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Occurrence and Management of PSII-Inhibitor-Resistant *Chenopodium album* L. in Atlantic Canadian Potato Production

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Received: 18 August 2020; Accepted: 9 September 2020; Published: 11 September 2020

Abstract: Potato producers in the Atlantic Canadian provinces of New Brunswick (NB) and Prince Edward Island (PE) rely on the photosystem II-inhibiting herbicide metribuzin for weed management. Recently, potato producers in the region have reported unacceptable common lambsquarters control following an application of metribuzin. Tissue and seed samples were collected from escaped common lambsquarters populations from across the potato producing regions of NB and PE and screened for the Ser264Gly mutation in *psbA*. Overall, 46% of sampled populations possessed the Ser264Gly mutation across the region. Cross-resistance testing to atrazine, metribuzin and linuron confirmed populations with the Ser264Gly were resistant to triazines and triazinones but remained susceptible to linuron. Dose response analysis determined a moderate level of resistance to metribuzin in common lambsquarters which would not be controlled in producers fields. A field experiment was conducted in Fredericton, NB and Harrington, PE, to determine if currently registered and unregistered products and tank-mixes would control PSII-inhibitor-resistant common lambsquarters in potato. All evaluated products, with the exception of S-metolachlor, provided control equivalent to the weed-free check without compromising potato yield or quality. This study demonstrates that PSII-inhibitor-resistant common lambsquarters are found in Atlantic Canadian potato production systems, but can be controlled with currently registered herbicides and rates with alternative modes of action.

Keywords: common lambsquarters; herbicide resistance; metribuzin; photosystem II inhibitor; potato; Ser264Gly

1. Introduction

The Atlantic Canadian provinces of New Brunswick (NB), and Prince Edward Island (PE), are the largest potato (*Solanum tuberosum* L.) producing regions in Canada with over 40% of total Canadian potato acreage seeded in these two provinces [1]. Shifts in management from two-pass to one-pass systems in the region have reduced reliance on hilling and cultivation for weed management. In a

two-pass system, potatoes are planted followed by hilling at the potato ground crack, whereas in a one-pass system potatoes are hilled at planting with no additional soil disturbance. Potato producers have limited broadleaf herbicide options post-potato emergence and rely on preemergence photosystem II (PSII)-inhibitor herbicides for season-long weed control. Metribuzin—a triazinone PSII-inhibitor—is the most widely used herbicide in potato production [2] and estimated to be applied to over 75% of potato acreage in the Atlantic region (L MacKinnon, personal communication). Linuron—a urea-substituted PSII-inhibitor—is also widely used in the region and applied to 27% of potato acreage in nearby Maine, USA [2]. Producers in the region have little familiarity with alternative modes of action currently available for potato production. In Atlantic Canada, rates of metribuzin typically range from 0.42 to 0.51 kg ha^{-1} and 0.56 to 0.62 kg ha^{-1} for one- and two-pass systems, respectively; whereas linuron rates typically range from 0.86 kg ha^{-1} to 1.1 kg ha^{-1} in both systems.

PSII-inhibiting herbicides function through binding to the Qb-binding site of the D1 protein of PSII. Herbicide-binding blocks electron flow from Qa to Qb causing over-reduction of Qa and formation of triplet state chlorophyll which interacts with O_2 to form $^1O_2$. Triplet state chlorophyll and $^1O_2$ interact with and remove hydrogen ions from cell membranes, inducing lipid peroxidation leading to plant death. The various subgroups of PSII-inhibiting herbicides function through similar pathways, however, utilize different binding patterns at the Qb-binding site [3]. Resistance to PSII inhibiting herbicides has been well documented worldwide with resistance confirmed in 74 and 29 species for triazines and substituted ureas, respectively [4]. The majority of triazine-resistance has resulted from point mutations in the chloroplast *psbA* gene, which alters conformation of the target site on the D1 protein and prevents herbicide-binding [5]. The most common mutation conferring triazine-resistance worldwide is a serine to glycine substitution at amino acid position 264 (Ser264Gly) which continues to allow for plastoquinone binding at the Qb site while preventing triazine-binding [6]. Ser264Gly confers a high and moderate level of resistance to triazine and triazones while remaining susceptible to substituted urea and nitrile herbicides. In addition to the Ser264Gly mutation, seven other mutations have been documented, Ala251Val, Asn266Thr, Leu218Val, Phe255Ile, Ser264Thr, Phe255Val and Val219Ile each conferring specific cross-resistance patterns to triazine, triazone, substituted urea and nitrile herbicides [6]. Several incidences of non-target site resistance mechanisms to PSII-inhibiting herbicides have been reported including detoxification via glutathione s-transferases in *Abutilon theophrasti* Medik [7].

