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Evaluation of crop-topping strategies to reduce common lambsquarters (*Chenopodium album*) seed production in potato production systems

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Abstract

Potato producers in Canada's Atlantic provinces of Prince Edward Island (PE) and New Brunswick rely on photosystem II (PSII)-inhibiting herbicides to provide season-long weed control. Despite this fact, a high proportion of common lambsquarters populations in the region have been identified as resistant to this class of herbicides. Crop-topping is a late-season weed management practice that exploits the height differential between weeds and a developing crop canopy. Two field experiments were conducted in Harrington, PE, in 2020 and 2021, one each to evaluate the efficacy of a different crop-topping strategy, above-canopy mowing or wick-applied glyphosate, at two potato phenological stages, on common lambsquarters viable seed production and potato yield and quality. Mowing common lambsquarters postflowering decreased viable seed production (72% to 91%) in 2020 but increased seed production (78% to 278%) in 2021. Mowing had minimal impact on potato marketable yield across cultivars in both years. In contrast, treating common lambsquarters with wick-applied glyphosate had variable impacts on seed output in 2020 but dramatically reduced seed production (up to 95%) in 2021 when treatments were applied preflowering. Glyphosate damage to potato tubers was not influenced by timing and resulted in a 14% to 15% increase in culled tubers due to black spotting and rot. Our results highlight the importance of potato and common lambsquarters phenology when selecting a crop-topping strategy and demonstrate that above-canopy mowing and wick-applied glyphosate can be utilized for seedbank management of herbicide-resistant common lambsquarters in potato production systems.

Introduction

Potato is the highest-value horticultural crop in Canada, with an estimated farm gate value of US $1 billion in 2020 (CATSNet 2021). Canada's Atlantic provinces of Prince Edward Island (PE) and New Brunswick account for 37% of seeded Canadian potato acreage and 48% of Canada's fresh potato exports (CATSNet 2021). Potato production systems are subject to a variety of pests that must be mitigated to ensure crop profitability. For example, uncontrolled weed growth costs Canadian potato producers an estimated US$61 million in potential annual yield loss due to reductions in tuber number and quality (Ganie et al. 2023). Furthermore, weeds can serve as alternative hosts to the myriad of insect pests, pathogens, and diseases affecting potato production (Boydston et al. 2008). Pest management tactics in potato often rely on the use of chemical pesticides, with herbicides composing 25% of annual potato pesticide use (Fernandez-Cornejo et al. 2014). Atlantic Canadian potato producers rely on preemergent applications of photosystem II (PSII)-inhibiting herbicides including either metribuzin, a Group 5 triazinone, or linuron, a Group 5 substituted urea (WSSA 2021). These herbicides are applied to over 75% of potato acreage in the Atlantic Canada region (L. MacKinnon, personal communication, 2019). Producers who once relied on a combination of early-season cultivation and row formation (hilling) at ground crack (conventional hilling) followed by a preemergence herbicide application have since transitioned to a one-pass hilling system. In a one-pass hilling system, planting and row formation are carried out simultaneously, and they are followed shortly after by a preemergent PSII-inhibiting herbicide application. This management shift has been found to reduce soil losses by 40% due to reduced soil disturbance, but it does not include burying and killing of early-emerging weed species as in conventionally hilled potatoes (Rajalahti et al. 1999; Xing et al. 2011). In-season broadleaf weed control options in potato are limited to rimsulfuron and metribuzin due to crop safety and limited investment in weed management in horticultural crops (Ganie et al. 2023). Therefore the switch to one-pass hilling results in a near-total reliance on a single preemergent herbicide application of metribuzin or linuron to provide season-long weed control in potato from planting to harvest.

Common lambsquarters is a summer annual broadleaf weed that occurs in various environments and cropping systems throughout the northern hemisphere (Bajwa et al. 2019; Warwick and Marriage 1982; Williams 1963). Its continuous germination pattern allows for multiple flushes throughout the season (Bassett and Crompton 1978; Ogg and Dawson 1984), and plants can grow up to 2.5 m tall to rapidly overtop a crop canopy, reducing light availability for the crop (Bassett and Crompton 1978; Mahoney and Swanton 2008). As such, common lambsquarters is considered one of the most economically significant weeds in potato production systems, with yield losses reported up to 85% (Eberlein et al. 1997; Parks et al. 1996). Common lambsquarters generally sets seed in late summer and early fall and can produce between 30,000 and 176,000 seeds per plant (Harrison 1990; Stevens 1932). The small, black seeds have little endosperm and can persist in the soil seedbank for more than 20 years (Lewis 1973; Stevens 1932). Common lambsquarters has historically been controlled in potato with metribuzin and linuron. However, widespread resistance of common lambsquarters to the PSII-inhibiting herbicide metribuzin now occurs across the Atlantic Canada potato-growing region (McKenzie-Gopsill et al. 2020).

Weed control tactics are generally applied prior to or shortly after emergence to protect yield potential, as weeds that emerge before or with the crop during the critical period for weed control have a larger impact on yield than late-emerging weeds (Knezevic et al. 2002). Weeds that escape control during this period, whether through misapplication or resistance to herbicides, are much more difficult to manage due to limited in-crop options in potato. Crop-topping is the use of a nonselective management tactic near the end of the growing season when the crop is maturing and the target weed species is flowering (Tidemann et al. 2021). This tactic is used to control weeds that escape early-season management and minimize weed seed production. Recent work has shown varying levels of success with mechanical and chemical tactics for control of weeds overtopping a crop canopy. For example, Simard et al. (2018) had limited success with mechanical control of common lambsquarters overtopping a soybean [*Glycine max* (L.) Merr.] canopy with a mechanical weed puller at a targeted 10-cm weed height to use crop height differential. Although the weed puller damaged common lambsquarters, common ragweed (*Ambrosia artemisiifolia* L.), and redroot pigweed (*Amaranthus retroflexus* L.) in soybean, weeds that started seed formation prior to treatment still produced viable seeds when left on the ground in the field. In controlled conditions, Butler et al. (2013) found that mowing common lambsquarters once reduced total biomass production by 25%, and multiple clippings reduced inflorescence weight by 90%. Common lambsquarters mowed to 5 cm and 10 cm had less total dry weight than that cut to 20 cm, but reducing inflorescence dry weight required repeated clipping treatments (Butler et al. 2013). Meyers et al. (2016) demonstrated greater than 90% control of Palmer amaranth (*Amaranthus palmeri* S. Watson) when glyphosate was applied with a wick weeder overtopping a sweet potato [*Ipomoea batatas* (L.) Lam.] canopy at 7 and 8 wk after planting. Furthermore, sweet potato yield increased as the wick application timing was delayed. However, Meyers et al. (2017) and Gilreath et al. (2000) found that sequential wick applications reduced sweet potato and pepper yields, respectively, due to increased herbicide exposure and glyphosate drip. To date, no studies have investigated the feasibility of crop-topping in potato production systems.

Further exploration into weed management tactics that can be applied in-season in potatoes to prevent weed seed set and deplete seed viability and seedbank stores is necessary to counter the rise of herbicide-resistant weed biotypes (Geddes and Davis 2021; Hill et al. 2016). This is particularly true in horticultural crops like potato, for which few in-season weed management options exist (Ganie et al. 2023). In addition, the use of weed management tactics that select against tall weeds can be a strategy to promote a more diversified and therefore less competitive weed community in a horticultural rotation (MacLaren et al. 2020). The objective of the present study was to investigate crop-topping in potato using both mechanical and chemical strategies. We set up two crop-topping experiments, one to evaluate the use of a mower and another to evaluate the use of wick-applied glyphosate, for control of common lambsquarters overtopping a potato canopy using three potato cultivars of varying growth habits. We hypothesized, first, that crop-topping prior to the full flowering of common lambsquarters would increase common lambsquarters control and maximize reductions in seed production but compromise potato yield compared to later applications and, second, that the growth patterns of potato cultivars would influence efficacy and crop injury from crop-topping.

