INVESTIGATING IN-SEASON MANAGEMENT STRATEGIES FOR TRIAZINE RESISTANT COMMON LAMBSQUARTERS (*CHENOPODIUM ALBUM* L.) IN ATLANTIC CANADIAN POTATO PRODUCTION

by

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Dalhousie University is located in Mi'kma'ki, the

ancestral and unceded territory of the Mi'kmaq.

We are all Treaty people.

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Abstract

Potato (*Solanum tuberosum* L.) producers in Canada's Atlantic provinces of Prince Edward Island (PE) and New Brunswick (NB) rely on photosystem II (PSII)-inhibiting herbicides to provide season-long weed control. Despite this, a high proportion of common lambsquarters (*Chenopodium album* L.) populations have been identified as resistant to this class of herbicides. With the absence of new herbicide chemistries, weed science research has regained focus on preventative integrated weed management (IWM) strategies. As such, this project aims to investigate common lambsquarters biology and seedbank dynamics to optimize control tactics that increase mortality, deplete the weed seedbank, and decrease germination and viable seed shed. Crop-topping common lambsquarters post-flowering by mowing or wick-applied glyphosate reduced common lambsquarters harvest index and viable seed production. Soil-incorporation of fast-establishing cover crops reduced the common lambsquarters seedbank as well as populations in subsequent potato crop. Combined, this study demonstrates how alternative integrated weed management strategies can be utilized for seedbank management of herbicide-resistant common lambsquarters in potato production systems.

Keywords: potato, *Solanum tuberosum* L.; common lambsquarters, *Chenopodium album* L.; integrated weed management (IWM); herbicide resistance; seedbank; seed viability; germination; crop-topping; cover crops.

List of Abbreviations and Symbols Used

Abbreviation	Definition
°C	degree Celsius
%	percentage
µm	micron
µmol	micromole
a.i	active ingredient
ae	acid equivalent
ALS	acetolactase synthase
ATP	adenosine triphosphate
BBCH	Biologische Bundesanstalt, Bundessortenamt und CHemische Industrie
C:N	carbon to nitrogen ratio
CAD	Canadian dollars
cm	centimetre
CO_2	carbon dioxide
g	grams
h	hour
H_2O	water
ha	hectare
HI	harvest index
HSD	honestly significant difference
IWM	integrated weed management
kg	kilograms
km	kilometre
l	litre
L×D	length× diameter
m	metre
mL	millilitre
mm	millimetre
MOA	mode of action
MMOA	multiple modes of action
NADPH	nicotinamide adenine dinucleotide phosphate
NB	New Brunswick
NTSR	non-target-site resistance
OM	organic matter
PE	Prince Edward Island
pH	potential of hydrogen
POST	post-emergent
PP	pre-plant
PPI	pre-plant incorporated
PQ	plastoquinone
PSII	Photosystem II
RPDH	resource pool diversity hypothesis
$Ser_{264}Gly$	serine to glycine substitution at amino acid site 264

SOA	site of action
T	tonne
TSR	target-site resistance
TSW	thousand seed weight
VSP	viable seed production
WAA	week(s) after application
WAH	week(s) after hilling
WAP	week(s) after planting

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Chapter 1: General Introduction

1.0 Introduction

Potatoes (*Solanum tuberosum* L.) are ranked the world's fourth most important food crop after rice, wheat and maize and are vital food security crops (Zhang et al. 2017). The plant has been grown for consumption for thousands of years and over time, as cropping systems intensify, so too has their stressors. This literature review explores the potato production system, the common lambsquarters (*Chenopodium album* L.) weed that infests the crop, and triazine resistance that has been reported in common lambsquarters populations in potato production systems in the Atlantic Canadian region. Inadequate weed control in potato production causes up to 85% yield loss (Eberlein et al. 1997). Common lambsquarters is the most economically significant weed in potato production systems (Parks et al. 1996). The objective of this project is to investigate common lambsquarters biology and seedbank dynamics to determine and optimize control options to increase mortality, deplete the weed seedbank, and decrease germination and viable seed shed. Alternative cultural, chemical, and mechanical control methods will be investigated in Atlantic Canadian potato production systems. Methods include the use of cover cropping mixes and termination methods, wick weeding, and mowing. This review gives reference to research in integrated weed management (IWM) that has developed strategies and techniques that may prove useful in managing triazine resistant common lambsquarters in potato cropping systems.