Common lambsquarters (*Chenopodium album* L.) is a highly competitive, cosmopolitan weed of significant economic importance in wide variety of crops. Yield losses in potato due to competition with common lambsquarters have been reported to approach 85% due to reductions in tuber weight and quality [8,9]. PSII-inhibitor-resistant common lambsquarters populations have been documented since 1971 [10] and are now reported in 20 countries worldwide [4]. Recently, producers in the Atlantic region have begun reporting poor control of common lambsquarters following applications of metribuzin. To date, no studies have sought to confirm if the poor control now observed in Atlantic Canada was due to herbicide resistance. Therefore, the objectives of the present study were to (1) document incidence of PSII-inhibitor-resistance in common lambsquarters across the potato-producing regions of NB and PE, (2) investigate presence of Ser264Gly in the *psbA* gene of common lambsquarters conferring PSII-inhibitor-resistance and (3) evaluate alternative preemergence herbicide options for control of PSII-inhibitor-resistant common lambsquarters in Atlantic Canadian potato production.

2. Materials and Methods

2.1. Collection of Common Lambsquarters Populations

Leaf samples of common lambsquarters were collected from producer potato fields at total of 191 sites across the potato-producing regions of Prince Edward Island, and New Brunswick, Canada, in 2017, 2018 and 2019. Site selection was non-random and consistent with previous weed surveys to identify unknown incidence of herbicide resistance [11,12]. All samples were collected from potato

fields with visible common lambsquarters escapes. Field history was unknown at time of collection. Leaf samples from 5 plants field^{-1} were collected from August until September prior to potato top-kill. At each field location, a young leaf sample was collected and placed in a paper envelope. Leaf samples were stored in a plastic bag with 10 g of silica gel orange (Sigma-Aldrich, Mississauga, ON, Canada) at 4 °C prior to analysis. Samples were analyzed individually. Leaf samples from 39, 44, and 108 populations were collected in 2017, 2018 and 2019, respectively. Sample locations were GPS-referenced for seed collection (Figure 1). Where possible, seeds were collected from mature common lambsquarters plants in fields which had been previously sampled for tissue analysis prior to potato harvest in September and October. Inflorescences from 20 random plants field^{-1} were clipped, placed in a bag and hand-threshed. Seeds collected from a single field were bulked. Seed samples from 8, 37, and 3 populations were collected in 2017, 2018 and 2019, respectively.