Materials and Methods

Experimental Design

Field experiments were established at the Harrington Experimental Farm (46.35°N, 63.15°W) in Harrington, PE, Canada, in 2020 and 2021. Soil at Harrington is characterized as a fine sandy loam (Orthic Humo-Ferric Podzol, Canadian System of Soil Classification; Humic Cryorthods, U.S. Soil Taxonomy; OM 3% to 3.2%, pH 6.6). Two independent experiments were established: one to evaluate the use of a mower and the other to evaluate the use of wick-applied glyphosate. All other experimental parameters were identical. Both experiments were organized as randomized strip plots with four replicates, three whole-plot factors, and three strip-plot factors per experiment. Whole-plot factors were potato growth habits according to Canadian Food Inspection Agency (CFIA) cultivar descriptions (semi-erect, 'NorValley' in 2020 and 'Eva' in 2021; spreading, 'Shepody'; upright, 'Yukon Gold') (CFIA 2015), and strip-plot factors were mowing timing and wick application timing (none, early, late) in the mowing and wick-applied glyphosate experiment, respectively ($n = 36$ per experiment). Fields were cultivated (Triple K Cultivator; Kongskilde, Alberslund, Denmark) and spring-tooth harrowed twice, and potato rows were formed prior to hand-planting potatoes. Untreated Elite 1 potato sets were hand-planted on June 4, 2020, and May 25, 2021, at 31-cm, 38-cm, and 31-cm spacing for semi-erect, spreading, and upright cultivars, respectively. Fertility rate varied by cultivar and was banded at planting prior to row closure at the following rates: 150-200-135 kg ha^{-1} (N-P-K) for the semi-erect and upright cultivars and 160-200-135 kg ha^{-1} (N-P-K) for the spreading cultivar according to local recommendations. Rows were closed mechanically, and imidacloprid (ADMIRE® 240, 240 g ai L^{-1}; Bayer Crop Science, Calgary, AB, Canada) was applied in-furrow at a rate of 312 g ai ha^{-1} to provide broad-spectrum control of insect pests. Additional insecticide and fungicide applications were made as required according to local recommendations. Plots consisted of two 5 × 1 m potato rows with one 5 × 1 m potato guard row on adjacent sides for a total plot area of 5 × 4 m (20 m^2). Potato hills were formed 4 wk after planting on June 22, 2020, and June 24, 2021. Potatoes were top-killed at maturity with broadcast diquat (Reglone®, 240 g ai L^{-1}; Syngenta

Table 1. Mean height of potato and common lambsquarters (CHEAL) prior to early and late mowing and wick weeding treatment application in two separate experiments in 2020 and 2021 at Harrington PE.[a]

	Mow			Wick		
Timing	Potato	CHEAL	Mower	Potato	CHEAL	Wick bar
	cm					
2020						
Early	58 ± 2	77 ± 4	68	57 ± 2	72 ± 2	67
Late	69 ± 3	134 ± 3	79	67 ± 2	117 ± 5	77
2021						
Early	62 ± 1	95 ± 2	72	60 ± 2	89 ± 2	70
Late	58 ± 3	115 ± 3	68	49 ± 2	120 ± 3	59

[a]Values are means ± SE. The height of the mower and wick bar for each treatment is also shown.

Canada, Calgary, AB, Canada) at a rate of 840 g ai ha^{-1} on September 15, 2020, and September 21, 2021. To evaluate the effects of treatments on yield, one treated row per plot was mechanically harvested on October 1, 2020, and September 30, 2021.

Mowing: Treatment Application

To evaluate the effects of crop-topping with a mower on common lambsquarters and potato, plots were crop-topped at two phenological stages. The early mowing treatment was conducted prior to common lambsquarters flowering, which corresponded to stage 51 according to the BBCH scale (Meier 2018), and the late mowing treatment was made after common lambsquarters flowering at stage 69 according to the BBCH scale (Meier 2018). Potatoes were at or before late flowering and early tuber formation (BBCH 67/42) for the early mowing treatment and at early fruit development and early tuber formation (BBCH 71/43) for the late mowing treatment. Prior to treatment application, the heights of three common lambsquarters and three potato plants per plot were recorded to determine the average heights of common lambsquarters and potato across the entire experiment. The mower height was set at 10 cm above the average potato height, at 68 cm and 79 cm in 2020 and 72 cm and 68 cm in 2021 for early and late mowing timings, respectively (Table 1). Mowing treatments were conducted on July 30 and August 20 in 2020 and on July 27 and August 16 in 2021 for the early and late mowing timings, respectively. Hedge trimmers were used to simulate a crop mower at a travel speed of 5 km h^{-1} for all treatments. For both treatment timings, the entire plot was mowed in a single direction at the set height.

Wick-Applied Glyphosate: Treatment Application

To evaluate the effects of crop-topping with wick-applied glyphosate to common lambsquarters and potato, plots were crop-topped at two phenological stages. Early and late wick treatments were conducted at the same time as the mowing experiment, and common lambsquarters and potatoes were at the same phenological stages as described earlier. The wick bar used in this study comprised one 304.8 × 7.62 cm (L × D) and two 76.2 × 7.62 cm (L × D) PVC pipes affixed to stainless steel brackets of the same length (15' Loader Model Wick Weeder; Vogels Wick Weeders, Kippen, ON, Canada). The system was gravity fed by a 20-L tank affixed to the top of the bracket that allowed product to flow to the attached wick bars. A one-part glyphosate (Roundup WeatherMAX®, 540 g ae L^{-1}; Monsanto, Winnipeg, MB, Canada) and two-parts water solution for a concentration of 180 g ae L^{-1} of glyphosate was used for both treatment timings, per the manufacturer's instructions. The wick bar was mounted on a front-end loader tractor to allow for height adjustment. Prior to treatment application, the heights of three common lambsquarters and three potato plants per plot were recorded to determine the average common lambsquarters and potato heights across the experiment. The wick bar was set 10 cm above the average potato height, at 67 cm and 77 cm in 2020 and 70 cm and 59 cm in 2021 for early and late timing of wick treatments, respectively (Table 1). Owing to logistical challenges with the wick bar, only one potato row (5 m^2) in each plot was treated at both treatment timings in a single direction at the set height. All measurements, including yield, were taken from the treated potato row.

Data Collection

Data collection in Experiments 1 and 2 was identical. The impact of mowing and wick-applied glyphosate on common lambsquarters control and potato injury was visually assessed 3 wk after treatment application on a 0 to 100 scale where 0 was no effect and 100 was complete plant death. To evaluate the effects of crop-topping with a mower or wick-applied glyphosate on common lambsquarters biomass allocation, three common lambsquarters plants per plot were tagged immediately following treatment application and monitored for the remainder of the season. Prior to seed development, tagged plants were covered by a low-density polyethylene bag (1.2 × 1.5 m [L × D]) to capture shattered seed. Prior to potato harvest, tagged common lambsquarters was cut at the base of the plant and dried on a greenhouse bench for 1 wk. Plants were then sieved with a 200-mm sieve and carefully cleaned using a benchtop seed blower to separate vegetative and reproductive biomass. Vegetative biomass (g $plant^{-1}$) was dried to constant weight at 60 C prior to weighing. Reproductive biomass (g $plant^{-1}$) was weighed, and triplicate 50-seed subsamples were counted and weighed to determine thousand seed weight (TSW) (g). Entire seed samples were used for determination of TSW when fewer than 150 seeds were in a sample. Vegetative and reproductive biomasses were used to compute harvest index by dividing the weight of seed biomass by the weight of total biomass. To evaluate the effects of crop-topping on common lambsquarters seed viability, germination tests were conducted on triplicate 50-seed subsamples per plant. Entire seed samples were used for germination tests when there were fewer than 150 seeds in a sample. Ten-millimeter petri plates were lined with filter paper and moistened with 5 mL of distilled H_2O. Seeds were added to the filter paper and separated from each other to limit mold growth. Samples were covered with a piece of filter paper, sealed with parafilm, and placed in a growth cabinet (Precision™ Plant Growth Chamber, 504 L; Thermo Scientific, Mississauga, ON, Canada) in the dark at 22 C (Burton et al. 2016). Samples were left to germinate for 14 d. Germinated seeds, determined by the presence of a visible radicle or hypocotyl, were then counted to determine germination percentage. Viability of nongerminated seeds was evaluated with a pinch test, where viable seeds were firm when pinched, and these were added to the germinated seeds to determine total viability of the sample. Seed production, measured as viable seeds per plant, was computed using calculated seed biomass, TSW, and germination percentage.

