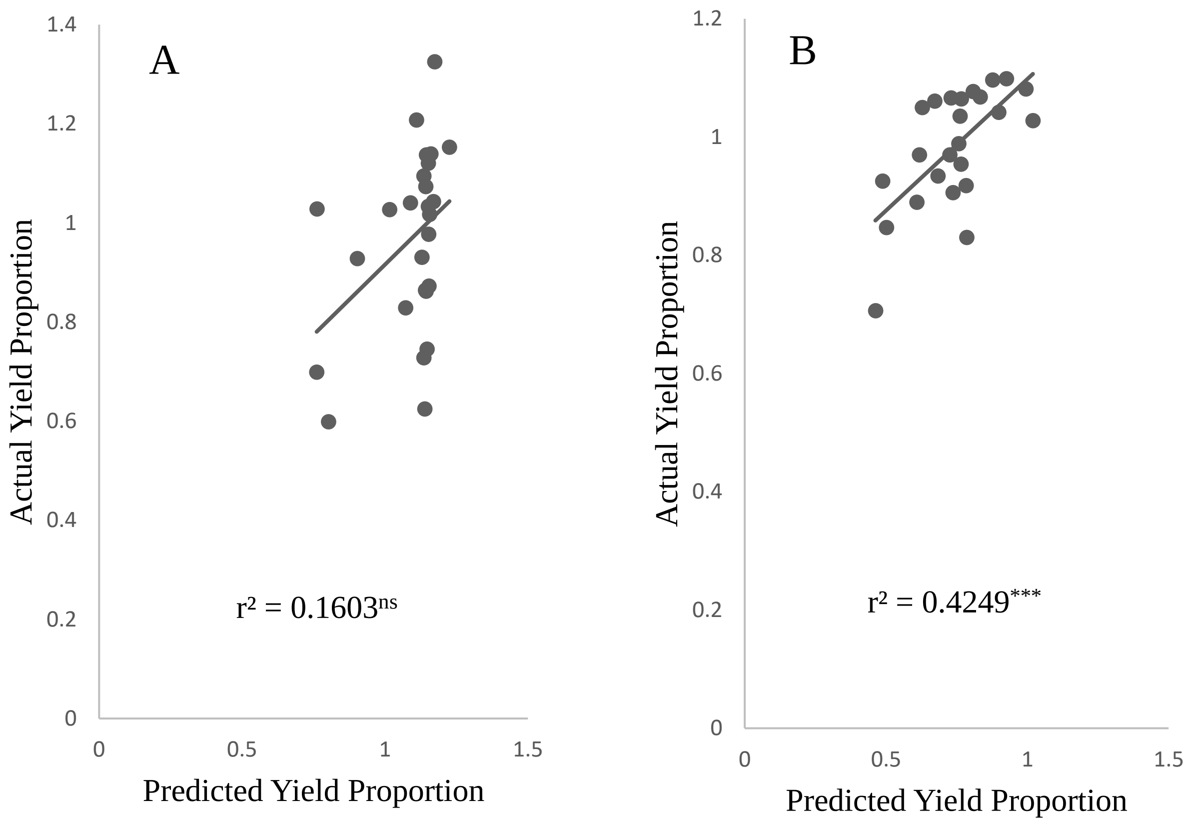
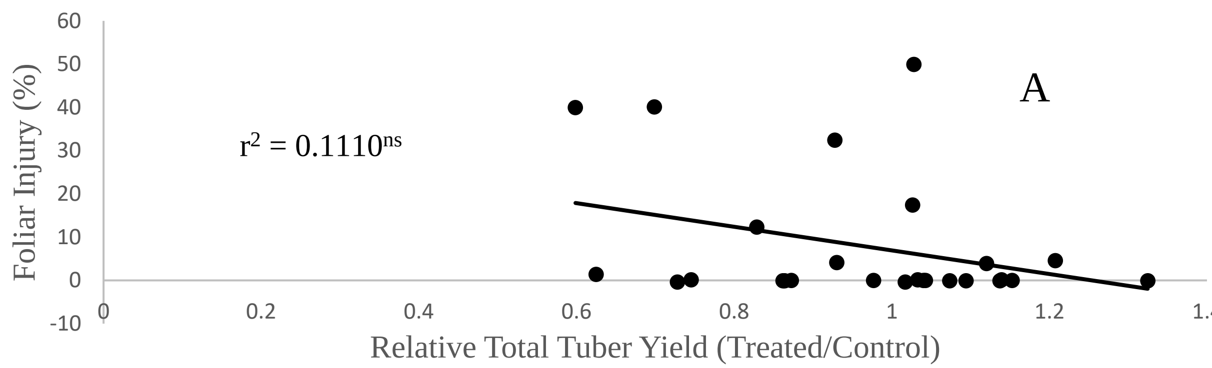


Figure 2. Correlation of actual yield proportion and predicted yield proportion (treated/control) using the predictive model by Love et al. (1993) in 2016 (A) and 2017 (B). The correlation of determination was not significant (^{ns}) for the 2016 trial and was significant at the $\alpha = 0.01$ (***) level for the 2017 trial.

Relationship of foliar injury and relative plant height to relative total tuber yield

Foliar injury and relative plant height didn't correlate with RTTY during 2016 growing season. Because most genotypes didn't exhibit foliar injury at 21 DAT (Figure 3). Even the genotypes affected by metribuzin treatment, recovered from the foliar injury symptoms by the time of assessment. The correlation of determination (r^2) between foliar injury and RTTY and between relative plant height and RTTY was 0.1110 and 0.1905, respectively.