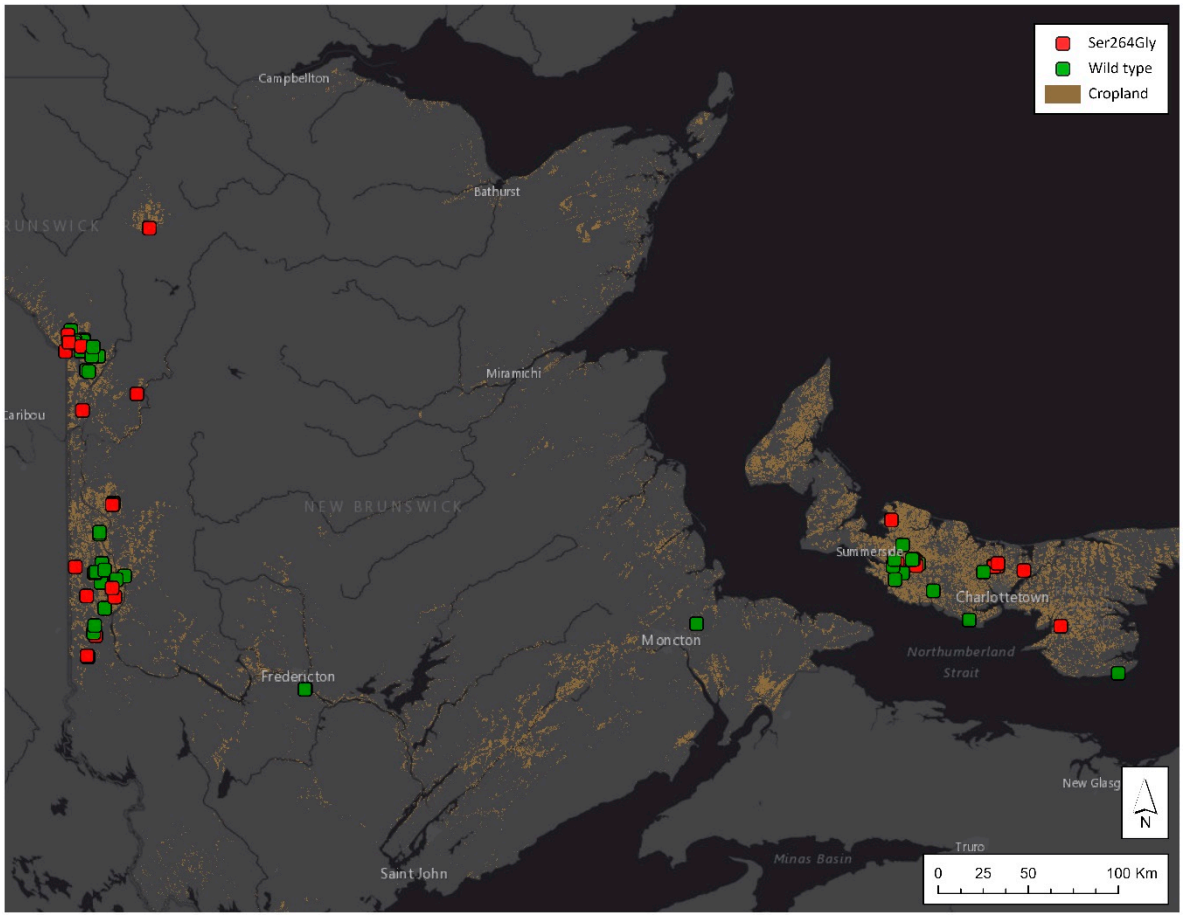

Figure 1. Location of collected common lambsquarters populations from New Brunswick and Prince Edward Island potato fields screened for possession of the Ser264Gly mutation in *psbA*. Populations that tested positive for Ser264Gly are highlighted in red; wild-type are in green.

2.2. Identifying Target-Site Mutation

Genomic DNA of common lambsquarters was extracted from fresh leaf tissue (n = 191) using Qiagen DNeasy Plant Mini Kit (Qiagen, Inc., Mississauga, Canada) according to the manufacturer's instructions. A pair of primers and a pair of probes were constructed based on the *psbA* gene sequence of common lambsquarters to test for the well-known Ser264Gly mutation [13]. PCR primers were 5′-TCATGGTTATTTCGGCCGATTGAT-3′ and 5′-GCCAAGCAGCTAAGAAGAAGTGTAA-3′. The probes were 5′-CTTTCAATATGCTAGTTTCAA-3′ (VIC; serine(wild type)) and 5′-CAATATGCT GGTTTCAA-3′ (FAM; glycine(resistant)). Quantitative PCR was performed on an AriaMx (Agilent, CA, USA).

2.3. Single-Dose Assays

Seeds of collected populations (n = 48) were surface-sterilized in a 5% hypochlorite solution (Thermo Fisher Scientific, Mississauga, ON, Canada) with 0.1% Tween (Thermo Fisher Scientific, Mississauga, ON, Canada) for 30 min followed by triple rinsing with dH_2O prior to planting. Ten seeds population^{-1} were seeded into square pots (8.5 × 8.5 × 10 cm, L × W × H) containing a 50:50 mix of sterilized Harrington, PE, field soil (Orthic Humo-Ferric Podzol, 3% organic matter, pH 6.6) and sterilized play sand (Quikrete Premium Play Sand, Home Depot, North York, ON, Canada). Greenhouse conditions were 22/16 °C day/night temperatures with a 14/10 h day/night photoperiod. Supplemental lighting was provided by high pressure sodium lights (550 µmol m^{-2} s^{-1}). A single irrigation line to each pot provided 150 mL of water day^{-1}. One week after emergence, pots were thinned to 3 plants pot^{-1} and fertilized with 100 mL of commercial fertilizer (N–P–K, 24%–8%–16% *w/w*; Miracle Grow, Scotts, Marysville, OH, USA). At the two- to three-leaf stage, herbicide screening was conducted as a randomized complete block design using discriminating doses of the following herbicides: metribuzin (Sencor 75DF, Bayer CropScience Inc., Phoenix, AZ, USA) at 750 g a.i. ha^{-1}, atrazine (Aatrex 480, Syngenta Canada, Guelph, ON, Canada) at 1 kg a.i. ha^{-1} and linuron (Lorox L, Tessenderlo Kerley Inc., Phoenix, AZ, USA) at 1 kg a.i. ha^{-1} in addition to an untreated control [14]. Experimental units consisted of 3 pots of 3 plants pot^{-1} and were replicated thrice. All treatments were applied in a single-track research spray chamber (DeVries Manufacturing, Hollandale, MS, USA) equipped with a single TP8001 EVS (TeeJet Technologies, Springfield, MA, USA) nozzle set to deliver 200 L ha^{-1} at 210 kPa. Following treatment, plants were returned to the greenhouse and monitored. Three weeks after application (WAA), plants were rated as dead (susceptible) or alive (resistant). Remaining above-ground biomass was harvested, dried to constant moisture at 60 °C and weighed.

2.4. Herbicide Dose–Response

Seeds of select populations were surface sterilized as previously described. Soil and greenhouse conditions were as described above for single-dose assays. Number of seeds was adjusted for each population based on previous germination tests to achieve a target density of 10 plants pot^{-1}. One week after emergence, pots were thinned to 5 plants pot^{-1} and fertilized with commercial fertilizer (N–P–K, 24%–8%–16% *w/w*; Miracle-Gro, Scotts, Marysville, OH, USA) as required. When seedlings reached the 2 to 3 leaf stage, two independent dose–response experiments were established as randomized complete blocks. Experimental units consisted of 3 pots of 5 plants pot^{-1} replicated four times for each experiment. The doses for metribuzin and linuron were as follows: metribuzin 0, 110, 275, 550, 1100, 2200, 4400 and 8800 g a.i. ha^{-1} and linuron 0, 220.8, 552, 1104, 2208, 4416, 8832 and 17,664 g a.i. ha^{-1}. Treatments were applied as described above in a single-track research spray chamber. Following treatment, seedlings were returned to the greenhouse and monitored for 6 weeks after application (WAA). Plants were rated weekly on a 0 to 100% scale where 0 is no injury and 100 is plant death. Six WAA, remaining above-ground biomass was harvested and dried to constant weight at 60 °C.