To evaluate the impact of crop-topping with a mower or wick-applied glyphosate on potato, marketable potato and cull yields were determined from harvested plots. Potatoes were graded according to the CFIA potato grading scale (CFIA 2015) using an

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optical grader (Celox-P-UHD; New Tec, Odense, Denmark) and sorted into small (3.8 to 5.7 cm and 3.8 to 5.08 cm) and Canada #1 (5.7 to 8.9 cm and 5.08 to 8.9 cm) size classes for round and long potatoes, respectively. Potatoes in these two size classes were counted, weighed, added together, and considered marketable yield. Small (<3.8 cm), large (>8.9 cm), misshapen, or sunburned potatoes were counted, weighed, and considered cull yield. To quantify marketable yield lost to glyphosate injury in the wick-applied glyphosate treatment, tubers exhibiting black spotting and rot indicative of glyphosate damage (Supplementary Figure 1 A) were counted as culls and added to cull yield.

Statistical Analysis

All statistical analysis was conducted in the R software environment (RStudio version 4.2.1; R Core Team 2022). All data from both experiments were analyzed separately. Common lambsquarters total biomass, seed biomass, harvest index, TSW, germination percentage, and viable seed production were analyzed with linear mixed effects models with cultivar, treatment timing, year, and their interaction as fixed effects and replication as a random effect using the R package NLME (Pinheiro et al. 2022). To quantify the impact of crop-topping on potato yield, the percentage of yield lost to culls was calculated for each plot to standardize initial differences in yield among potato cultivars. Potato marketable yield, cull yield, and percentage of yield lost to culls was then analyzed with linear mixed effects models with cultivars, timing, year, and their interaction treated as fixed effects and replication as a random effect. The assumptions of analysis of variance (ANOVA) were evaluated by visual inspection of residual plots. Values with large residuals were considered outliers and removed to conform with ANOVA assumptions. Effects were considered significant at $P \leq 0.05$. Where appropriate, least square means were estimated and compared with a Tukey's honestly significant difference test and a Type I error rate of $\alpha = 0.05$ with the R package EMMEANS (Lenth et al. 2022). To investigate relationships between potato height and yield parameters and between common lambsquarters height and biomass allocation, as well as between germination percentage and TSW, correlation and regression analysis was conducted using the base functions in RStudio.

Results and Discussion

Impact of Crop-Topping with a Mower on Common Lambsquarters and Potato

Common lambsquarters and potato visual injury 3 wk after application were similar in both years and were therefore combined for presentation. Mowing at early and late treatment timings had no visual impact on potato injury and minimal impact on common lambsquarters in both years (Table 2). A small increase in common lambsquarters visual injury was observed at late treatment timing compared with early timing (11% vs. 3%; Table 2). Overall, mowing resulted in minimal injury to potato and common lambsquarters.

There was an effect of year, mow treatment timing, and the interaction of year, cultivar, and mow treatment timing on common lambsquarters total biomass ($P < 0.01$), seed biomass ($P < 0.01$), and harvest index ($P = 0.03$), and data are presented separately by year (Table 3). Mowing did not affect common lambsquarters total biomass in any potato cultivar in 2020 (Figure 1 A, C, and E). Late mowing did, however, reduced common lambsquarters harvest index by 60% to 70% relative to the control in 2020 (Figure 1 A, C, and E). Results in 2021 were more variable. Early mowing decreased common lambsquarters total biomass in the upright potato cultivar (Figure 1 F) but increased total biomass in the spreading cultivar (Figure 1 D). Similarly, late mowing increased common lambsquarters total biomass in the semi-erect (Figure 1 B) and upright (Figure 1 F) potato cultivars. Despite changes to total biomass accumulation in 2021, mowing timing had minimal impact on common lambsquarters harvest index, which ranged from 12% to 25% and from 20% to 22% in early and late mow treatments, respectively (Figure 1 B, D, and F).

Table 2. Effects of crop-topping with a mower or wick-applied glyphosate in two separate experiments on visual ratings of potato and common lambsquarters (CHEAL) injury at early and late treatment timings in 2020 and 2021 at Harrington PE.[a]

Timing	Mow		Wick	
	Potato injury	CHEAL injury	Potato injury	CHEAL injury
	%			
Control–early	0 ± 0	0 ± 0	0 ± 0	0 ± 0
Early	0 ± 0	3 ± 3	33 ± 5	32 ± 7
Control–late	0 ± 0	0 ± 0	0 ± 0	13 ± 7
Late	1 ± 0	11 ± 2	49 ± 5	32 ± 5

[a]Values are means ± SE. Visual injury ratings were estimated on a 0 to 100 scale, where 0 is no plant injury and 100 is complete plant death.

Like the effects on common lambsquarters biomass accumulation and allocation, germination percentage was affected by mow timing ($P < 0.01$), year ($P < 0.01$), and the interaction of year, cultivar, and treatment timing ($P = 0.03$) (Table 3), yet minimal differences were found between treatment timings between cultivars (Supplementary Figure 2). Despite the minimal effect on germination percentage, viable seed production was impacted by cultivar ($P < 0.01$), mowing timing ($P < 0.01$), year ($P < 0.01$), and the interaction of year and cultivar ($P < 0.01$) and of year and timing ($P < 0.01$) (Table 3) with consistent effects from treatments within years (Figure 2). Late mowing reduced common lambsquarters viable seed production by 72% to 91% in all cultivars in 2020 (Figure 2 A, C, and E). In contrast, regardless of timing, mowing increased viable seed production by 78% to 278% in 2021 (Figure 2 B, D, and F).

Common lambsquarters TSW was impacted by mowing timing ($P < 0.01$), year ($P < 0.01$), and their interaction ($P < 0.01$) (Table 3). No differences in TSW across mowing timings or potato cultivars were found in 2020 (Figure 2 A, C, and E). In contrast, common lambsquarters TSW was increased by early mowing in the semi-erect (Figure 2 B) and upright (Figure 2 F) potato cultivars compared with the control in 2021. The common lambsquarters germination percentage was positively correlated with TSW and increased as TSW increased (Figure 3).

Like our study, other authors have found inconsistent results when mowing common lambsquarters. For example, in controlled conditions, Butler et al. (2013) observed that common lambsquarters cut once near anthesis recovered 97% of its inflorescence dry weight and that repeated cuts throughout the season were required to reduce seed production. In contrast, the greater reduction of common lambsquarters seed production by delaying mowing to after flowering (BBCH 69) in our study is consistent with the findings of Hill et al. (2016), who

Table 3. ANOVA table of common lambsquarters total biomass, seed biomass, harvest index, germination percentage, and thousand seed weight by year, cultivar, treatment timing, and their interaction following crop-topping with a mower or wick-applied glyphosate.[a,b]

Covariance parameters	ndf/ddf	Total biomass	Seed biomass	Harvest index	Germination	TSW	Viable seed production
Mower							
Yr	1/69	**<0.0001**	**<0.0001**	**<0.0001**	**0.0001**	**<0.0001**	**<0.0001**
Clt	2/69	0.2745	0.1318	0.8360	0.9218	0.9630	**0.0092**
Time	3/69	**0.0057**	**0.0012**	**<0.0001**	**<0.0001**	**0.0001**	**<0.0001**
Clt × Time	6/69	**0.0241**	**0.0008**	0.2181	**0.0170**	0.0932	0.2172
Yr × Clt	2/69	0.2406	**0.0309**	0.1951	**<0.0001**	0.1859	**0.0093**
Yr × Time	3/69	**<0.0001**	**0.0137**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
Yr × Clt × Time	6/69	**0.0002**	**<0.0001**	**0.0313**	**0.0266**	0.5853	0.3781
Wick-applied glyphosate							
Yr	1/69	**<0.0001**	**<0.0001**	**0.0228**	**0.0364**	**0.0179**	0.9144
Clt	2/69	0.4255	0.3289	0.2760	0.1271	0.8298	0.8021
Time	3/69	**0.0065**	**0.0017**	<0.0001	**<0.0001**	**0.0039**	**<0.0001**
Clt × Time	6/69	**0.0257**	**0.0002**	0.1220	**0.0170**	0.7680	0.1367
Yr × Clt	2/69	0.2723	0.1169	**0.0375**	**<0.0001**	0.3543	0.5159
Yr × Time	3/69	**<0.0001**	**0.0182**	**<0.0001**	0.0578	0.0992	**0.0316**
Yr × Clt × Time	6/69	**<0.0001**	**<0.0001**	**0.0056**	**0.0019**	**0.0387**	0.7759