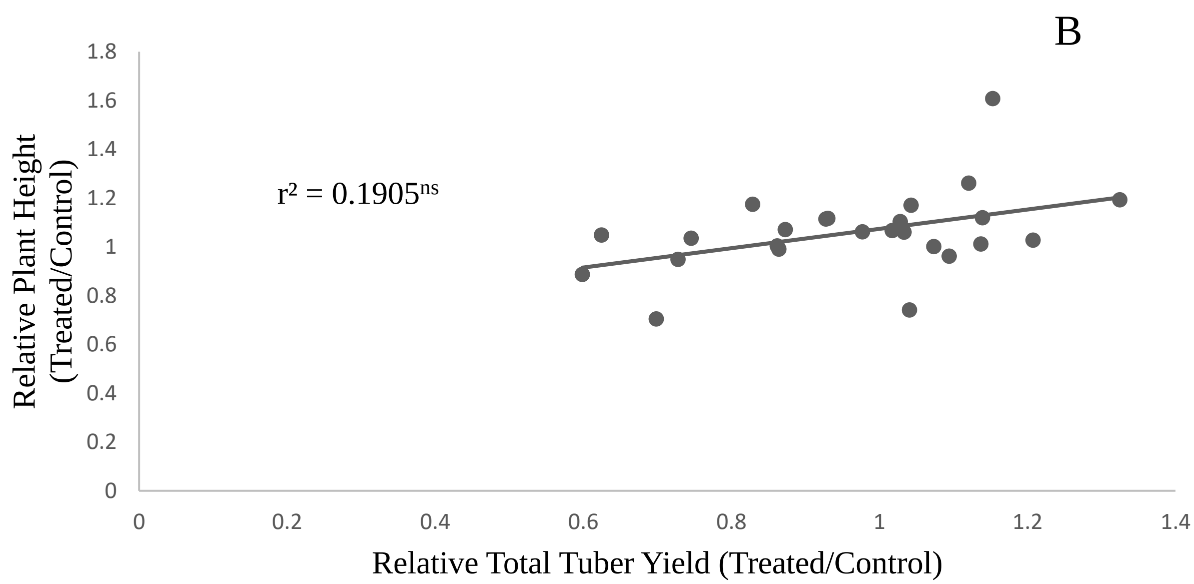


Figure 3. Correlation of foliar injury (A) measured at 21 days following metribuzin application and relative plant height (B) before harvest (Treated/Control) to relative total tuber yield (product of dividing the yield of treated plots by the yield of the control plot within the same block) in 2016. Correlation of determinations were not significant (^{ns}).

In 2017, the correlation between foliar injury and RTTY was significant ($P < 0.1$) for all the dates measured (Figure 4 and 5). The relationship produced r^2 values of 0.4636, 0.4338, and 0.428 for foliar injury at 7 DAT, 14 DAT, and 21 DAT, respectively. The correlation was higher when foliar injury was assessed at 7 days following metribuzin application versus 14 or 21 days after, which indicated the importance of evaluating genotypes shortly after a metribuzin application since all will have some recovery with time.

The correlation of determinations were comparatively lower than the results found by Love et al. (1993). The differences in correlation of determinations between 2016 and 2017 growing season were attributed to environmental differences. In 2016, the cloud cover was 0%, where as in 2017, cloud cover was 100% (Table 2). In previous studies, researchers have reported that varying degrees of metribuzin phytotoxicity depended on temperature, soil moisture, cloud cover, humidity and light intensity (Phatak and Stephenson 1973; Fortino and Splittstoesser 1974; Hutchinson 2012).

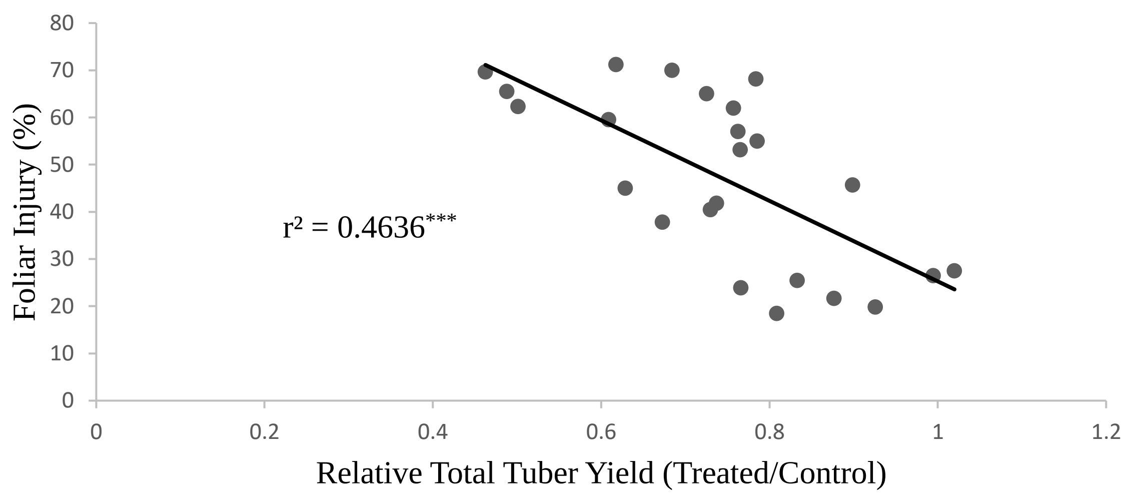


Figure 4. Correlation of foliar injury measured at 7 days after metribuzin application with relative total tuber yield (Treated/Control) in 2017. The correlation of determination was significant at the $\alpha = 0.01$(***) level.