2.5. Evaluation of PRE-Emergence Herbicide Options

A field experiment was conducted in 2018 and 2019 at the Harrington Experimental Farm (46°20′57.60″N, 63°9′8.23″W) in Harrington, PE, Canada and at the Fredericton Research Farm (45°55′22.53″N, 66°36′29.49″W) in Fredericton, NB, Canada. Soil at Harrington (OM 3%, pH 6.6) and Fredericton (OM 3%, pH 6.2) is classified as a Orthic Humo-Ferric Podzol. The experiment was established as a randomized complete block design with 3 replications and 14 treatments. Prior to planting, fields were disked, cultivated, harrowed twice and then potato rows formed. Fresh-cut and untreated potato (*cv.* Russet Burbank) sets were hand-planted at 38 cm plant spacing with 0.91 m spaced rows. Fertilizer, according to provincial recommendations, was banded at planting prior to row closure. Rows were closed mechanically following planting. Plots measured 5 m in length and consisted of 2 potato rows and a guard row on either side for a total of 4 potato rows per treatment.

In 2018, potatoes were planted on 28th May and 5th June and in 2019 on 29th May and 5th June in Harrington and Fredericton, respectively. Plots were hilled approximately 4 weeks after planting when potatoes reached the ground crack stage. Hilling completely covered emerged potato shoots. Treatments were applied immediately after hilling on 27th June in 2018 and 25th June in 2019 in both Harrington and Fredericton. Treatments were applied with a CO_2-pressurized backpack sprayer equipped with a 1.5 m boom and 4, TP8002 vs. (TeeJet Technologies, Springfield, MA, USA) nozzles spaced 50 cm apart set to deliver 200 L ha^{-1} at 210 kPa. Treatments and rates are listed in Table 1, a weed-free and weedy check were also included. Plots were maintained weed-free by hand-weeding.

Table 1. Treatment list with active ingredients, herbicide rates (g a.i. ha^{-1}), trade names, Weed Science Society of America (WSSA) herbicide groups and chemical family evaluated in Russet Burbank potatoes in Harrington PE and Fredericton NB in 2018 and 2019.

Herbicide Active Ingredient	Herbicide Rate (g a.i. ha^{-1})	Trade Name	WSSA Herbicide Group	Chemical Family
Metribuzin	1100	Sencor 75DF	5	Triazinone
Linuron	2208	Lorox L	7	Substituted urea
S-metolachlor	1600	Dual II Magnum	15	Acetamide
Saflufenacil	25.2	Eragon	14	Uracil amide
Dimethenamid-P	693.36	Frontier Max	15	Acetamide
Sulfentrazone	105.12	Authority	14	Aryl triazinone
Fomesafen	240 + 0.1% NIS [1]	Reflex + Agral 90	14	Amide
Metribuzin + linuron	825 + 1800	Sencor 75DF + Lorox L	5 + 7	*See above*
S-metolachlor + metribuzin	1570 + 372.5	Boundary LQD	15 + 5	*See above*
Metribuzin + sulfentrazone	600 + 105.12	Sencor STZ	5 + 14	*See above*
Saflufenacil + dimethenamid-P	74.8 + 660	Integrity	14 + 15	*See above*
Fomesafen + S-metolachlor + metribuzin	240 + 1570 + 372.5 + 0.1% NIS	Reflex + Boundary LQD + Agral 90	14 + 15 + 5	*See above*

[1] NIS—nonionic surfactant.

Visual estimates of potato phytotoxicity were collected 4 and 8 WAA on a 0 to 100% scale where a rating of 0 was defined as no injury and 100 was defined as plant death. Common lambsquarters control was rated 4 and 8 WAA on a 0 to 100% scale where a rating of 0 was defined as no injury and 100 was defined as total common lambsquarters death. At 4 and 8 WAA, common lambsquarters density and biomass was determined in each plot through counting all common lambsquarters and other weed species within a 0.5 m^2 quadrat and cutting at the soil surface. Common lambsquarters were dried to constant moisture at 60 °C and weighed.

Potatoes were top-killed with diquat (300 g a.i. ha^{-1}; Reglone, diquat ion 240 g a.i. L^{-1}, (Syngenta Canada, Guelph, ON, Canada) on September 24th and September 20th in 2018 and October 1st and September 17th in 2019 at Harrington and Fredericton, respectively. At physiological maturity, one row per treatment was mechanically harvested. Potatoes were graded with an optical grader (Celox-*P*-UHD, New Tec, Odense, Denmark) into small (3.8–5 cm) and Canada #1 (5–8.9 cm) size classes. Smaller (<3.8 cm), larger (>8.9 cm), misshapen and sunburnt potatoes were removed and counted as culls. Marketable yield was calculated as the sum of small and Canada #1 yield. Specific gravity was calculated using the weight-in-water and weight-in-air method with a 5 kg sample of marketable tubers.