1.1 Potato Production

Globally, Canada ranked fourth for table-stock potato exports valued at CAD$330 million in 2021 (CATSNet 2021). Potatoes are the largest vegetable crop grown in Canada with

approximately 64% destined for the processing market (CATSNet 2021). This includes uses such as frying, animal feed, alcohol, and other food products. Canada's Atlantic provinces of Prince Edward Island (PE) and New Brunswick (NB) seeds 56,251 hectares of potatoes and accounts for 43% of Canada's fresh potato exports (CATSNet 2021). PE is the most intensively farmed potato-growing province in this region and accounts for 23% of the potato hectarage in Canada. Agricultural land represents 43% of the total land base in PE, of which 14% is dedicated to potato production with international exports totalling $406 M in 2019 (Agriculture and Land 2020).

1.1.1 Intensity of Potato Production

Potato production systems are impacted by numerous abiotic and biotic factors. This makes potato production laborious and intensive. The demand for inputs corresponds to an increased cost of production. Compared to crops grown in western Canada such as canola (*Brassica napus* L.) and wheat (*Triticum aestivum* L.), costing $171 and $155 per hectare, respectively, potato cropping systems require greater inputs that total upwards of $1,300 per hectare (Manitoba 2019; PE Potato 2019). Cost of production per hectare continues to rise and has increased by 14% since 2014, with substantial increases to seed, fertilizer and crop protectants (PE Potato 2019). In the US, potatoes receive 10.2% of total pesticide used by active ingredient (a.i) despite accounting for only 0.2% of total farmed acres (Fernandez-Cornejo et al. 2014; USDA 2014). Pesticide use on US potatoes increased from 10 million kilograms of a.i per hectare in 1960 to 59 million kilograms in 2008, of which 2.6 million kilograms were herbicides (Fernandez-Cornejo et al. 2014). Of pesticides applied, 25% is herbicide, 15% is insecticide, and 55% is fungicide (Fernandez-Cornejo et al. 2014). It has been estimated that without pesticides, the worldwide production of potatoes would decline by 58% (Oerke 2006).

1.1.2 Pesticide Intensity in Potato Production

With annual application rates ranging from 2.8 to 4.1 kilograms of a.i per hectare annually, PE has a higher intensity of pesticide use compared to other Canadian provinces (EC 2011; Wagner et al. 2002). In addition, PE potato producers routinely make 12 to 15 pesticide applications per year. Crop protectants account for 10% of operating costs, which corresponds to the intensity of the potato growing system (PE Potato 2019).

Due to high weed, disease, and insect pest pressures, potato production relies heavily on chemical pesticides, which has led to the development of resistance across different taxa. Examples of pesticide resistance in potato include Colorado potato beetle (*Leptinotarsa decemlineata* Say), late blight (*Phytophthora infestans* (Mont.) de Bary), and common lambsquarters (Howatt and Hodgson 1954; Hare 1980; Bettini et al. 1987).

1.2 Common Lambsquarters (*Chenopodium album* L.)

1.2.1 Biology of Common Lambsquarters

Common lambsquarters is a summer annual broadleaf weed that can grow from 1 cm to 1.5 m tall. An average plant can produce over 72,000 seeds (Stevens 1932). Common lambsquarters produces black, round seeds that have little endosperm and can persist in the soil for more than 30 years (Eslami and Ward 2021). Seed must be on the surface of the soil or no deeper than 2.5 cm in order to successfully germinate (Weaver 1988). The plant also produces flat, brown seed that does not undergo an extended period of dormancy and can germinate from 0.5 - 3.0 cm deep within the soil. Germination can successfully occur in various environments, though conditions of drought, low nitrates and low red/far-red ratios of light have been found to

hinder plant establishment (Henson 1970; Cumming 1963). The seed has no obvious mechanism of dispersal and is shed locally. Long distance dispersal can be accomplished through human activities and via faeces of livestock and birds. Due to its short life cycle and continuous emergence pattern, common lambsquarters contributes a large number of viable seeds to the weed seed bank annually (Harrison 1990; Brown et al. 2022). Common lambsquarters can establish in variable soil moisture, pH, and temperature, allowing the seed to germinate throughout the growing season (Bassett and Crompton 1978). Common lambsquarters is well adapted to high-input cropping systems and competes with crop species by germinating early in the spring and commencing uptake of available soil nutrients. It is known to release phytotoxic secondary metabolites into the rhizosphere which suppress germination and growth of plants present in its surrounding growing environment (Caussanel and Kunesch 1979; Qasem and Hill 1989). In addition, common lambsquarters serves as an alternate host to several economically important crop pests including *Stagonospora atriplicis,* beet yellows virus (*Closteroviridae spp.*), and northern root knot nematode (*Meloidogyne hapla*), thus increasing crop management requirements (McKenzie and Dingley 1996; Bartsch et al. 2001; Gharabadiyan et al. 2012).