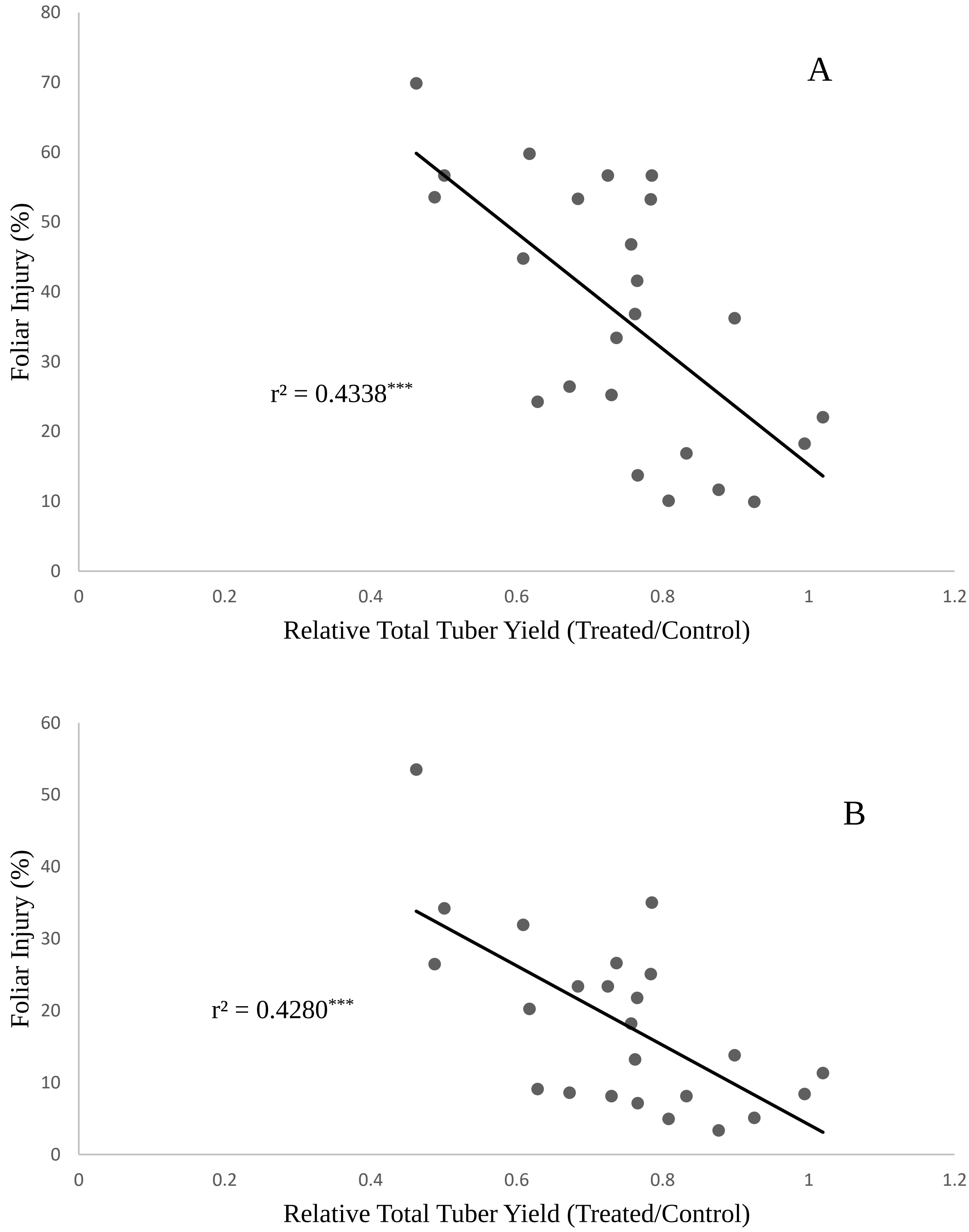


Figure 5. Correlation of foliar injury measured at 14 (A) and 21 (B) days after metribuzin application and relative total tuber yield (Treated/Control) in 2017. The correlation of determination was significant at the $\alpha = 0.01$(***) level.

In 2017, the correlation between relative plant height and RTTY was significant ($P < 0.1$) when relative plant height was taken at 14 DAT and 21 DAT with r^2 values of 0.1808 and 0.3226, respectively (Figure 6). Relative plant height taken at 7 DAT and before harvest didn't have significant relationship with RTTY. The r^2 values were 0.0593 and 0.0067 at 7 DAT and before harvest, respectively.

Relative plant height was not a good indicator of yield reduction due to metribuzin sensitivity. The genotypes did not show significant differences between treated and untreated plots in both years except for plant height at 14 DAT and 21 DAT in 2017. However, the correlation of determination only increased from 0.0593 at 7 DAT to 0.3226 at 21 DAT. The r^2 value was lowest before harvest (0.0067). The differences in plant height between treated and untreated plots increased as the interval between metribuzin application and evaluation of plant height was increased. However, before harvest, the metribuzin sensitive genotypes had recovered and there were no significant differences in plant height between treated and untreated plots. Love and Haderlie (1989) reported strong correlation of relative plant height and relative yield when they took plant height data at 70 DAT. Further research might include additional data points like plant height at 40 DAT and 50 DAT, which may provide a stronger correlation with total tuber yield.