2.6. Statistical Analysis

All statistical analysis was carried out in SAS v9.4 (SAS Institute, Cary, NC, USA). Data from dose–response experiments was analyzed with Proc NLIN in SAS using untransformed biomass data. Metribuzin and linuron data were fit with a 3-parameter log-logistic function (1) where d is the

above-ground biomass when dose = 0, LD_{50} is the herbicide dose providing 50% reduction in biomass and b is the slope of the curve at dose = LD_{50}. Goodness-of-fit was evaluated using mean square error.

$$f(x) = d + 1 + e\hat{}[b(\log x - \log LD_{50})] \quad (1)$$

Data collected from the discriminating dose and the PRE-herbicide evaluation experiment were analyzed with generalized linear mixed effects models in SAS using Proc Glimmix and a Gaussian distribution. Fixed effects were population, herbicide treatment (products or doses) and their interactions and random effects were replication, year, location and their interactions. In-season data (potato phytotoxicity, common lambsquarters and weed visual ratings, density and biomass), were analyzed with repeated measures through time. Weed-free and weedy control were removed from analyses of visual ratings. Residual analysis was conducted using proc univariate to confirm ANOVA assumptions. Significance of covariance parameters was investigated with a Wald's test. No significant effect of year, location or their interaction was found, therefore, data was pooled for analysis. In-season data least square means were compared with Tukey's HSD ($\alpha = 0.05$). Yield was compared to weedy check using linear contrast statements with a Type I error rate of $\alpha = 0.05$.

3. Results and Discussion

3.1. PSII-Inhibitor-Resistant Common Lambsquarters Is Widespread across Atlantic Canada

Common lambsquarters populations possessing the Ser264Gly mutation were found across all sampled potato-producing regions of NB and PE demonstrating widespread incidence of PSII-inhibitor-resistance (Figure 1). Overall, 46% of sampled populations possessed the Ser264Gly mutation with a higher prevalence in sampled populations found in PE (53%) than NB (42%) (Table 2). Where seed was available, single-dose herbicide assays confirmed all populations possessing the Ser264Gly mutation were resistant to atrazine and metribuzin, but not linuron (Table 2). In addition, while fewer populations were sampled using single-dose assays compared to those with molecular markers, the relative percentage of resistant to wild-type populations across the region appeared to be similar between methods. These results are in confirmation with previous findings demonstrating the Ser264Gly mutation confers a high and moderate level of resistance to triazine and triazinone herbicides, respectively, but not other PSII-inhibitors [6].

Table 2. Results of single-dose herbicide assays, presence of serine264-glycine (Ser264Gly) mutation and specific cross resistance patterns for screened New Brunswick (NB) and Prince Edward Island (PE) common lambsquarters populations.

Location	Populations Screened	Single-Dose Assay (% Resistant)			% with $Ser_{264}Gly$ Mutation (Populations Screened)
		Metribuzin [1]	Atrazine [2]	Linuron [3]	
NB	35	29%	37%	6%	42% (121)
PE	13	54%	20%[4]	8%	53% (70)

[1] Metribuzin at 750 g ha^{-1}; [2] Atrazine at 1000 g ha^{-1}; [3] Linuron at 1000 g ha^{-1}.

The resistance index of collected common lambsquarters populations to metribuzin was between 127 and 263 (Table 3). The metribuzin LD_{50} of the susceptible population was 0.003 kg ha^{-1} whereas the LD_{50} of resistant populations ranged from 0.38 to 0.79 kg ha^{-1}. All populations were susceptible to linuron and controlled with the lowest dose tested (0.22 kg ha^{-1}) (Table 3). The estimated LD_{50} of populations to linuron ranged from 0.005 to 0.04 kg ha^{-1}. Estimated metribuzin LD_{90} values, which give an indication of acceptable control in a producer field, for PSII-inhibitor-resistant common lambsquarters populations ranged from 1.02 to 4.08 kg ha^{-1}. Given that typical use rates of metribuzin in NB and PE potato production are 0.42 to 0.51 kg ha^{-1} and 0.56 to 0.62 kg ha^{-1} for one- and two-pass

systems, respectively; no tested common lambsquarters populations would be controlled in producer fields. All resistant populations identified via dose–response possessed the Ser264Gly mutation, whereas, it was lacking in the susceptible population. The Ser264Gly mutation maintains susceptibility to non-triazine PSII-inhibiting herbicides such as linuron [6]. Indeed, linuron controlled all populations at all tested doses. Together, these results provide further support that a Ser264Gly mutation is a mechanism conferring resistance to PSII-inhibitors in Atlantic Canada.

Table 3. Nonlinear regression parameter estimates ± SE for dose–response to metribuzin and linuron for susceptible and resistant common lambsquarters populations from New Brunswick (NB) and Prince Edward Island (PE) potato fields. Estimated LD_{90} (kg ha^{-1}) is also included.