[a]Values are P-values. Boldface indicates that the effect was considered significant ($P \leq 0.05$).
[b]Abbreviations: Clt, cultivar; df/ddf, numerator degrees of freedom/denominator degrees of freedom; Time, treatment timing; TSW, thousand seed weight; Yr, year.

found that mowing common lambsquarters at flowering (BBCH 60) or when immature seeds were present (BBCH 81) decreased seed shed by up to 99% in soybean. Weed seed size and weight can be highly plastic and affected by the growing environment of the parent plant (Winn 1985). We observed a contrasting trade-off across years in response to mowing. In 2020, overall investment in common lambsquarters seed production dropped and viable seed decreased when mowed late. In contrast, in 2021, mowing increased investment in individual seed, and viable seed production increased. Several studies have documented rapid declines in seed number per plant and maintenance of seed weight in common lambsquarters in response to crowding stress (Colquhoun et al. 2001) and decreased light intensity and nitrogen availability (Mahoney and Swanton 2008). Stress periods during later development are known to contribute to declines in seed number while maintaining seed weight and viability in highly plastic species like soybean (McKenzie-Gopsill et al. 2016). Low overall resource availability in 2020 due to an extended period of drought (AAFC 2023) may have contributed to declines in viable seed production of common lambsquarters when mowed late. The contrasting response of increased viable seed production by mowing in 2021 may be due to greater resource availability in that year (AAFC 2023), the R-selected life history strategy of common lambsquarters, and the breaking of apical dominance allowing for an increased number of inflorescences and increased seed production. Together, these results suggest that crop-topping with a mower postflowering can contribute to declines in viable seed production when resources are not sufficient to allow common lambsquarters to recover, thus likely limiting the efficacy of this technique to years with minimal precipitation only.

Potato marketable yield ($P < 0.01$), cull yield ($P < 0.01$), and percentage of yield lost to culls ($P < 0.01$) were affected by the interaction of cultivar and year, yet were not impacted by mowing timing (Table 4). In 2020, marketable yield was 23.5, 20.5, and 14.4 T ha^{-1} in the semi-erect, spreading, and upright cultivar, respectively (Figure 4 A). Furthermore, in 2020, cull yield varied from a low of 0.5 T ha^{-1} in the upright cultivar to 1.3 T ha^{-1} in the semi-erect cultivar (Figure 4 A). The percentage of total yield lost to culls ranged from 3% to 6% in 2020 and was highest in the spreading (6%) and semi-erect (5%) potato cultivars (Figure 4 A). In contrast, marketable yield was higher in 2021 than in 2020 (Figure 4) and was 36.1, 32.0, and 31.3 T ha^{-1} in the semi-erect, spreading, and upright cultivar, respectively. The increase in marketable yield in 2021 was accompanied by increased cull yield and the percentage of yield lost to culls, which ranged from 4% to 9% (Figure 4 B). Similar to 2020, the percentage lost to culls was highest in the spreading cultivar (9%) compared with the semi-erect and upright cultivars (Figure 4 B).

The minimal impact of mowing on potato marketable yield in our study contrasts with several studies that have documented improvements to yields in tuber crops following crop-topping. Meyers et al. (2016) found that crop-topping with a mower in sweet potato at or beyond mid-fruit ripening (BBCH 85/47) decreased cull yield while improving marketable yield. This treatment timing coincided with sweet potato tuber bulking, whereby water, nutrients, and carbohydrates shifted from aboveground vegetation production to belowground reproductive development. By removing the fruits of a tuber-producing crop, resources required for sexual reproduction can be reallocated to the reproductive structures, thus improving tuber quality and marketable yields. Such a response has been observed in several potato cultivars (Jansky and Thompson 1990) and wild tuber–forming plants (Van Drunen and Dorken 2012). Among potato cultivars in this study, however, the trade-off between sexual and asexual reproduction appears to be dependent on environment. Minimal injury to potato reported from early and late mowing, combined with strong competition from common lambsquarters, may have contributed to minimal shifts in reproductive allocation and the incongruences with previous studies. Together our results suggest that potato marketable yields are dependent on cultivar selection and environment and that improved understanding of shifts in biomass allocation in response to crop-topping with a mower in potato is required to elucidate the potential positive effects of mowing on yield.

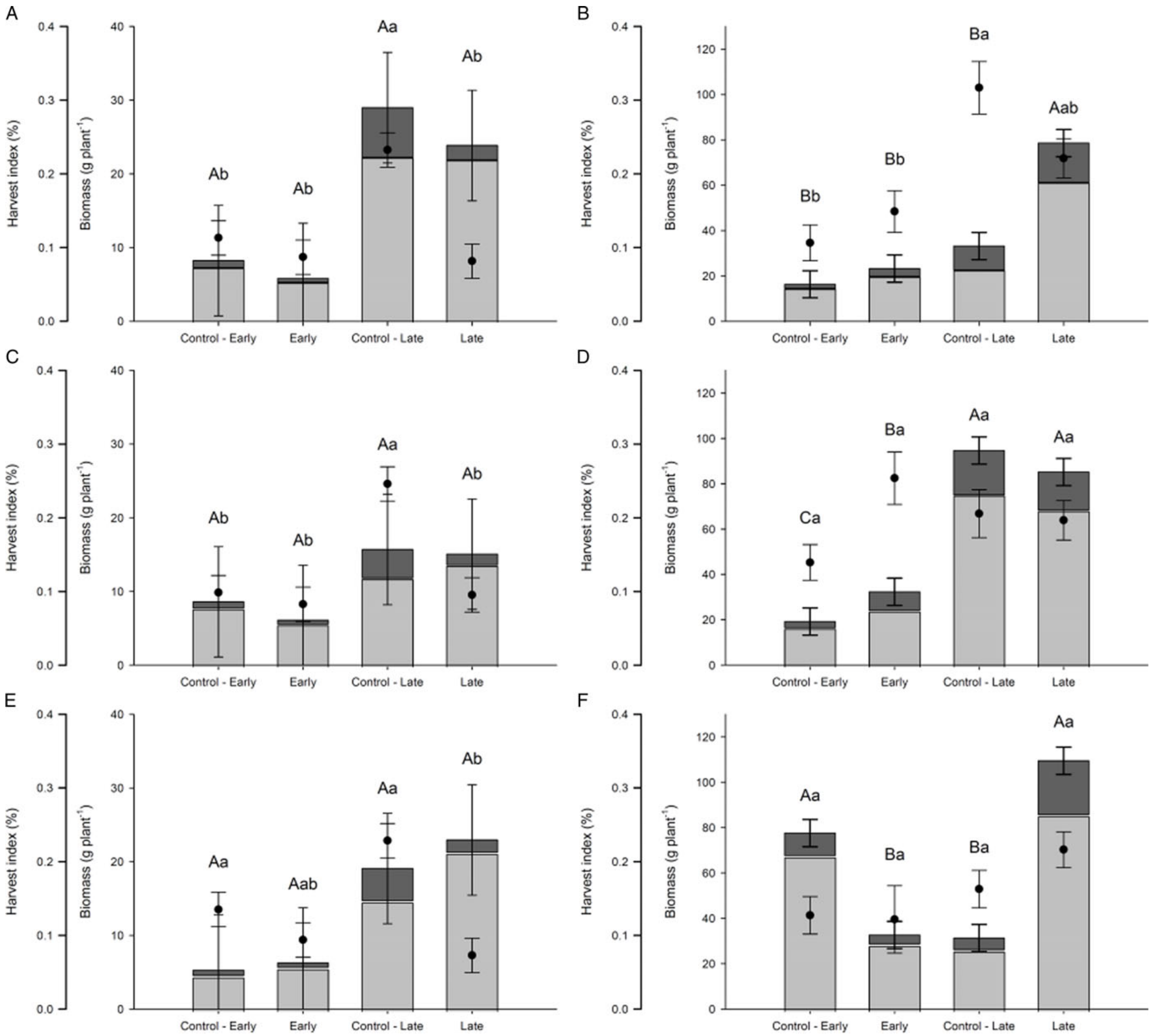

Figure 1. The effect of early and late crop-topping with a mower on common lambsquarters vegetative (light gray bars) and reproductive (dark gray bars) biomass allocation and harvest index (circles) in 2020 (A, C, E) and 2021 (B, D, F) in Harrington PE in semi-erect (A, B), spreading (C, D), and upright (E, F) potato cultivars. Data are least square means ± SEM of total biomass. Values not connected by the same letter are significantly different according to Tukey's honestly significant difference ($\alpha = 0.05$). Uppercase letters refer to the effect of treatment timing on total biomass (vegetative and reproductive) accumulation, and lowercase letters refer to the effect of treatment timing on harvest index.