1.2.2 Control of Common Lambsquarters

Cultural, mechanical, biological, and chemical control tactics can be used to successfully manage common lambsquarters. Cultural methods to control common lambsquarters include high crop planting density and narrow crop row spacing, mulching, use of cover crops, intercropping, and nitrogen management (Bajwa et al. 2019). Mechanical methods of control include mowing, hoeing, hilling, solarisation, flaming, and tillage (Bajwa et al. 2019). Mowing at the three-leaf stage has been shown to provide 100% control of common lambsquarters (Bassett and Crompton 1978). Repeated mowing throughout the growing season can reduce common

lambsquarters total dry weight and inflorescence dry weight by 79% and 90%, respectively (Butler et al. 2013). Biological control such as the use of *Ascochyta caulina* (P. Karst) fungal spores, in combination with reduced rates of metribuzin and rimsulfuron, may effectively control common lambsquarters (Vurro et al. 2001). While various herbicide chemistries are effective at controlling common lambsquarters, potato production in the Atlantic Canadian region typically involves the use of pre-emergent herbicides. Of these herbicides, metribuzin is reported to be used on 70% of potato hectarage in PE (L MacKinnon, personal communication 2019).

1.3 Herbicide Resistance

Herbicide tolerance is the inherent ability of a species to survive and reproduce after an herbicide has been applied. This may occur naturally in a species, without selection pressures such as herbicide application or genetic manipulation (WSSA 1998). In contrast, herbicide resistance is the inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide that would otherwise be lethal to a wild biotype.

1.3.1 Resistance of Common Lambsquarters to Triazine Herbicides

Various common lambsquarters biotypes resistant to photosystem II (PSII)-inhibitors, acetolactate-synthase (ALS) inhibitors (group 2), and synthetic auxin (group 4) herbicides have been confirmed worldwide (Bajwa et al. 2019). The first global report of PSII-inhibitor herbicide resistance was with common groundsel (*Senecio vulgaris* L.) in the United States in 1968 (Holt 1992). Since then, over 80 species worldwide are confirmed PSII-resistant (Heap 2024). PSII-inhibitor herbicides are prone to resistance largely due to the frequency of their use and their application over large areas for multiple years. The majority of resistance reports are amongst *Amaranthus*, *Chenopodium*, *Echinochloa*, and *Solanum* spp. infesting US corn cropping systems

(Heap 2024). Within potato production, common lambsquarters is most commonly resistant to PSII-inhibitor herbicides (Bajwa et al. 2019). Throughout Canada, triazine resistant common lambsquarters have been reported within potatoes, corn, spring wheat, spring barley (*Hordeum vulgare* L.), and soybean (*Glycine max* L. Merr.) cropping systems (McKenzie-Gopsill et al. 2020; Heap 2024).

1.3.2 Causes and Mechanisms of Herbicide Resistance

Resistance is an evolutionary process that progresses through the use, and overuse, of herbicides that select for naturally occurring genetic mutations in weed populations (Jasieniuk et al. 1996). Herbicide resistance can be broadly categorized as target-site resistance (TSR) and non-target-site resistance (NTSR). TSR involves genetic mutations and changes to the herbicide target-site resulting in reduced herbicide efficacy due to reduced herbicide binding at the target-site. This can occur via target-site mutation such as an amino acid substitution or deletion, or overexpression of a target-site through gene amplification or changes in the transcription factor (Yu and Powles 2014; Gaines et al. 2020). NTSR occurs when mechanisms minimize the amount of active ingredient reaching the target-site. This can include vacuole sequestration, decreased rates of herbicide absorption or translocation, and increased rates of herbicide metabolism (Yu and Powles 2014; Gaines et al. 2020).

Many herbicides across different chemistries inhibit photosynthesis. In the case of triazines, they compete with plastoquinone (PQ) at the PQ binding site on the D1 protein in the PSII reaction centre of the photosynthetic electron transport chain. Inhibiting electron transport within PSII stops the production of NADPH and ATP as well as the carbon reduction cycle.

Consequentially this inhibits carbon fixation, causing carbohydrate starvation, oxidative stress and the generation of free radicals causing cell damage and leads to plant death.