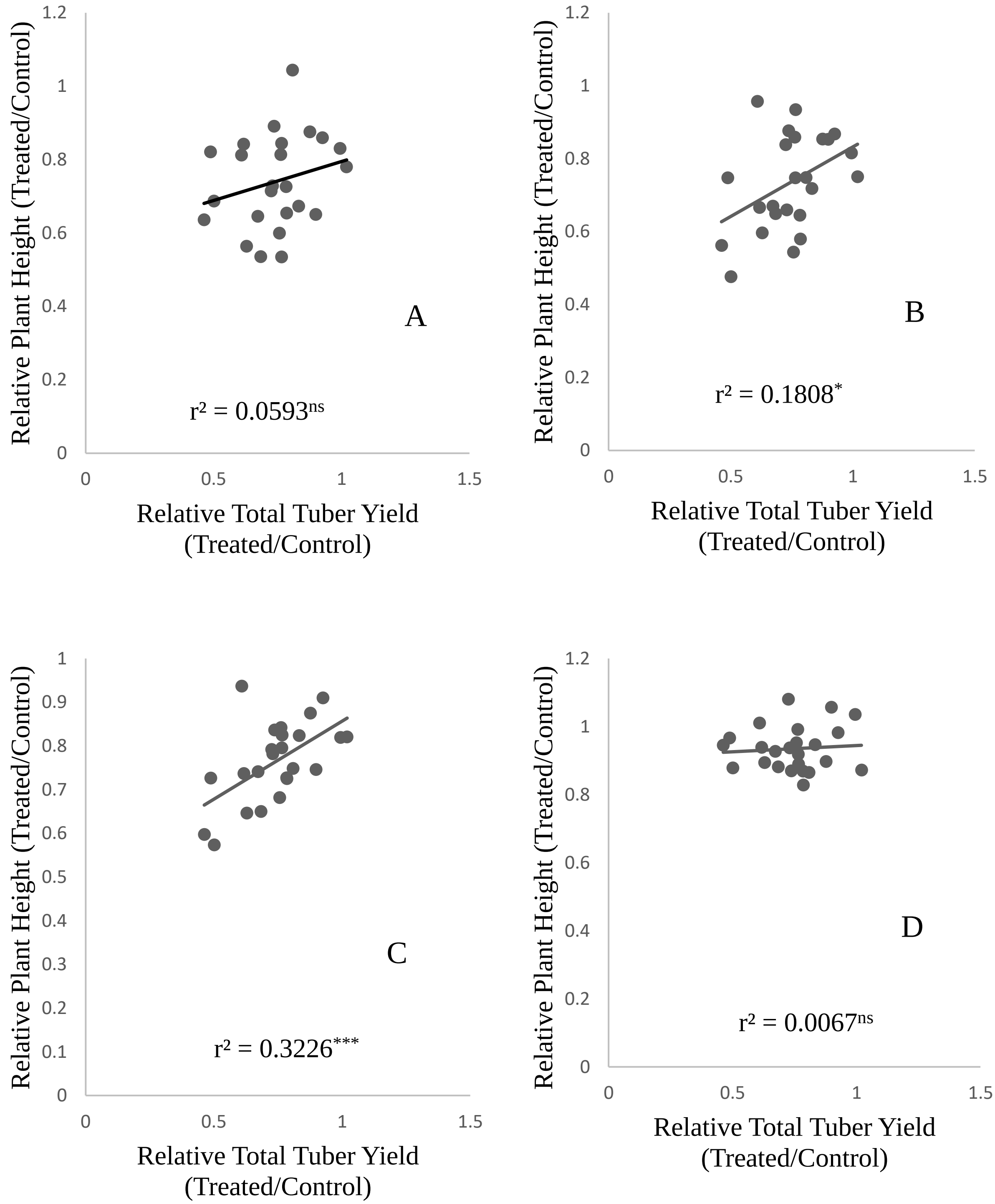


Figure 6. Correlation of relative plant height measured at 7 (A), 14 (B), 21 (C) days after metribuzin application, and before harvest (D) to relative total tuber yield in 2017. Correlation of determinations were significant at $\alpha = 0.1$ (*), 0.05 (**), and 0.01 (***) level. ^{ns} indicates non significance.

Relationship of foliar injury and relative plant height to relative marketable yield

In 2016, foliar injury and relative plant height did not have a significant correlation with relative marketable yield. The r^2 values for the relationship between relative marketable yield with foliar injury and relative plant height was 0.0032 and 0.0070, respectively. In 2017, foliar injury was significantly ($P < 0.1$) correlated with relative marketable yield. The correlation of determination decreased from 0.396 at 7DAT to 0.3143 at 14 DAT (Figure 7). However, the r^2 value increased slightly at 21 DAT (0.3219). Conversely, relative plant height at 21 DAT was significantly related to relative marketable yield with a correlation of determination of 0.1922 (Figure 8). Relative marketable yield was not significantly correlated to plant height measured at 7 DAT ($r^2 = 0.0452$), 14 DAT ($r^2 = 0.0869$), or just prior to harvest ($r^2 = 0.0146$).

The correlation of foliar injury and relative plant height to relative marketable yield was similar to that of relative total tuber yield. One thing to note here is that, the r^2 values were lower for all the variables measured in case of marketable yield. The possible reason may be that, the application of metribuzin increased the production of tubers in the 0-113 g weight range. Foliar injury and recovery might possibly make plants more juvenile and delay maturity for some genotypes. This could lead to a smaller tuber size profile.

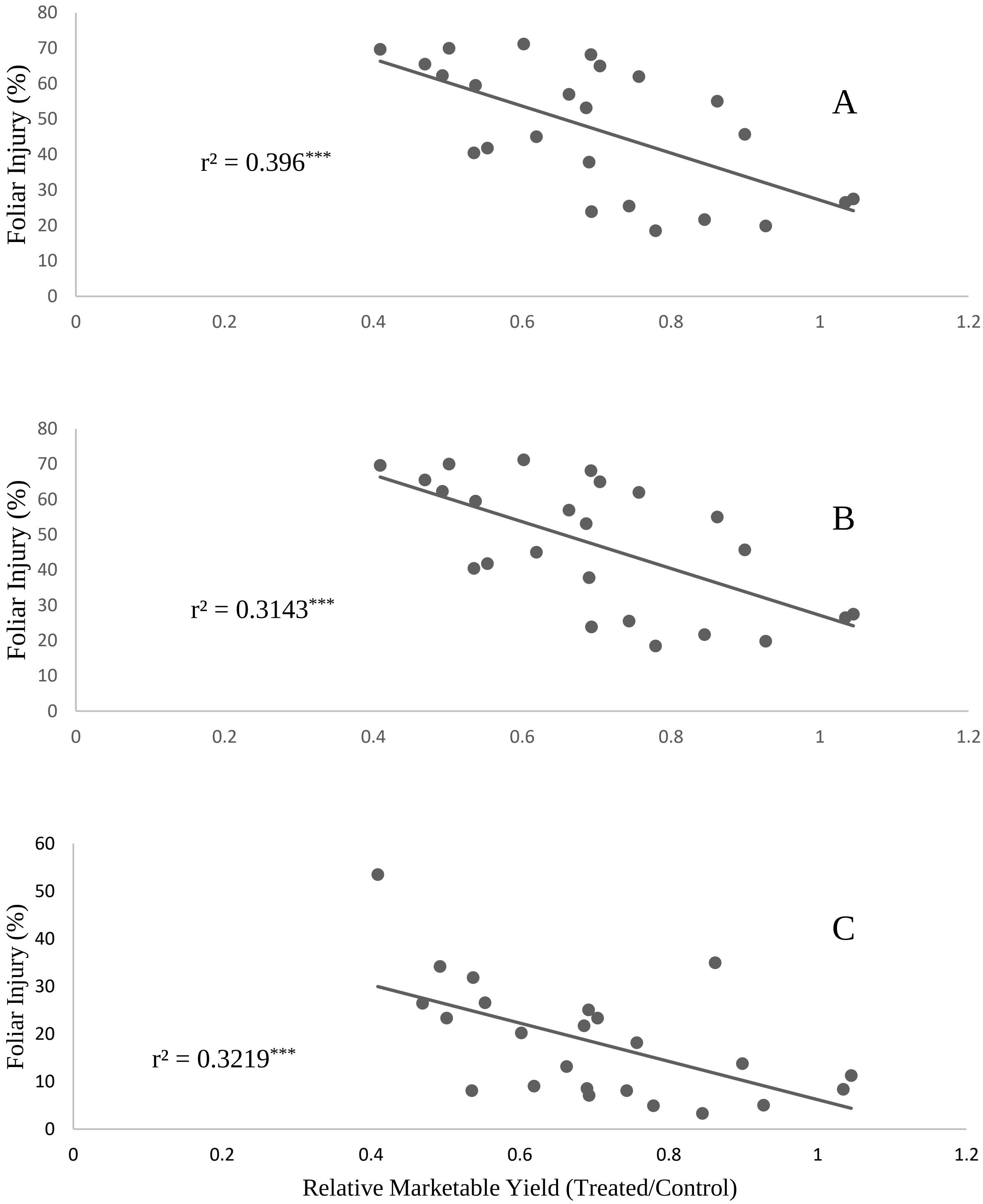


Figure 7. Correlation of foliar injury measured at 7 (A), 14 (B), and 21 (C) days after metribuzin application and relative marketable yield (Treated/Control) in 2017. The correlation of determination was significant at the $\alpha = 0.01$(***) level.