Impact of Wick Weeding Timing on Common Lambsquarters and Potato

Potato visual injury and common lambsquarters visual injury 3 wk after application were similar across both years and averaged for presentation (Table 2). Potato injury increased from 33% to 49% from early and late wick-applied glyphosate, respectively (Table 2). Potato visual injury symptoms included leaf chlorosis and formation of necrotic tissue along the leaf margins and at the growing point (Supplementary Figure 1 B). In contrast, common lambsquarters visual injury did not differ between early and late treatment timings and was 32% overall (Table 2). Visual injury symptoms included wilting of the main stem and severe necrosis of leaves and reproductive tissue (Supplementary Figure 1 C and D).

Common lambsquarters total biomass ($P < 0.01$), seed biomass ($P < 0.01$), and harvest index ($P < 0.01$) were affected by the interaction of wick weeding timing, cultivar, and year (Table 3). Seed biomass was increased in late treatments compared with early in 2020. However, the late treatment did not differ from the control (Figure 5 A, C, and E). The increase in seed biomass in 2020 resulted in an increase in the harvest index in control–late and late treatments compared with early treatments and ranged from 31% to 40% (Figure 5 A, C, and E). In contrast, early treatment in 2021 increased common lambsquarters total biomass compared with the control in the spreading and upright potato cultivars (Figure 5 D and F) yet did not differ in the semi-erect potato cultivar (Figure 5 B). Similarly, late treatment increased common lambsquarters total biomass over the control in the upright potato

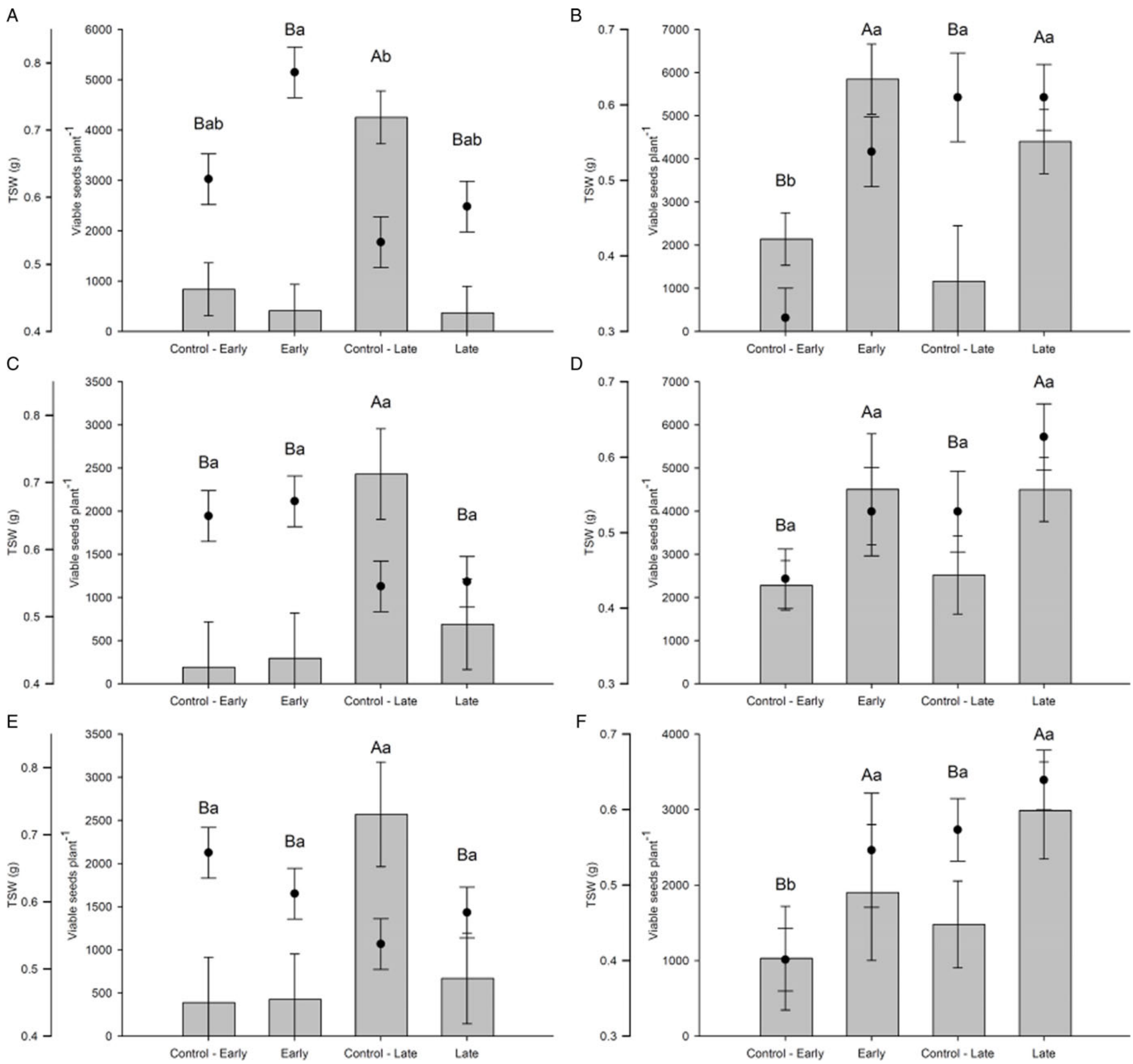

Figure 2. Effect of early and late crop-topping with a mower on common lambsquarters viable seeds plant^{-1} (bars) and thousand seed weight (TSW) (circles) in 2020 (A, C, E) and 2021 (B, D, F) in Harrington PE in semi-erect (A, B), spreading (C, D), and upright (E, F) potato cultivars. Data are least square means ± SEM. Values not connected by the same letter are significantly different according to Tukey's honestly significant difference (α = 0.05). Uppercase letters refer to the effects of treatment timing on viable seed plant^{-1}, and lowercase letters refer to the effects of treatment timing on TSW.

cultivar (Figure 5 F). These changes to biomass accumulation in 2021, however, had minimal impact on common lambsquarters harvest index. In general, harvest index increased in the late treatments compared with the early treatments. However, no differences were found between late wick treatment timing and controls (Figure 5 B, D, and F). Whereas common lambsquarters total biomass increased from early wick treatment in the upright cultivar, the harvest index drastically declined from 31% in the control to 1% following the early wick-applied glyphosate treatment (Figure 5 F).