Herbicide	Population	*d*	*b*	LD_{50} kg ha^{-1}	LD_{90} kg ha^{-1}	Resistance Index
Metribuzin	S	0.72 ± 0.05	0.53 ± 0.00	0.003 ± 0.00	0.18	–
	R1	1.57 ± 0.20	2.21 ± 1.04	0.38 ± 0.10	1.02	127
	R2	4.90 ± 0.29	1.33 ± 0.24	0.79 ± 0.14	4.08	263
	R3	6.07 ± 0.28	1.48 ± 0.22	0.76 ± 0.10	3.36	253
	R4	2.29 ± 0.19	1.90 ± 0.59	0.61 ± 0.12	1.92	203
Linuron	S	1.26 ± 0.09	0.57 ± 0.28	0.005 ± 0.01	0.13	–
	R1	1.81 ± 0.05	5.29 ± 0.54	0.04 ± 0.00	0.05	–
	R2	1.31 ± 0.07	0.65 ± 0.17	0.01 ± 0.01	0.22	–
	R3	1.02 ± 0.06	2.22 ± 0.62	0.03 ± 0.00	0.06	–
	R4	1.74 ± 0.06	7.86 ± 1.17	0.04 ± 0.00	0.05	–

The use of molecular markers can greatly accelerate the speed and ease at which resistance-testing is conducted [15], yet several caveats remain. Indeed, while all susceptible populations did not possess the Ser264Gly mutation, several populations which lacked Ser264Gly displayed resistance to one or more of atrazine, metribuzin or linuron in the single-dose assay (Table 4). For example, two populations from NB (NB6, NB7) were found to lack the Ser264Gly mutation and were not controlled by 1 kg ha^{-1} of atrazine. These populations were controlled with 750 g ha^{-1} of metribuzin and 1 kg ha^{-1} of linuron. One population from PE (PE16) was not controlled with 1 kg ha^{-1} of atrazine nor 750 g ha^{-1} of metribuzin but was controlled by 1 kg ha^{-1} of linuron. Further, one population from NB (NB5) was not controlled by 1 kg ha^{-1} of atrazine or 1 kg ha^{-1} of linuron. Several *psbA* target-site mutations were identified which confer cross-resistance patterns consistent with our results. Populations NB6 and NB7 displayed low, high and low levels of resistance for metribuzin, atrazine and linuron, respectively (Table 4). This pattern is similar to the response of PSII-inhibitor-resistant *Amaranthus retroflexus* L., which possess a Phe274Val substitution [16]. The high level of resistance to metribuzin, atrazine and linuron found in NB5 is similar to *A. retroflexus* in Ontario with a Ala251Val substitution [16]. Other reports, however, found Ala251Val to confer low level resistance to the triazinone metamitron and remain susceptible to atrazine and linuron in Swedish *C. album* [17]. The moderate and low levels of resistance found in PE16 to PSII-inhibiting herbicides is not consistent with previously published mutations and suggest a possible alternative resistance mechanism. Together, this demonstrates that in addition to the well characterized Ser264Gly mutation, common lambsquarters populations in Atlantic Canada may have additional mechanisms of resistance. Further studies sequencing *psbA* investigating additional mechanisms are warranted.

Table 4. Cross resistance patterns for populations lacking the Ser264Gly mutation. Classification in cross resistance pattern based off % biomass of treated compared to control: S (susceptible)—<25%; L (low)—25–50%; M (M)—51–75%; H (high)—>76%.

	Cross Resistance Pattern		
Population	**Metribuzin**	**Atrazine**	**Linuron**
NB5	H	H	H
NB6	L	H	L
NB7	L	H	L
PE16	S	L	L

3.2. PSII-Inhibitor-Resistant Common Lambsquarters Is Controlled by Other Modes of Action

Potato had a high degree of tolerance to all products tested and displayed 0% crop injury at 4 and 8 WAA (data not shown). All products provided visual control of common lambsquarters at 4 ($p < 0.001$) and 8 WAA ($p < 0.001$), however, differences in control across products was observed (Table 5). S-metolachlor plus metribuzin, metribuzin plus sulfentrazone, saflufenacil plus dimethenamid-P and fomesafen plus S-metolachlor plus metribuzin consistently provided >90% common lambsquarters control at 4 and 8 WAA. S-metolachlor alone (65% and 65%) and dimethenamid-P alone (68% and 66%) provided the least control of common lambsquarters at 4 and 8 WAA, respectively. Common lambsquarters control declined from 4 to 8 WAA with linuron (89% vs. 77%), saflufenacil (84% to 69%) and fomesafen (82% to 62%), however, increased with metribuzin (81% vs. 88%) and sulfentrazone (79% vs. 86%).

Table 5. Least square means and multiple means comparisons for common lambsquarters visual control (% control) and dry biomass (g m^{-2}) in Russet Burbank potatoes in response to various preemerge herbicides in Harrington PE and Fredericton NB in 2018 and 2019 at 8WAA. Means not connected by the same letter are significantly different according to Tukey's LSD at $p < 0.05$.