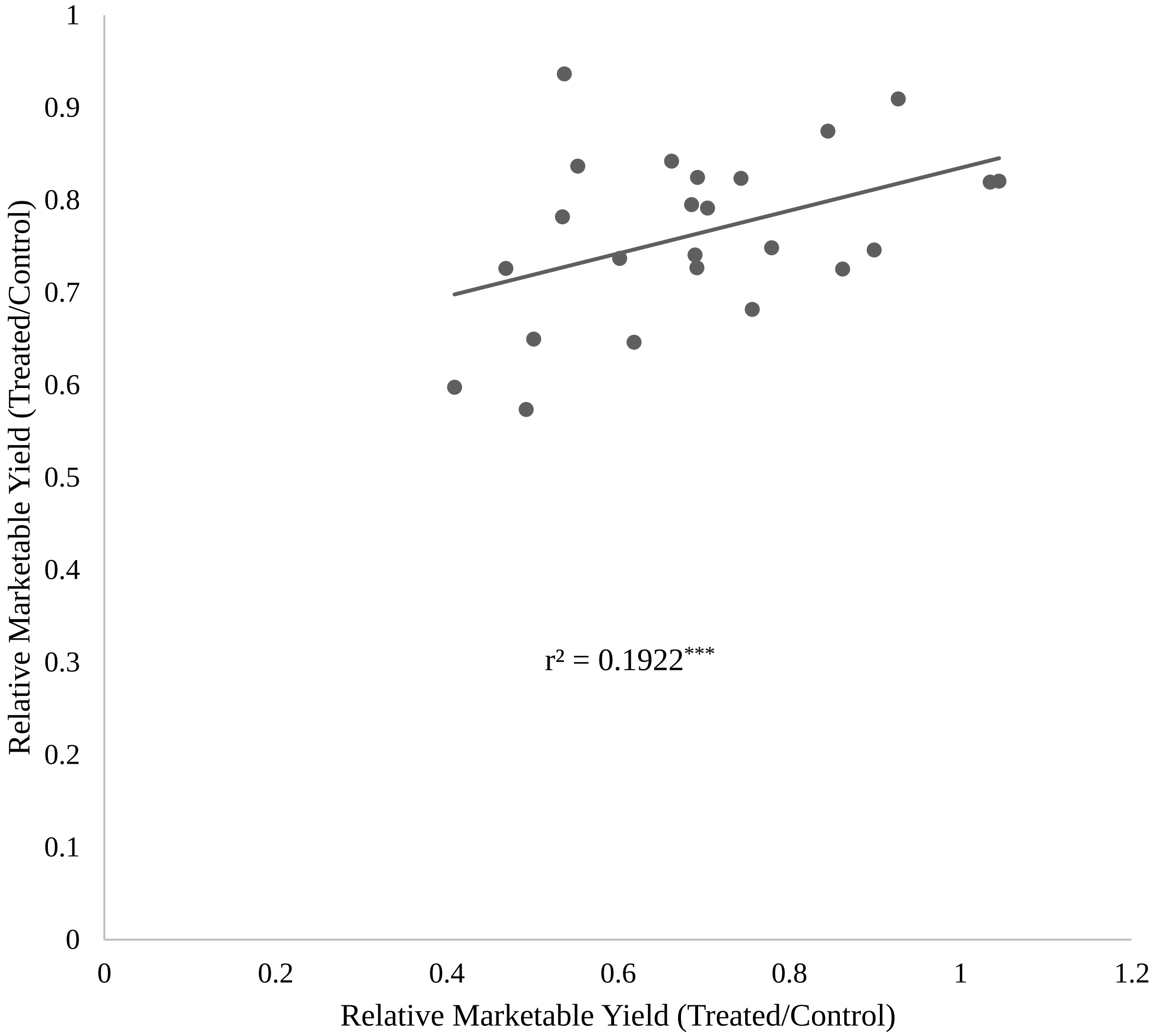


Figure 8. Correlation of relative plant height measured at 7 days following metribuzin application with relative marketable yield in 2017. Correlation of determinations were significant at $\alpha = 0.01$ (***) level. ^{ns} means not significant.

Selection of regression model

Total tuber yield

In 2016, neither foliar injury (FI) nor relative plant height (RPH) were significantly correlated with relative yield. Thus the 2017 data were used to create new models. Foliar injury data (taken at 7 DAT, 14 DAT, and 21 DAT) and relative plant height data (taken at 7 DAT, 14 DAT, 21 DAT, and before harvest) in all possible combinations were used to make 19 regression models. Among them, models 1-7 were linear regression models and models 8-19 were linear-log regression models. Most of the predicted yield proportions obtained from the new models were significantly ($P<0.1$) correlated with actual yield proportion (Table 5). However, predicted yield proportions obtained from model 4 and model 7 were not significantly ($P < 0.1$) correlated with actual yield proportion. Predicted yield proportion generated by model 10 had the highest correlation of determination ($r^2 = 0.5344$) (Table 5). Model 14 ($r^2 = 0.5016$) and model 18 ($r^2 = 0.5206$), were also able to predict 50% of the variance in actual yield proportion. However, there is a problem with correlation. It can not give any indication of how well the model will do when it is asked to make new predictions for data it has not already seen. That is why the models were not selected only based on r^2 value. The regression coefficients of all the models were also investigated. Results indicate that regression coefficients for models 1, 2, 3, 5, 6, 12, and 18 were significantly different from zero (Table 6). Therefore, based on the r^2 value and regression coefficients, models 1, 2, 3, 5, 6, 10, and 18 were selected for leave-one-out-cross validation (LOOCV).

Table 5. Relationship of predicted yield proportions obtained from new linear and linear-log regression models with actual yield proportions. The models used foliar injury data (taken at 7 DAT, 14 DAT, and 21 DAT) and relative plant height data (taken at 7 DAT, 14 DAT, 21 DAT, and before harvest) in all possible combinations as independent variables for genotypes produced at Inkster, ND, 2017.