Resistance to PSII-inhibiting herbicides is commonly due to a point mutation in the chloroplast *psbA* gene. This point mutation changes the nucleic acid codon and codes for a different amino acid sequence, thus altering the D1 protein target-site conformation and prevents herbicide binding (Lu et al. 2018). In the case of triazine resistance, this mutation is most commonly found at amino acid position 264 in the D1 protein and involves a serine to glycine substitution ($Ser_{264}Gly$) (Beckie and Tardif 2012). Competition between triazines and PQ at the PQ binding site is lessened with the presence of the $Ser_{264}Gly$ amino acid substitution which removes a hydrogen bond otherwise available for triazine binding (Powles and Yu 2010). Other mutations conferring resistance have been found, however, are less common than $Ser_{264}Gly$ (Powles and Yu 2010). This mutation compromises PQ binding and comes with a cost of reduced photosynthesis and plant fitness (Powles and Yu 2010). Globally, the $Ser_{264}Gly$ amino acid substitution has been documented in numerous species and is associated with high-level resistance, typically selected by triazine herbicides (Beckie and Tardif 2012). Other non-target-site resistance mechanisms conferring triazine resistance have been found in *Lolium rigidum* L. (Yu and Powles 2014).

1.4 Integrated Weed Management

Integrated weed management (IWM) is a multi-faceted approach to managing weeds that combines preventative, cultural, mechanical, chemical, and biological tactics (Beckie and Harker 2017). Prevention is one of the first steps to successful IWM and focuses on limiting the spread of weeds. These tactics include cleaning equipment and crop seed, and exhausting the soil

seedbank. Cultural practices focus on increasing the competitiveness of the crop and include tactics such as reduced row spacing, nutrient management, and use of cover crops. Chemical weed management utilizes herbicides and can involve the use of tank mixes, chemical rotations, and alternative application methods. Mechanical means of IWM involve physical practices that disrupt seed germination and destroy plants in order to prevent seed set. These tactics can include tillage, mowing, burning, and harvest weed seed management. Investigation into IWM tactics to control common lambsquarters in potato production systems in this project will include soil seedbank management, above-canopy mowing and wick weeding, and the use of cover crop rotations and various termination methods.

1.4.1 Seedbank Management

Understanding the biology and the fate of weed seeds is an important component of IWM. The focus of weed management requires realignment away from solely integrated herbicide management towards a proactive weed program that targets the weed seedbank (Norsworthy et al. 2012). Taking a proactive approach to IWM will utilize direct and indirect management strategies before resistance is present.

An important part of a weed's lifecycle involves the weed seedbank. The seedbank is the resting place for weed seeds and is the source of future weed populations (Hossain and Begum 2015). The transition from seed to mature plant is influenced by environmental conditions and management practices. Seeds can remain dormant for many years and common lambsquarters seed remain viable in soil for 20 years or more (Lewis 1973; Toole and Brown 1946). While short-term weed management strategies target the aboveground biomass that competes with crops, long-term management involves targeting the seedbank communities.

Seedbanks can be managed indirectly by removing above ground weeds and reduce seed production, thereby reducing deposits into the weed seedbank (Swanton and Booth 2004). In contrast, direct management involves increasing mortality of seeds already in the seedbank and manipulating seed germination and seedling emergence such that subsequently emerged seedlings can be killed prior to seed production and seedbank replenishment (Swanton and Booth 2004). Sources of seed mortality include decomposition, consumption by an animal, pathogen attack, lethal germination, and desiccation (Hossain and Begum 2015). Direct management involves mechanical and chemical control, often effective early in the crop lifecycle or immediately following crop harvest through harvest weed seed control measures that prevent seed that has been produced by weed escapes from entering the seedbank.

1.4.2 Use of Cover Crops for Weed and Weed Seedbank Management

Cultural weed management utilizes various agronomic practices that increase crop competitiveness. Beckie and Harker (2017) state the most important herbicide-resistant weed management practice is enhancing crop diversity. This can include lengthening and diversifying crop rotation, use of cover crops, green manures, and living mulches. Crop rotation is the sequence in which crops are planted from year to year (Swanton and Booth 2004). Crop diversity involves rotating between weed-competitive species with a mix of monocots and dicots, and spring- and winter-planted, cool- and warm-season annuals and perennials. A diverse crop rotation will exert different selection pressures on the weed community and weed seedbank. Rotations may include grasses, broad-leaf species, *Brassica* species, and legume species, or even a mix to combine beneficial effects. Common crops in PE include winter cereals such as wheat or rye, or broad leaf crops like buckwheat, brown mustard, clover and peas, and mixes with vetch

and Timothy. The resource pool diversity hypothesis (RPDH) predicts that weed-crop competition for soil resources decreases with increasing diversity of the soil resource pool (Smith et al. 2010). This suggests that a more diverse rotation containing cover crops and cover crop mixes increases resource competition and decreases weed competition. MacLaren et al. (2019) recommend that multi-species mixes be comprised of a variety of competitive abilities and possess the ability to produce biomass in order to suppress weeds. Having diverse crops in rotation allows for the use multiple of herbicides each year and the potential for rotation of herbicide mode of action (MOA) between years. This includes pre-plant soil residual, post-emergent and in-season, post-harvest and fall herbicide applications. By increasing crop diversity and chemical control use patterns, producers can further rely on mechanical and cultural practices as a means to diversify weed control practices.