Common lambsquarters plants were significantly larger with greater biomass in 2021 compared with 2020, which may have contributed to differences in response to wick-applied glyphosate. Schuster et al. (2007) noted that glyphosate absorption was similar between common lambsquarters plants with heights of 2.5, 7.5, and 15 cm, yet noted variation in tolerance across populations regardless of size. Larger plants, however, translocated glyphosate more rapidly through basipetal movement, which can be attributed to their larger carbohydrate sinks (Schuster et al. 2007). We observed that early treatments in 2021 increased biomass production of common lambsquarters. Hormetic effects, including stimulation of biomass productivity by low doses of glyphosate, have been reported in several crop and weed species (Brito et al. 2018), including common lambsquarters (Nadeem et al. 2016). Nadeem et al. observed a stimulatory effect of glyphosate on common lambsquarters seedling shoot length and seedling

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Table 4. ANOVA table of potato marketable yield, cull yield, and percentage of yield lost to culls by year, cultivar, treatment timing, and their interaction following crop-topping with a mower or wick-applied glyphosate.[a,b]

Covariance parameters	ndf/ddf	Marketable yield	Cull yield	Percentage yield lost to culls
Mower				
Yr	1/116	**<0.0001**	**<0.0001**	**0.0015**
Clt	2/116	**<0.0001**	**<0.0001**	**<0.0001**
Time	3/116	0.5770	0.1957	0.0503
Clt × Time	6/116	0.4995	0.5719	0.2423
Yr × Clt	2/116	**0.0008**	**<0.0001**	**<0.0001**
Yr × Time	3/116	0.2975	0.2439	0.2493
Yr × Clt × Time	6/116	0.9692	0.9545	0.8736
Wick-applied glyphosate				
Yr	1/116	**<0.0001**	**<0.0001**	**0.0002**
Clt	2/116	**<0.0001**	0.6138	0.0679
Time	3/116	0.1527	**<0.0001**	**<0.0001**
Clt × Time	6/116	0.6622	0.6152	0.1753
Yr × Clt	2/116	0.2349	0.2200	0.5415
Yr × Time	3/116	**0.0004**	0.1397	0.9658
Yr × Clt × Time	6/116	0.7277	0.7842	0.9926

[a]Values are P-values. Boldface indicates that the effect was considered significant ($P \le 0.05$).
[b]Abbreviations: Clt, cultivar; df/ddf, numerator degrees of freedom/denominator degrees of freedom; Time, treatment timing; Yr, year.

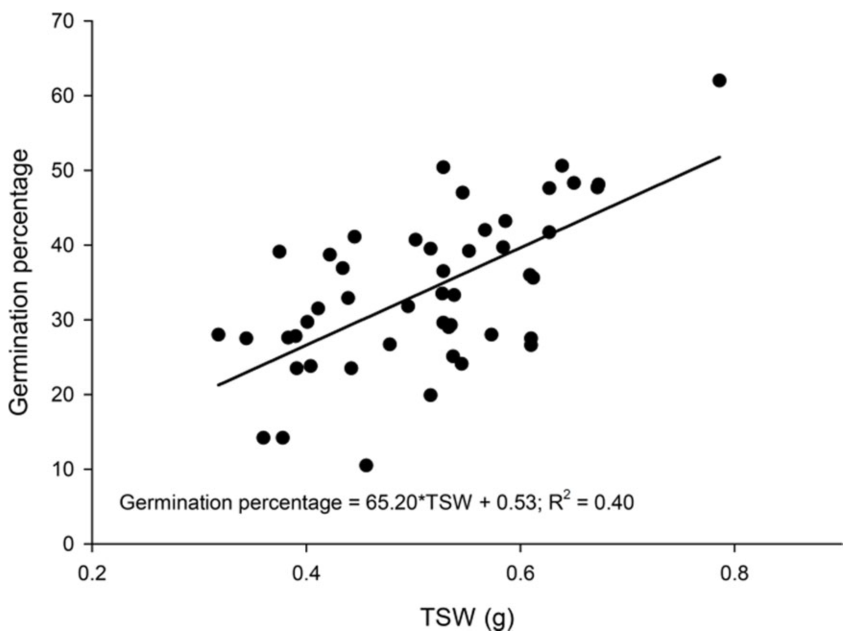

Figure 3. Relationship between thousand seed weight (TSW) and germination percentage of common lambsquarters seed following crop-topping with a mower or wick-applied glyphosate.

biomass up to a concentration of 16 g ae ha^{-1}. Despite the high concentration of glyphosate used in the present study (180 g ae L^{-1}), visual injury on common lambsquarters was generally confined to the upper portion of the plant. Therefore the high tolerance of common lambsquarters, the sublethal dose, and possible hormetic effects of glyphosate may provide an explanation for improved biomass productivity by early wick treatments.

Common lambsquarters germination percentage ($P < 0.01$) and TSW ($P = 0.04$) were impacted by the interaction of wick application timing, potato cultivar, and year (Table 3). The overall common lambsquarters germination percentage was highly variable and ranged from 10.5% to 50.4% across treatments and years (Supplementary Figure 3). In general, the common lambsquarters germination percentage declined (19% to 55%) with early and late treatment in the semi-erect and upright potato cultivars in 2020; however, differences were not significant between treatments and controls (Supplementary Figure 3 A and E). In 2021, the common lambsquarters germination percentage was decreased by 82% and 75% in the spreading (Supplementary Figure 3 D) and upright cultivar (Supplementary Figure 3 F), respectively, following wick-applied glyphosate.

Common lambsquarters viable seed production was impacted by wick application timing ($P < 0.01$) and the interaction of timing and year ($P = 0.03$) (Table 3). In 2020, late treatment with wick-applied glyphosate decreased viable seed production in the semi-erect cultivar (36%), yet increased

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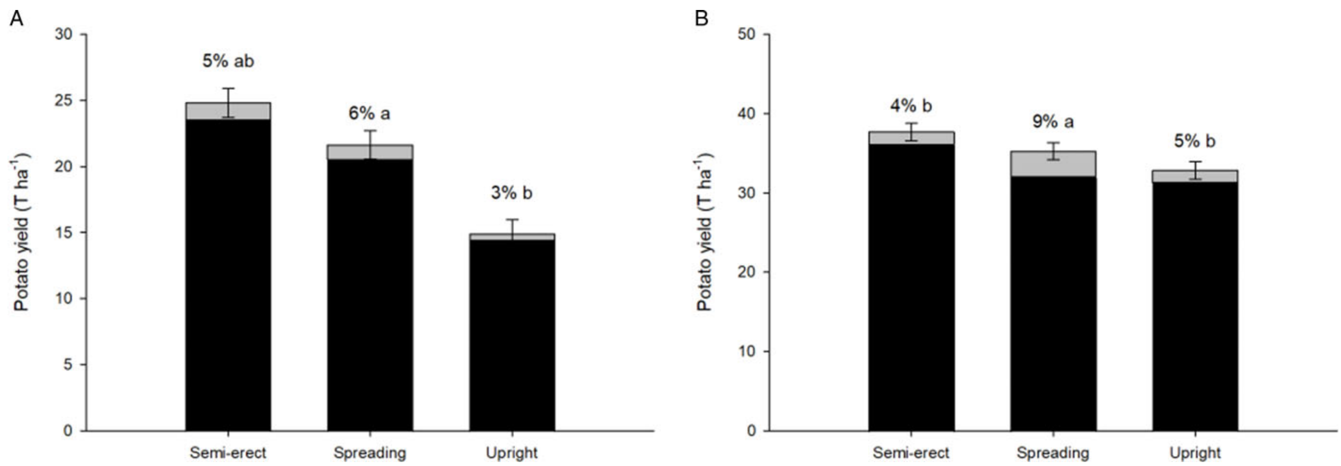

Figure 4. Effect of crop-topping with a mower on yield of marketable tubers (black bars) and culled tubers (gray bars) in 2020 (A) and 2021 (B) of semi-erect, spreading, and upright potato cultivars. Data are least square means ± SEM. Values above bars indicate percentage of yield lost to culls, and letters refer to the effects of treatment timing on percentage of yield lost to culls. Values not connected by the same letter are significantly different according to Tukey's honestly significant difference (α = 0.05).

viable seed production (85%) in the upright cultivar (Figure 6 A and F). In contrast, viable seed production declined (95%) following early wick-applied glyphosate in the spreading and upright cultivars in 2021 (Figure 6 D and F). Common lambsquarters TSW did not differ by wick application timing across cultivars in 2020 (Figure 6 A, C, and E). Similarly, common lambsquarters TSW did not differ by wick weeding timing in 2021, except for late wick weeding in the semi-erect cultivar, which decreased compared with the control (Figure 6 B, D, and F).