Data used to create the models		**Model No.**	**r^2**
Only Foliar Injury	At 7 DAT	1	0.4636^{***}
	At 14 DAT	2	0.4338^{***}
	At 21 DAT	3	0.4280^{***}
Only Relative Plant Height	At 7 DAT	4	0.0582^{ns}
	At 14 DAT	5	0.2054^{*}
	At 21 DAT	6	0.3486^{**}
	Before harvest	7	0.0051^{ns}
Foliar Injury at 7 DAT & Relative Plant Height at 7 DAT		8	0.4697^{***}
Foliar Injury at 7 DAT & Relative Plant Height at 14 DAT		9	0.4911^{***}
Foliar Injury at 7 DAT & Relative Plant Height at 21 DAT		10	0.5344^{***}
Foliar Injury at 7 DAT & Relative Plant Height at harvest		11	0.4830^{***}
Foliar Injury at 14 DAT & Relative Plant Height at 7 DAT		12	0.4351^{***}
Foliar Injury at 14 DAT & Relative Plant Height at 14 DAT		13	0.4559^{***}
Foliar Injury at 14 DAT & Relative Plant Height at 21 DAT		14	0.5016^{***}
Foliar Injury at 14 DAT & Relative Plant Height at harvest		15	0.4442^{***}
Foliar Injury at 21 DAT & Relative Plant Height at 7 DAT		16	0.4303^{***}
Foliar Injury at 21 DAT & Relative Plant Height at 14 DAT		17	0.4674^{***}
Foliar Injury at 21 DAT & Relative Plant Height at 21 DAT		18	0.5206^{***}
Foliar Injury at 21 DAT & Relative Plant Height at harvest		19	0.4284^{***}

*, **, *** indicate significance at $\alpha = 0.1$, 0.05, and 0.01 probability levels, respectively. ^{ns} indicates non significance.

Table 6. P values of the estimated regression coefficients for the regression models designed to predict total yield loss due to metribuzin sensitivity, Inkster, ND, 2017.

Data used to make the model		**Model No.**	**Pr > $\lvert t\rvert$**		
			Intercept	**Log (PHR)**	**FI**
Only Foliar Injury	At 7 DAT	1	<0.0001***		0.0003***
	At 14 DAT	2	<0.0001***		0.0005***
	At 21 DAT	3	<0.0001***		0.0005***
Only Relative Plant Height	At 7 DAT	4	<0.0001***	0.256^{ns}	
	At 14 DAT	5	<0.0001***	0.0261**	
	At 21 DAT	6	<0.0001***	0.0024***	
	Before harvest	7	<0.0001***	0.7414^{ns}	
Foliar Injury at 7 DAT & Relative Plant Height at 7 DAT		8	<0.0001***	0.6276^{ns}	0.0006***
Foliar Injury at 7 DAT & Relative Plant Height at 14 DAT		9	<0.0001***	0.2986^{ns}	0.0025***
Foliar Injury at 7 DAT & Relative Plant Height at 21 DAT		10	<0.0001***	0.0882^{ns}	0.0087***
Foliar Injury at 7 DAT & Relative Plant Height at harvest		11	<0.0001***	0.3844^{ns}	0.0002***
Foliar Injury at 14 DAT & Relative Plant Height at 7 DAT		12	<0.0001***	0.827*	0.0012***
Foliar Injury at 14 DAT & Relative Plant Height at 14 DAT		13	<0.0001***	0.366^{ns}	0.0053***
Foliar Injury at 14 DAT & Relative Plant Height at 21 DAT		14	<0.0001***	0.1057^{ns}	0.0191**
Foliar Injury at 14 DAT & Relative Plant Height at harvest		15	<0.0001***	0.5372^{ns}	0.0005***
Foliar Injury at 21 DAT & Relative Plant Height at 7 DAT		16	<0.0001***	0.7725^{ns}	0.0013***
Foliar Injury at 21 DAT & Relative Plant Height at 14 DAT		17	<0.0001***	0.2261^{ns}	0.0042***
Foliar Injury at 21 DAT & Relative Plant Height at 21 DAT		18	<0.0001***	0.0569*	0.0121**
Foliar Injury at 21 DAT & Relative Plant Height at harvest		19	<0.0001***	0.9^{ns}	0.0007***

*, **, *** indicate significance at $\alpha = 0.1$, 0.05, and 0.01 probability levels, respectively. ^{ns} indicates non significance.

Marketable yield

Regression models were also created to predict marketable yield. Foliar injury data (taken at 7 DAT, 14 DAT, and 21 DAT) and relative plant height data (taken at 7 DAT, 14 DAT, 21 DAT, and before harvest) in all possible combinations were used to make 19 regression models. Most of the predicted marketable yield proportions obtained from the new models indicated significant ($P<0.1$) correlation with actual marketable yield proportion except for models 4, 5, and 7(Table 7). Predicted yield proportion generated by model 11 had the highest correlation of determination ($r^2 = 0.43$) (Table 7). However, to select the best fit model the regression coefficients of these models were investigated. Regression coefficients for models 1, 2, 3, and 6 were significantly different from zero (Table 8). These models were selected for further LOOCV analysis.

Table 7. Relationship of predicted marketable yield proportions obtained from new linear and linear-log regression models with actual marketable yield proportions. The models used foliar injury data (taken at 7 DAT, 14 DAT, and 21 DAT) and relative plant height data (taken at 7 DAT, 14 DAT, 21 DAT, and before harvest) in all possible combinations as independent variables for genotypes produced at Inkster, ND, 2017.

Data used to create the models		**Model No.**	$\mathbf{r^2}$
Only Foliar Injury	At 7 DAT	1	0.40^{***}
	At 14 DAT	2	0.31^{***}
	At 21 DAT	3	0.32^{***}
Only Relative Plant Height	At 7 DAT	4	0.05^{ns}
	At 14 DAT	5	0.10^{ns}
	At 21 DAT	6	0.21^{*}
	Before harvest	7	0.01^{ns}
Foliar Injury at 7 DAT & Relative Plant Height at 7 DAT		8	0.40^{***}
Foliar Injury at 7 DAT & Relative Plant Height at 14 DAT		9	0.40^{***}
Foliar Injury at 7 DAT & Relative Plant Height at 21 DAT		10	0.42^{***}
Foliar Injury at 7 DAT & Relative Plant Height at harvest		11	0.43^{***}
Foliar Injury at 14 DAT & Relative Plant Height at 7 DAT		12	0.31^{***}
Foliar Injury at 14 DAT & Relative Plant Height at 14 DAT		13	0.32^{***}
Foliar Injury at 14 DAT & Relative Plant Height at 21 DAT		14	0.34^{***}
Foliar Injury at 14 DAT & Relative Plant Height at harvest		15	0.33^{***}
Foliar Injury at 21 DAT & Relative Plant Height at 7 DAT		16	0.32^{***}
Foliar Injury at 21 DAT & Relative Plant Height at 14 DAT		17	0.34^{***}
Foliar Injury at 21 DAT & Relative Plant Height at 21 DAT		18	0.36^{***}
Foliar Injury at 21 DAT & Relative Plant Height at harvest		19	0.33^{***}

*, **, *** indicate significance at $\alpha = 0.1$, 0.05, and 0.01 probability levels, respectively. ^{ns} indicates non significance.