1.4.3 Chemical Weed Management

Herbicides target a particular plant function such as photosynthesis or amino acid synthesis to inhibit plant growth, and is referred to as the herbicide mode of action (MOA). Herbicides bind-to, and inhibit particular plant proteins, and are referred to as a herbicide site of action (SOA). Herbicides available for chemical weed management in potato can be applied pre-plant (PP, before potato planting), after potato planting but pre-emergent (PRE) to weeds or potato, and post-emergent (POST) after potato planting and after weeds emerge. Pre-plant herbicides are applied to soil prior to crop planting and may be pre-plant incorporated (PPI) into soil with secondary tillage prior to crop planting.

Efforts in herbicide resistance management include herbicide rotation and utilization of herbicides that target different SOA (Beckie and Reboud 2009). Herbicide rotations involve use

of herbicides of different MOA to multiple crops over multiple growing seasons in a particular field and has been cited as the most commonly used herbicide resistance management practice (Beckie 2006; Beckie 2007). Current emphasis of herbicide resistance management includes herbicides rotation and mixtures, as well as bioherbicides and eco-nanotechnology (Perotti et al. 2020; Gaines et al. 2021). Herbicide mixtures are the combination of two or more herbicides having multiple modes of action (MMOA) and are applied simultaneously in a single mixture. Beckie and Reboud (2009) found that herbicide mixtures are more effective at mitigating herbicide resistance evolution than herbicide rotation alone.

Targeted herbicide applications allow for the use of non-selective or alternative MOA herbicides to be used on a target weed species without the risk of injuring non-target vegetation. Non-selective herbicides are broad-spectrum and capable of injuring and killing most plants. Wick-applicators apply herbicide to weed foliage by wiping the plant with a saturated material, often a rope or sponge. These applicators are designed to target weeds growing above the crop canopy, typically with a 5 to 10 cm crop to weed height differential and have been proven effective for providing adequate weed control in soybeans, lowbush blueberries and sweet potatoes (Dale 1979, Wu and Boyd 2012, Meyers et al. 2016). The length of potato stems ranges from 45 to 60 cm, whereas common lambsquarters can reach heights of 1.5 m, providing a height differential adequate for wick-applicator use (Basset and Crompton 1978; CFIA 2015a)

1.4.4 Mechanical Weed Management

Mechanical weed management includes the use of tillage, mowing, and hand weeding for control of weed species. Tillage influences the seed environment by drying out the soil, shifting weed seeds vertically, and uprooting or cutting the roots of growing seedlings. Swanton et al.

(1999) found an interaction between the vertical distribution of weed seeds, soil type, tillage type, and tillage depth. No-till systems contain 90% of the weed seedbank in the top 5 cm of soil whereas only 1% is found at 10-15 cm depths (Swanton et al. 1999). In chisel plough and moldboard plough systems, however, 66% and 63% of the seeds were located within the top 5-10 cm, respectively (Swanton et al. 1999). Soil disturbance has been found to stimulate germination; however, soil mixing places seeds at deeper soil depths and may lead to long-term weed persistence. Timing of tillage within the season and day-night cycles can impact the efficacy of control. Buhler (1997) found emergence of common lambsquarters was 44 to 71% less when tillage was conducted in the dark than in the light.

Limited studies have been conducted on the effects of mowing as an effective means of mechanical weed control (Gibson et al. 2011). Mowing works by mechanically cutting the top portion of weed plants that is growing above the crop canopy and leaving it on the soil surface. In most cases, crop residues are left on the soil surface as mulch. Between-row mowing systems reduce summer and winter annual weed cover and prevent yield loss (Donald 2007). Donald (2006) found a pre-herbicide combined with late between-row mowing in a corn system provided total weed control and yield that was similar to the weed-free check. If in-row weeds are controlled with pre-banded herbicides, there is potential to control late-emerging weeds between rows with mowing after canopy closure without diminishing yield (Donald 2006). Hill et al. (2016) found that viable seed production of common lambsquarters was reduced by 99% when terminated by cutting at the base of the plant to simulate hand hoeing, chopping to simulate mowing and applying glyphosate when immature was seed present.