	Common Lambsquarters		
Treatment	**4 WAA [1] (% Control)**	**8 WAA (% Control)**	**Biomass (g m^{-2})**
Weed-free control	100	100	0.0
Weedy control	0	0	63.2 a
Metribuzin	81 ab	88 ab	3.2 b
Linuron	89 ab	77 ab	1.9 b
S-metolachlor	65 b	65 ab	26.8 ab
Saflufenacil	84 ab	69 ab	9.0 b
Dimethenamid-P	68 ab	66 ab	14.8 b
Sulfentrazone	79 ab	86 ab	12.2 b
Fomesafen	82 ab	62 b	19.1 b
Metribuzin + linuron	91 ab	84 ab	16.3 b
S-metolachlor + metribuzin	90 ab	92 ab	2.7 b
Metribuzin + sulfentrazone	95 ab	93 ab	1.6 b
Saflufenacil + dimethenamid-P	97 a	92 ab	2.8 b
Fomesafen + S-metolachlor + metribuzin	99 a	95 a	0.3 b

[1] WAA—weeks after application.

Biomass did not differ across treatments at 4 WAA ($p = 1.000$, data not shown) and ranged from 0.2 to 3.4 g m^{-2}. At 8 WAA, however, biomass was significantly affected by all treatments evaluated ($p < 0.001$) (Table 5). Compared to the weedy check, all treatments except S-metolachlor, significantly reduced common lambsquarters biomass. Metribuzin (3.2 g m^{-2}), linuron (1.9 g m^{-2}), S-metolachlor plus metribuzin (2.7 g m^{-2}), metribuzin plus sulfentrazone (1.6 g m^{-2}), saflufenacil plus dimethenamid-P (2.8 g m^{-2}) and fomesafen plus S-metolachlor plus metribuzin (0.3 g m^{-2}) all

provided the greatest reduction in common lambsquarters biomass compared to the weedy control (63.2 g m^{-2}).

Herbicides with alternative modes of action are available for use in Atlantic Canadian potato production. Our results demonstrate that several active ingredients and tank-mixtures applied preemergence, effectively control PSII-inhibitor-resistant common lambsquarters in potato. All products evaluated provided effective control of common lambsquarters biomass except s-metolachlor. This is consistent with previous reports of poor control of common lambsquarters with s-metolachlor [18]. Similar to our results, tank-mixing S-metolachlor with metribuzin has been shown to improve control of common lambsquarters in potato [19]. Several authors have demonstrated excellent control of common lambsquarters with sulfentrazone alone at rates between 53 and 280 g ha^{-1} with minimal improvement in control when tank-mixed with metribuzin at rates between 280 and 560 g ha^{-1} [19,20]. In contrast, we found the addition of metribuzin (600 g ha^{-1}) to sulfentrazone (105.12 g ha^{-1}) improved control of common lambsquarters compared to sulfentrazone (105.12 g ha^{-1}) alone. In addition, poor control of common lambsquarters has been previously reported with dimethenamid-P alone up to 1.12 kg ha^{-1} [21] and, control can be significantly improved with the addition of a tank-mix partner such as saflufenacil [22]. Our results support this assertion. The poor control of common lambsquarters in response to fomesafen alone (240 g ha^{-1}) is consistent with previous reports in tomato [23]. The addition of S-metolachlor and metribuzin as tank-mix partners to fomesafen dramatically improved control of common lambsquarters. In agreement with our results, Peachey et al. found tank-mixing fomesafen with S-metolachlor provided excellent control of common lambsquarters [24]. Interestingly, while Peachey et al. found a tank-mix of S-metolachlor and fomesafen was effective on common lambsquarters, they attributed this to fomesafen [24]. This is in contrast to our results as it appeared common lambsquarters control was influenced by presence or absence of metribuzin as S-metolachlor alone or fomesafen alone provided poor control.

PSII-inhibitor-resistant common lambsquarters with a Ser264Gly mutation is present at the Harrington PE research farm according to dose–response (R1) and single-dose assays. Common lambsquarters, however, was controlled in all treatments which included metribuzin. This can be attributed to the use of a higher rate of metribuzin (1100 g ha^{-1}) which is above the LD_{50} (380 g ha^{-1}) of R1 (Table 3). As Ser264Gly provides a moderate level of resistance to triazinone herbicides such as metribuzin, it can be controlled with metribuzin at rates as low as 840 g ha^{-1} [10,25]. This may explain the control of common lambsquarters observed in our study despite confirmed resistance via a Ser264Gly mutation.