Table 8. P values of the estimated regression coefficients for the regression models designed to predict marketable yield loss due to metribuzin sensitivity. Inkster, ND. 2017.

Data used to make the model		**Model No.**	**Pr > |t|**		
			Intercept	**Log (PHR)**	**FI**
Only Foliar Injury	At 7 DAT	1	<0.0001***		0.001***
	At 14 DAT	2	<0.0001***		0.0044***
	At 21 DAT	3	<0.0001***		0.0038***
Only Relative Plant Height	At 7 DAT	4	<0.0001***	0.3083 ns	
	At 14 DAT	5	<0.0001***	0.1334 ns	
	At 21 DAT	6	<0.0001***	0.0243*	
	Before harvest	7	<0.0001***	0.6178 ns	
Foliar Injury at 7 DAT & Relative Plant Height at 7 DAT		8	<0.0001***	0.6443 ns	0.002***
Foliar Injury at 7 DAT & Relative Plant Height at 14 DAT		9	<0.0001***	0.8266 ns	0.0041***
Foliar Injury at 7 DAT & Relative Plant Height at 21 DAT		10	<0.0001***	0.4021 ns	0.012
Foliar Injury at 7 DAT & Relative Plant Height at harvest		11	<0.0001***	0.3141 ns	0.0009***
Foliar Injury at 14 DAT & Relative Plant Height at 7 DAT		12	<0.0001***	0.9213 ns	0.0093***
Foliar Injury at 14 DAT & Relative Plant Height at 14 DAT		13	<0.0001***	0.8023 ns	0.0174**
Foliar Injury at 14 DAT & Relative Plant Height at 21 DAT		14	<0.0001***	0.3537 ns	0.0524*
Foliar Injury at 14 DAT & Relative Plant Height at harvest		15	<0.0001***	0.4617 ns	0.0046***
Foliar Injury at 21 DAT & Relative Plant Height at 7 DAT		16	<0.0001***	0.7832 ns	0.0079***
Foliar Injury at 21 DAT & Relative Plant Height at 14 DAT		17	<0.0001***	0.6323 ns	0.0139**
Foliar Injury at 21 DAT & Relative Plant Height at 21 DAT		18	<0.0001***	0.2591 ns	0.0359*
Foliar Injury at 21 DAT & Relative Plant Height at harvest		19	<0.0001***	0.7246 ns	0.0051***

*, **, *** indicate significant at 0.1, 0.05, and 0.01 probability levels, respectively. ns indicates not significant.

Leave one out cross validation

Total tuber yield

LOOCV was used to validate the predictive ability of the generalized versions of the selected models. Model 3, where foliar injury at 21 DAT was used to predict yield loss, had the lowest mean square error (MSE = 0.3126) (Table 9). This model was finally selected due to it having the best ability to predict response of an independent sample. The resulting prediction equation is as follows:

$$YL = 0.8854 - 0.00776\,(FI)$$

Where, YL is the predicted proportion of uninjured crop yield expressed by crop injury and FI is the percent foliar injury. To determine the percent yield loss (PYL), the following equation can be used:

$$PYL = (1 - (0.8854 - 0.00776\,(FI))) \times 100$$

Table 9. Mean square error values of the selected models generated by leave one out cross validation method.

Data used to create the model		**Model No.**	**MSE**
Only Foliar Injury	At 7 DAT	1	0.3261
	At 14 DAT	2	0.3284
	At 21 DAT	3	0.3126
Only Relative Plant Height	At 14 DAT	5	0.3907
	At 21 DAT	6	0.4674
Foliar Injury at 7 DAT & Relative Plant Height at 21 DAT		10	0.3285
Foliar Injury at 21 DAT & Relative Plant Height at 21 DAT		18	0.3296

The model selected to predict total tuber yield loss due to metribuzin sensitivity had an r^2 value which was lower than other models. It had regression coefficients that were significantly different from zero and lowest mean square error (obtained from LOOCV). Careful inspection of the regression coefficients reveals some important features of the model. The intercept is lower than 1, which indicates that, with low levels of injury the model will predict yield decrease. The coefficient of foliar injury was negative indicating that if the percent injury increases, the yield proportion represented by injured/uninjured decreases.

In 2017, the previous model created by Love et al. (1993) had an r^2 value of 0.4249. The new model also had an r^2 value of 0.4280. However, the difference between these two models is, the new model does not include plant height data to predict yield loss. Investigating the regression coefficients, it has been found that the plant height did not have significant contribution to the model. Love et al. (1993) also reported that contribution of plant height reduction to their model was relatively small and was only a fraction of foliar injury. In this case the new model reduces the extra work needed to take plant height data. Moreover, using the new model, yield loss can be predicted 21 days following metribuzin application which is earlier than the previous model.

Marketable yield

In case of marketable yield, the lowest MSE, 0.0205, was obtained from model 1 (Table 10). Foliar injury at 7 DAT was the best predictor of marketable yield loss due to metribuzin sensitivity. The resulting prediction equation is as follows:

$$YL = 0.84461 – 0.00801 (FI)$$

Where, YL is the predicted proportion of uninjured crop yield expressed by crop injury and FI is the percent foliar injury. To determine the percent yield loss (PYL), the following equation can be used:

$$PYL = (1 - (0.84461 - 0.00801\ (FI))) \times 100$$

Table 10. Mean square error values of the selected models generated by leave one out cross validation method.

Data used to make the model		**Model No.**	**MSE**
Only Foliar Injury	At 7 DAT	1	0.0205
	At 14 DAT	2	0.0233
	At 21 DAT	3	0.023
Only Relative Plant Height	At 21 DAT	6	0.0284

The new model selected to predict marketable yield loss due to metribuzin sensitivity had an r^2 value of 0.40. The regression coefficients of this model had similar properties with slightly different values. This model can explain only 40% of the variance in actual yield reduction. Therefore, it would not be wise to use this predictive model to evaluate a genotype for marketable yield loss due to metribuzin sensitivity.

The new model to predict total tuber yield can be used to accurately screen large numbers of new cultivars and breeding selections to metribuzin sensitivity. It will also help crop consultants and industry personnel to better assess the seriousness of metribuzin injury early in the growing season.