Wick-applied glyphosate at the early timing reduced common lambsquarters seed production in 2021 only. The impact of glyphosate on reducing viable weed seed production has been reported in a variety of species, including pitted morning glory (*Ipomoea lacunosa* L.), velvetleaf (*Abutilon theophrasti* Medik.), and giant foxtail (*Setaria faberi* Herrm.) (Biniak and Aldrich 1986; Bennett and Shaw 2000; Culpepper and York 2000). Walker and Oliver (2008) observed that a single glyphosate application at flowering reduced seed production of numerous weed species by greater than 83%. Glyphosate accumulates in the plant reproductive sinks, including floral buds, where it disrupts embryo and endosperm development (Pline et al. 2001). Reduced seed production from early wick application made as flowering was initiated may be due to increased glyphosate absorption to sink tissues and disruption of subsequent flower and seed production. It is unclear why this effect was so dramatic in 2021 compared with 2020, but it may have been due to low biomass accumulation overall in 2020 and an extended drought period limiting glyphosate translocation (AAFC 2023). Therefore, although wick-applied glyphosate may provide a hormetic effect on common lambsquarters biomass production, doses can be sufficient to disrupt seed development and seed viability, and further studies with varying glyphosate doses are warranted. If integrated into weed management practices, wick-applied glyphosate could reduce common lambsquarters seed production and aid in significantly reducing seedbank stores.

The different response of common lambsquarters to wick-applied glyphosate treatments between potato cultivars may be related to morphological features of each cultivar. Many potato cultivars do not vary in their ability to suppress weeds (Colquhoun et al. 2009; Conley et al. 2001). On the other hand, early-emerging, short stature, and highly branched cultivars have been shown to provide superior weed suppression over erect, less leafy cultivars (Barbaś et al. 2020). Although our results do not show a consistent response, environmental differences between years may influence potato emergence and early canopy development across cultivars. These differences may in turn have affected wick treatment interception and subsequently common lambsquarters growth and seed production.

Potato marketable yield ($P < 0.01$) was impacted by the interaction of year and wick timing, yet cull yield ($P < 0.01$) and percentage of yield lost to culls ($P < 0.01$) differed by year and wick timing, but not their interaction (Table 4). Overall, potato marketable yield was 71% greater ($P < 0.01$) in 2021 than in 2020 and averaged 33.1 and 19.4 T ha^{-1}, respectively (Figure 7). Cull yield was 70% greater ($P < 0.01$) in 2021 than in 2020 and averaged 2.91 and 9.53 T ha^{-1}, respectively (Figure 7). Regardless of wick application timing or year, wick-applied glyphosate consistently increased the percentage of yield lost to culls by 14% to 15% (Figure 7). These results suggest that wick weeding negatively impacts potato yield and quality. The timing of wick application did not influence this effect. Yield losses following wick treatments were likely due to interception with the wick bar and subsequent phytotoxic effects of glyphosate across potato cultivars (Bailey et al. 2002; Friesen and Wall 1984; Hutchison et al. 2017). Felix et al. (2011) found that potato yields were most sensitive to glyphosate injury when applied at the hooking (BBCH 51/40) and tuber initiation (BBCH 57/41) stages, potentially due to disruptions in sucrose shunting. Similarly, Meyers et al. (2016) found that sweet potato tolerance to glyphosate drip from a wick bar increased as the plants matured. This highlights the importance of potato cultivar

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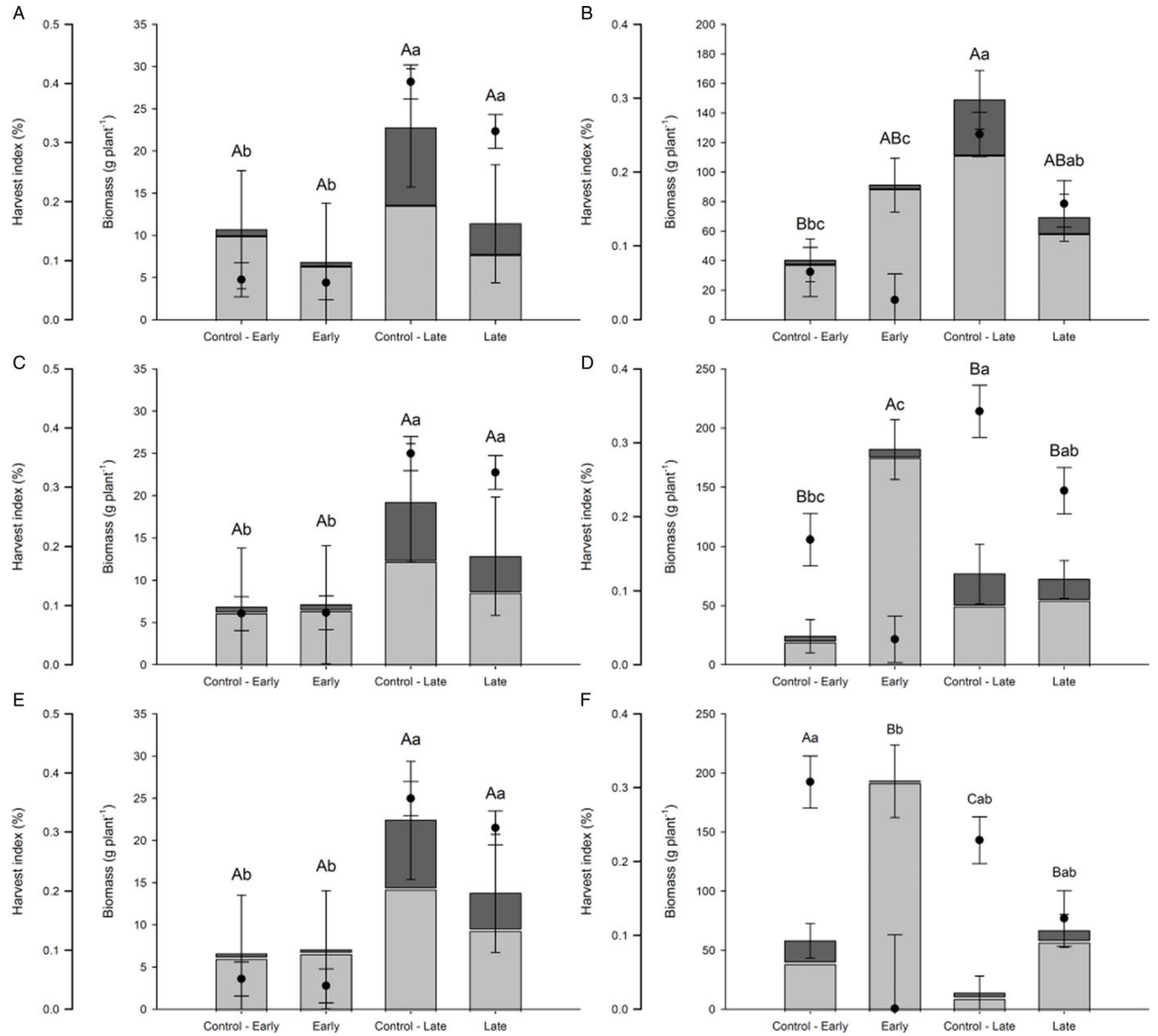

Figure 5. Effect of early and late crop-topping with wick-applied glyphosate on common lambsquarters vegetative (light gray bars) and reproductive (dark gray bars) biomass allocation and harvest index (circles) in 2020 (A, C, E) and 2021 (B, D, F) in Harrington PE in semi-erect (A, B), spreading (C, D), and upright (E, F) potato cultivars. Data are least square means ± SEM of harvest index. Values not connected by the same letter are significantly different according to Tukey's honestly significant difference (α = 0.05). Uppercase letters refer to the effect of treatment timing on total biomass accumulation, and lowercase letters refer to the effect of treatment timing on harvest index.

growth pattern as an important consideration for crop-topping with a wick bar and of possible evaluation of a range of wiper designs and changes to the physical properties of the herbicide solution to reduce risk of glyphosate drip onto potato plants (Harrington and Ghanizadeh 2017).

Our results demonstrate that crop-topping in potato production systems can be a viable method of late-season common lambsquarters control and can be incorporated into an integrated weed management program to target the weed seedbank. Further research into treatment applications made at additional potato and common lambsquarters phenological stages and using a range of glyphosate rates should be considered. Elucidation of the critical period of weed seed control (Geddes and Davis 2021) in common lambsquarters and timing crop-topping applications to this period may provide greater reductions in viable seed return. Furthermore, combining wick or mow treatments together with potato fungicidal spray application schedules could provide a low-cost integration of herbicide-resistant weed management strategies to potato production systems. Additional research into sequential and bidirectional wick and mow treatments and other crop-topping methods, such as electricity, may provide further avenues to improve consistency in reducing common lambsquarters seed production without compromising yield.