1.5 Research Approach

The main objective of this research project is to investigate common lambsquarters biology and seedbank dynamics to determine and optimize control options to increase mortality, deplete the weed seedbank, and decrease germination and viable seed shed.

1.5.1 Evaluation of Crop-Topping with Mowing and Wick-Weeding

Objective: Investigate crop-topping with above-canopy mowing and wick-applied glyphosate for in-season control of common lambsquarters over-topping a potato canopy using three potato cultivars of varying growth habits.

Hypotheses:

1. The growth patterns of the semi-erect and upright potato cultivars will increase potato damage and negatively impact yield.
2. Early crop-topping will increase common lambsquarters control and maximize reductions in seed production but will reduce potato yield compared to later crop topping applications.

1.5.2 Evaluation of Cover-Crop Rotations for Common Lambsquarters Suppression

Objective: Evaluate several cover crops and termination methods to suppress common lambsquarters populations in a potato rotation.

Hypotheses:

1. Cover crops with higher stand densities will decrease common lambsquarters seed germination, density, and contributions towards the weed seedbank.

2. Cover crops terminated with methods that increase soil ground cover will decrease the germinable fraction of the common lambsquarters seedbank.
3. The cover crops terminated with methods that soil-incorporate biomass will increase potato yield and quality.

Chapter 2: Evaluation of crop-topping strategies to reduce common lambsquarters (*Chenopodium album* L.) seed production in potato production systems

2.0 Abstract

Potato (*Solanum tuberosum* L.) producers in the Atlantic Canadian provinces of Prince Edward Island (PE) and New Brunswick (NB) rely on photosystem II (PSII)-inhibiting herbicides to provide season-long weed control. A high proportion of lambsquarters (*Chenopodium album* L.) populations in the region have been identified as resistant to PSII-inhibiting herbicides and are increasingly difficult to control in potato with existing management tactics. Crop-topping is a post-emergent weed management practice that exploits the height differential between weeds and a developing crop canopy. Two field experiments were conducted in Harrington, PE in 2019 and 2020 to evaluate the efficacy of a different crop-topping strategy, above-canopy mowing or wick-applied glyphosate. The experiment was conducted at two common lambsquarters phenological stages to measure viable seed production (VSP) and potato yield and quality. Mowing common lambsquarters post-flowering increased harvest index (HI) (140%) in 2019 but decreased reproductive biomass (76% to 84%), HI (67%-72%) and VSP (59% to 72%) in 2020. Mowing reduced cull yield over both years but minimal increases to potato marketable yield were observed in 2019 and no increase was observed in 2020. In contrast, treating common lambsquarters with wick-applied glyphosate had variable impacts on seed output in both years but dramatically reduced HI (15%), germination percentage (32%-63%) and VSP (>50%), in 2020 when treatments were applied post-flowering. Glyphosate damage to potato tubers was influenced by timing in 2019 and increased culled tubers by 7- to 13-fold. Our study highlights the importance of crop and weed 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.

2.1 Introduction

Potato (*Solanum tuberosum* L.) is the highest-value horticulture crop in Canada, with an estimated farm gate value of $1.42B CAD in 2019 (CATSNet 2021). The Atlantic provinces of Prince Edward Island (PE) and New Brunswick (NB) produce 37% of all Canadian potatoes 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 $82 CAD million in potential annual yield loss due to reductions in tuber number and quality (Ganie et al. 2023). Furthermore, weeds can serve as alternate 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 metribuzin, a Group 5 triazinone, and linuron, a Group 5 substituted urea (WSSA 2021). These herbicides are applied to over 75% of potato hectarage in the PE 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 pre-emergence 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 pre-emergence 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 pre-emergent herbicide application of metribuzin or linuron to provide season-long weed control in potato from planting to harvest.

Common lambsquarters (*Chenopodium album* L.) is a summer annual broadleaf weed that occurs in various environments and cropping stems 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 and plants can grow up to 1.5 m tall to rapidly over-top a crop canopy, reducing light availability for the crop (Bassett and Crompton 1978; Ogg and Dawson 1984; 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). 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 crop 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 systems. Crop-topping is the use of a non-selective 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 over-topping a crop canopy. For example, Simard et al. (2018) had limited success with mechanical control of common lambsquarters over-topping 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 the inflorescence dry weight required repeated mowing 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 over-topping a sweet potato (*Ipomoea batatas* (L.) Lam.) canopy at 7 and 8 weeks after planting (WAP). 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 (*Capsicum annuum* L.) 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 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 chemical and mechanical strategies to suppress viable common lambsquarters seed shed. 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 over-topping a potato canopy using three potato cultivars of varying growth habits. We hypothesized first that the growth patterns of the semi-erect and upright potato cultivars would increase potato damage and negatively impact yield when compared to the spreading cultivar and, second, that early crop-topping will increase common lambsquarters control and maximize reductions in seed production but will reduce potato yield.