CONCLUSION

Field experiments were conducted to evaluate a predictive model established by Love et. al (1993) which can predict yield loss due to metribuzin injury. The overall goal of this study was to create a new model to predict yield loss due to metribuzin sensitivity for the environmental condition of potato growing regions in North Dakota, if necessary.

Comparison of predicted and observed yield reductions demonstrated the model's inability to accurately predict metribuzin sensitivity in ND. Foliar injury was highly correlated to yield reduction and was highest at 7 DAT. Relative plant height did not have strong relationship with yield reduction. Therefore, the finally selected model only uses foliar injury at 21 DAT data to predict yield loss. Foliar injury and relative plant height were not a good indicator of marketable yield loss. We suggest not to use foliar injury and plant height reduction to predict marketable yield loss in potato due to metribuzin sensitivity.

Future research should investigate the model's accuracy in case of different types of potato genotypes i.e. determinate and indeterminate. Effect of metribuzin on other variables like vine maturity should also be investigated.

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APPENDIX

Table A1. ANOVA for total tuber yield affected by metribuzin and genotype, Inkster, ND, 2016.

Source	DF	MS	F Value
Rep	1	347.61	9.15***
Metribuzin	1	41.82	1.1
Genotype	25	217.11	5.71***
Metribuzin X Genotype	25	33.93	0.89

*, **, *** indicate significant at 0.1,0.05, and 0.01 probability levels, respectively.

Table A2. ANOVA for relative plant height before harvest affected by metribuzin and genotype, Inkster, ND, 2016.

Source	DF	MS	F Value
Rep	1	4323.01	24.78***
Metribuzin	1	340.77	1.95
Genotype	25	1094.04	6.27***
Metribuzin X Genotype	25	132.34	0.76

*, **, *** indicate significant at 0.1,0.05, and 0.01 probability levels, respectively.

Table A3. ANOVA for foliar injury at 21 DAT affected by metribuzin and genotype, Inkster, ND, 2016.

Source	DF	MS	F Value
Rep	1	0.62	0.01
Metribuzin	1	1448.89	19.05***
Genotype	25	225.12	2.96***
Metribuzin X Genotype	25	225.23	2.96***

*, **, *** indicate significant at 0.1,0.05, and 0.01 probability levels, respectively.

Table A4. ANOVA for marketable yield affected by metribuzin and genotype, Inkster, ND, 2016.

Source	DF	MS	F Value
Rep	1	13.40	0.32
Metribuzin	1	302.25	7.24***
Genotype	25	322.19	7.72***
Metribuzin X Genotype	25	38.21	0.91

*, **, *** indicate significant at 0.1,0.05, and 0.01 probability levels, respectively.

Table A5. ANOVA for total tuber yield affected by metribuzin and genotype, Inkster, ND, 2017.

Source	DF	MS	F Value
Rep	2	108.91	4.78**
Metribuzin	1	2201.23	96.55***
Genotype	23	135.17	5.93***
Metribuzin X Genotype	23	35.80	1.57*

*, **, *** indicate significant at 0.1,0.05, and 0.01 probability levels, respectively.

Table A6. ANOVA for marketable yield affected by metribuzin and genotype, Inkster, ND, 2017.

Source	DF	MS	F Value
Rep	2	123.07	5.81***
Metribuzin	1	1917.92	90.59***
Genotype	23	246.25	11.63***
Metribuzin X Genotype	23	38.55	1.82*

*, **, *** indicate significant at 0.1,0.05, and 0.01 probability levels, respectively.

Table A7. ANOVA for relative plant height at 7 DAT affected by metribuzin and genotype, Inkster, ND, 2017.

Source	DF	MS	F Value
Rep	2	22.35	0.85
Metribuzin	1	2139.18	81.64***
Genotype	23	231.61	8.84***
Metribuzin X Genotype	23	26.07	0.99

*, **, *** indicate significant at 0.1,0.05, and 0.01 probability levels, respectively.

Table A8. ANOVA for relative plant height at 14 DAT affected by metribuzin and genotype, Inkster, ND, 2017.

Source	DF	MS	F Value
Rep	2	28.03	2.66*
Metribuzin	1	4767.36	452.92***
Genotype	23	292.60	27.8***
Metribuzin X Genotype	23	47.21	4.49***

*, **, *** indicate significant at 0.1,0.05, and 0.01 probability levels, respectively.

Table A9. ANOVA for relative plant height at 21 DAT affected by metribuzin and genotype, Inkster, ND, 2017.

Source	DF	MS	F Value
Rep	2	103.52	11.02***
Metribuzin	1	5981.57	636.55***
Genotype	23	245.08	26.08***
Metribuzin X Genotype	23	39.75	4.23***

*, **, *** indicate significant at 0.1,0.05, and 0.01 probability levels, respectively.

Table A10. ANOVA for relative plant height before harvest affected by metribuzin and genotype, Inkster, ND, 2017.

Source	DF	MS	F Value
Rep	2	338.89	8.15***
Metribuzin	1	615.65	14.81***
Genotype	23	838.97	20.18***
Metribuzin X Genotype	23	25.29	0.61

*, **, *** indicate significant at 0.1,0.05, and 0.01 probability levels, respectively.

Table A11. ANOVA for foliar injury at 7 DAT affected by metribuzin and genotype, Inkster, ND, 2017.

Source	DF	MS	F Value
Rep	2	3.91	0.05
Metribuzin	1	77179.13	1026.54***
Genotype	23	490.15	6.52***
Metribuzin X Genotype	23	492.09	6.55***

*, **, ***indicate significant at 0.1,0.05, and 0.01 probability levels, respectively.

Table A12. ANOVA for foliar injury at 14 DAT affected by metribuzin and genotype, Inkster, ND, 2017.

Source	DF	MS	F Value
Rep	2	248.84	5.31***
Metribuzin	1	46358.69	989.93***
Genotype	23	494.47	10.56***
Metribuzin X Genotype	23	495.52	10.58***

*, **, *** indicate significant at 0.1,0.05, and 0.01 probability levels, respectively.

Table A13. ANOVA for foliar injury at 21 DAT affected by metribuzin and genotype, Inkster, ND, 2017.

Source	DF	MS	F Value
Rep	2	129.44	4.76***
Metribuzin	1	11669.77	429.47***
Genotype	23	220.46	8.11***
Metribuzin X Genotype	23	222.38	8.18***

*, **, *** indicate significant at 0.1,0.05, and 0.01 probability levels, respectively.