3.3. Potato Yield Was Not Impacted by Preemergent Herbicides

Marketable potato yields of all treatments were greater than the weedy control and yield parameters of several treatments significantly differed from weedy check (Table 6). Total tuber yield in the dimethenamid-P treatments (36.24 T ha^{-1}) was significantly higher than weedy check ($p = 0.025$) and was the highest average total yield. Similarly, marketable tuber yield (33.98 T ha^{-1}) and Canada #1 tuber yield (22.73 T ha^{-1}) in dimethenamid-P treatments was significantly higher than weedy check ($p = 0.012$ and $p = 0.013$, respectively). This is consistent with previous reports of potato tolerance to dimethenamid-P up to rates of 2.9 kg ha^{-1} on low organic matter soils [26]. Marketable yield of metribuzin plus sulfentrazone treatments was significantly higher than the weedy check ($p = 0.0156$). Potato has a high tolerance to sulfentrazone with no negative impact on yield seen with rates up to 2.8 kg ha^{-1} [19]. In addition to control of PSII-inhibitor-resistant species, sulfentrazone in tank mixture with metribuzin effectively controls several other problematic weeds in Atlantic Canadian potato production including *A. retroflexus* [20,27,28], *Solanum sarrachoides* Sendtn. [20,27,28], *Echinochloa crus-galli* (L.) P. Beauv. [27] and *Digitaria sanguinalis* (L.) Scop [19]. Metribuzin plus sulfentrazone was recently registered for use in Atlantic Canadian potato production [29] and as such may be an effective alternative mode of action for potato producers.

Table 6. Least square means and preplanned contrasts for yield statistics for Russet Burbank potatoes in response to various preemerge herbicides in Harrington PE and Fredericton NB in 2018 and 2019.

Treatment	Total Tuber Yield (T ha^{-1})	Marketable Yield (T ha^{-1})	Can#1 Yield (T ha^{-1})
Weed-free control	34.94	30.75	20.99
Weedy control	29.39	27.11	16.19
Metribuzin	34.95	31.87	19.74
Linuron	32.67	31.10	19.43
S-metolachlor	34.79	32.18	21.67
Saflufenacil	29.39	27.73	18.16
Dimethenamid-P	36.24	33.98	22.73
Sulfentrazone	32.76	30.62	17.89
Fomesafen	33.83	31.92	21.15
Metribuzin + linuron	34.12	31.75	19.10
S-metolachlor + metribuzin	33.70	31.08	19.36
Metribuzin + sulfentrazone	37.47	33.72	22.46
Saflufenacil + dimethenamid-P	34.77	31.26	20.52
Fomesafen + S-metolachlor + metribuzin	33.73	30.81	20.12
Contrasts		*p* value	
Weed-free vs. weedy	0.067	0.172	0.064
Weedy vs. metribuzin	0.066	0.076	0.167
Weedy vs. linuron	0.272	0.135	0.206
Weedy vs. S-metolachlor	0.074	0.060	0.036
Weedy vs. saflufenacil	0.999	0.815	0.439
Weedy vs. dimethenamid-P	0.025	0.012	0.013
Weedy vs. sulfentrazone	0.259	0.187	0.503
Weedy vs. fomesafen	0.139	0.073	0.056
Weedy vs. metribuzin + linuron	0.116	0.084	0.255
Weedy vs. S-metolachlor + metribuzin	0.151	0.137	0.215
Weedy vs. metribuzin + sulfentrazone	0.009	0.016	0.017
Weedy vs. saflufenacil + dimethenamid-P	0.075	0.120	0.094
Weedy vs. fomesafen + S-metolachlor + metribuzin	0.148	0.670	0.127

4. Conclusions

Our results demonstrate PSII-inhibitor-resistant common lambsquarters is widespread across the potato-producing regions of New Brunswick and Prince Edward Island. In the majority of populations surveyed, PSII-inhibitor-resistance is conferred by the well characterized Ser264Gly mutation granting resistance to metribuzin and maintaining susceptibility to linuron. Results of screening with atrazine, metribuzin and linuron indicate additional mechanisms of resistance may be present in the region. Currently registered and unregistered preemergent herbicide active ingredients and tank mixtures effectively controlled PSII-inhibitor-resistant common lambsquarters without compromising potato yield or quality. To delay resistance, producers should focus on rotating herbicide modes of action and implementation of additional integrated weed management strategies. Weeds escaping herbicide treatment must be controlled to prevent proliferation of resistant populations [30], however, limited postemergent management options exist for potato. Future studies should focus on development of alternative management strategies such as herbicide tank-mixtures, crop rotations and cultivation for pre- and postemergent weed control in potato to delay the onset of further herbicide resistance and ensure long-term sustainability of Atlantic Canadian potato production.

Author Contributions: Conceptualization, A.M.-G., G.G. and M.L.; data curation, A.M.-G., G.G., M.L., S.I., S.H. and C.W.; methodology, A.M.-G., G.G. and M.L.; formal analysis, A.M.-G. and M.L.; writing—original draft, A.M.-G.; writing—review & editing, A.M.-G., G.G., M.L. and C.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Agriculture and Agri-Food Canada, J-001781 to AMG.

Acknowledgments: In addition, the authors wish to thank the technical support of Ashley Nicolle MacDonald, Erica Fava, Brahim Soufiane, Katherine Bisaillon, the Charlottetown weeds crew and the Harrington and Fredericton farm crew. The authors declare they have no conflicts of interest.

Conflicts of Interest: The authors declare no conflict of interest.

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