2.2 Materials and Methods

2.2.1 Experimental Design

Two field experiments were established at the Harrington Experimental Farm (46°20’37.020’’ N, 63°10’11.050’’ W) in Harrington, PE, Canada in 2019 and 2020. Soil at

Harrington is characterized as a fine sandy loam (Ferro-Humic Podsol, 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 as crop-topping strategies. 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'; spreading, 'Shepody'; upright, 'Yukon Gold') (CFIA 2015b), 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 plots 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 containing at least one eye were hand-planted on May 29, 2019 and June 4, 2020 at 31 cm, 38 cm, and 31 cm spacing for semi-erect, spreading, and upright cultivars, respectively. Fertilizer was banded at planting prior to row closure at 160- 200- 135 kg ha^{-1} (N-P-K) according to provincial 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 weeks after planting on June 25, 2019 and July 2, 2020. Potatoes were top-killed at maturity with broadcast diquat (Reglone®, 240 g ai L^{-1}; Syngenta Canada, Calgary, AB, Canada) at a rate of 840 g ai ha^{-1}

on September 11, 2019 and September 15, 2020. To evaluate the effects of treatments on yield, one treated row per plot was mechanically harvested on September 19, 2019 and October 1, 2020.

2.2.2 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 treatments were conducted prior to common lambsquarters flowering, which corresponded to stage 65 according to the BBCH (Biologische Bundesanstalt, Bundessortenamy und Chemische Industrie) scale and the late mowing treatment was made after common lambsquarters flowering at stage 66 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. A 10 cm height differential was not achieved in 2019 and the mower height was set to target the top 25% of common lambsquarters plants in the adjacent weedy sub-plots, at 44 cm and 75 cm for the early and late mowing timings, respectively (Table 2.1). The mower height was set at 10 cm above the average potato height, at 73 cm and 69 cm in 2020 for early and late mowing timings, respectively (Table 2.1). Mowing treatments were conducted on August 16 and August 23 in 2019 and on July 31 and August 21 in 2020 for early and late mowing timings, respectively. Hedge trimmers were used to simulate a crop mower at a travel speed of 5.0 km h^{-1} for all treatments. Hedge trimmers were held at the crop topping height while travelling through the plot and measured throughout mowing to maintain consistency within the plot. Trimmer

heights were recalibrated prior to mowing each plot. For both treatment timings, the entire plot was mowed in a single direction at the set height.

2.2.3 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. 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 (Figure 2.1; 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 two-parts glyphosate (Roundup WeatherMAX®, 540 g ae L^{-1}; Monsanto, Winnipeg, MB, Canada) and one-part water solution for a concentration of 360 g ae L^{-1} of glyphosate was used for both treatment timings in 2019 and a one-part glyphosate and two-parts water solution for a concentration of 180 g ae L^{-1} of glyphosate was used for both treatment timings in 2020, per the manufacturer's instructions. The wick bar was mounted to 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. A 10 cm height differential was not achieved in 2019 and the wick bar was set to target the top 25% of common lambsquarters plants in the adjacent weedy sub-plots, at 41 cm and 62 cm for the early and late mowing timings, respectively (Table 2.1). The wick bar was set 10 cm above the average potato height, at 71 cm and 56 cm in 2020 for early and late timing of wick treatments, respectively (Table 2.1). Wick-applied glyphosate

treatments were conducted on August 16 and August 23 in 2019 and July 30 and August 20 in 2020 for early and late mowing timings, respectively. Owing to logistical challenges with the wick bar, only one row (5 m^2) in each plot was treated at both treatment timings in a single direction at the set height at a travel speed of 6.5 km h^{-1} for all treatments. All measurements, including yield, were taken from the treated potato row.

Figure 2.1. Vogels 15' Loader Model Wick Weeder mounted to a front-end loader tractor (John Deere 6034) from early wick treatment in 2020.