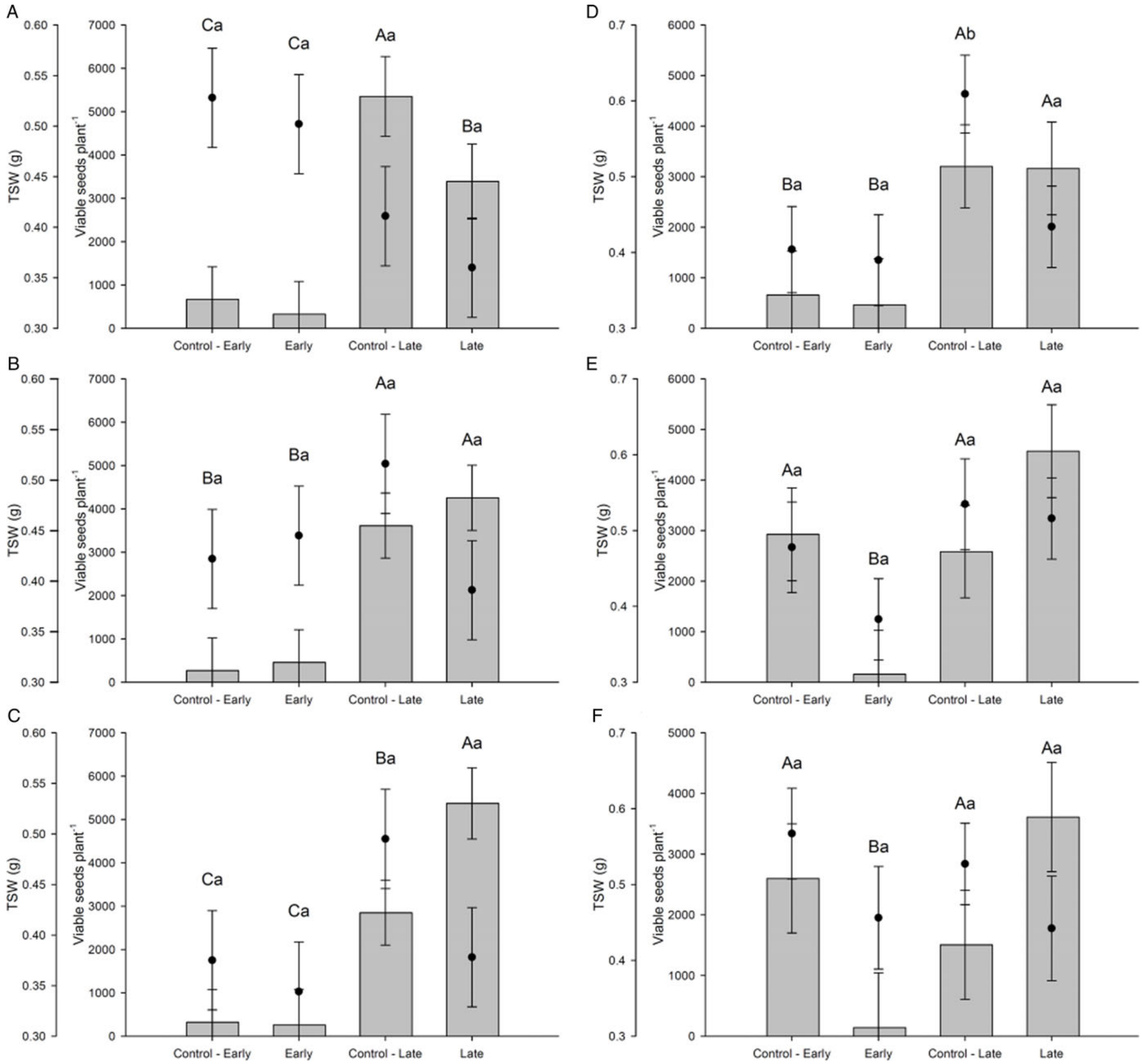

Figure 6. Effect of early and late crop-topping with wick-applied glyphosate on common lambsquarters viable seeds plant^{-1} (bars) and thousand seed weight (TSW) (circles) in 2020 (A, C, E) and 2021 (B, D, F) in Harrington PE in semi-erect (A, B), spreading (C, D), and upright (E, F) potato cultivars. Data are least square means ± SEM. Values not connected by the same letter are significantly different according to Tukey's honestly significant difference ($\alpha = 0.05$). Uppercase letters refer to the effects of treatment timing on viable seeds plant^{-1}, and lowercase letters refer to the effects of treatment timing on TSW.

Practical Implications

This study evaluated the efficacy and feasibility of two different crop-topping strategies in potato production systems, mowing or wick weeding, to target common lambsquarters resistant to PSII-inhibiting herbicides overtopping a potato canopy. Field studies were conducted over two growing seasons and quantified the effects of crop-topping strategies on common lambsquarters biomass production, reproductive allocation, and seed viability, as well as their effects on potato injury and marketable yield across several potato cultivars. We found that timing crop-topping with a mower to postflowering in common lambsquarters can reduce seed output with negligible effects on potato marketable yield across cultivars. We also show that the use of a wick-applied glyphosate can result in substantial injury to potato tubers with variable impact on common lambsquarters reproductive output regardless of timing and cultivar. This study contributes to the development of seedbank management strategies for common lambsquarters in potato production and demonstrates the viability of crop-topping as part of an integrated weed management plan.

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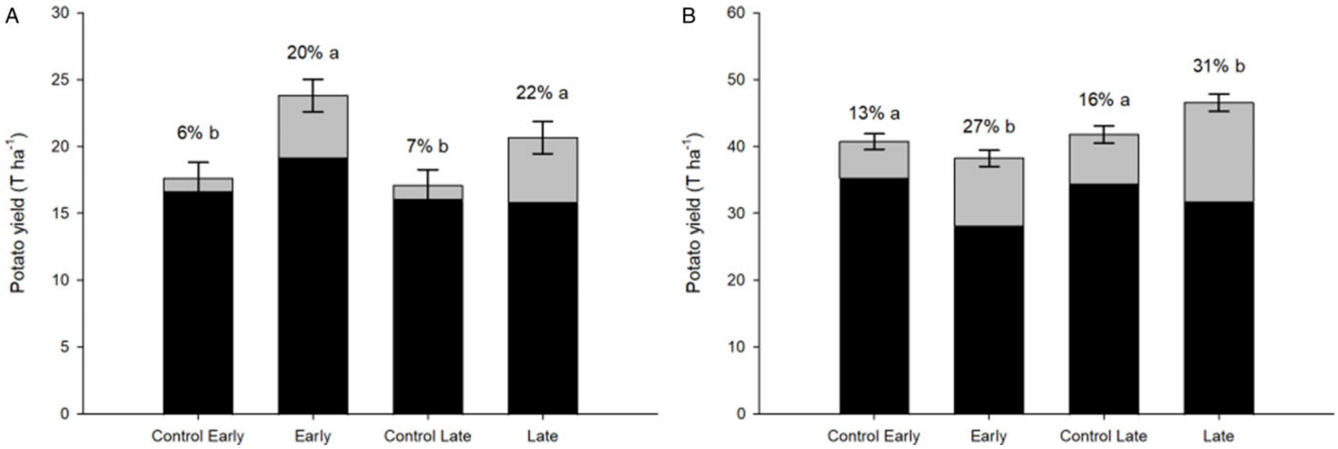

Figure 7. Impact of early and late crop-topping with wick-applied glyphosate on yield of potato marketable tubers (black bars) and culled tubers (gray bars) in 2020 (A) and 2021 (B). Data are least square means ± SEM. Values above bars indicate percentage of yield lost to culls, and letters refer to the effects of treatment timing on percentage of yield lost to culls. Values not connected by the same letter are significantly different according to Tukey's honestly significant difference ($\alpha = 0.05$).

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/wet.2023.61

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