Table 2.1. 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]

Timing	Mow			Wick		
	Potato	CHEAL	Mower height	Potato	CHEAL	Wick bar height
	cm					
			2019			
Early	64 ± 6	59 ± 17	44	63 ± 6	55 ± 13	41
Late	65 ± 7	88 ± 14	75	65 ± 7	82 ± 12	62
			2020			
Early	63 ± 5	94 ± 11	73	61 ± 7	84 ± 12	71
Late	59 ± 12	115 ± 17	69	46 ± 14	120 ± 16	56

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

2.2.4 Data Collection

Data collection in Experiments 1 and 2 was identical. 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 and covered by a low-density polyethylene bag (1.2 × 1.5 m [L × D]) immediately following treatment application to capture shattered seed for the remainder of the season. Plot biomass was measured by harvesting common lambsquarters at soil-level within one 0.25 m^2 quadrat per plot at 3 weeks after application (WAA). Plant material was bagged and placed on a greenhouse bench for 1 week to dry before being weighed. Prior to potato harvest, tagged common lambsquarters was cut at the base of the plant and dried on a greenhouse bench for 1 week. Plants were carefully hand threshed, sieved with a 200-mm sieve and then 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 sub-samples were counted and weighed to determine thousand seed weight (TSW) (g). Entire seed samples were used for determination on TSW when fewer than 150 seeds were in a sample. Vegetative and reproductive biomasses were used to compute harvest index (HI) 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 sub-samples 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 days. Germinated seeds, determined by the presence of a visible radicle or hypocotyl, were then counted to determine germination percentage. Viability of non-germinated 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. Viable seed production (VSP), 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 CFIA potato grading scale (CFIA 2015b) using an 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 were counted as culls and added to cull yield (Figure 2.2). 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.

Figure 2.2. Glyphosate damaged culls following wick application in (A) spreading early (B) spreading late (C) semi-erect early (D) semi-erect late (E) upright early and (F) upright late in 2020.

2.2.5 Statistical Analysis

All statistical analyses were performed using SAS v9.4 (SAS Institute, Cary, USA). Due to differences in treatments between experiments in 2019 and 2020 data were analyzed separately. Assumptions of normality, constant variance, and independence were tested using PROC UNIVARIATE. In both experiments, common lambsquarters plot biomass, total biomass, vegetative biomass, seed biomass, TSW, germination percentage, and VSP were analyzed with generalized linear mixed effects models using PROC GLIMMIX and a normal distribution with an identity link function. Common lambsquarters HI in the mowing experiment was also analyzed with generalized linear mixed effects models using PROC GLIMMIX and a normal distribution with an identity link function. HI in the wick-applied glyphosate was analyzed with a generalized linear mixed effects model using PROC GLIMMIX and a beta distribution with a logit link function. Cultivar, treatment timing, year, and their interactions were treated as fixed effects and replication was a random effect. Marketable yield, cull yield, and percentage lost to culls was analyzed with generalized linear mixed effects models using PROC GLIMMIX and a normal distribution with an identity link function. The whole-plot factor (potato cultivar) and strip-plot factor (treatment timing) and their interaction were treated as fixed effects, and replication, and the interaction of replication and cultivar, were treated as random effects. Orthogonal contrast statements were used to compare efficacy of wick and mow treatment timings to controls across potato cultivars with a Type I error rate of $\alpha = 0.05$. For all analyses, least square means and standard errors are presented.

2.3 Results and Discussion

2.3.1 Impact of crop-topping with a mower on common lambsquarters and potato

Mow timing had minimal impact on common lambsquarters total ($p=0.12$) and vegetative ($p=0.12$) biomass in 2019 (Table 2.2). There was an effect of mow treatment timing ($p<0.01$) and potato cultivar ($p=0.03$) on common lambsquarters total plot biomass in 2020 at 3 WAA (Table 2.2). Late mowing decreased common lambsquarters total plot biomass by 86% ($p<0.01$) and 61% ($p=0.01$) in the spreading and upright cultivars in 2020 at 3 WAA, respectively (Table 2.2; Figure 2.3). Total common lambsquarters biomass was affected by mow treatment timing ($p<0.01$) and the interaction of mow treatment timing and potato cultivar ($p=0.01$) in 2020 (Table 2.2). Late mowing reduced total common lambsquarters biomass by 45% ($p<0.01$) in the spreading cultivar in 2020 (Table 2.2; Figure 2.3). Vegetative biomass in 2020 was affected by mow treatment timing ($p<0.01$), however no treatment differences were detected amongst cultivars (Table 2.2; Figure 2.3).

Table 2.2. ANOVA table of common lambsquarters 3 WAA plot biomass, total biomass, vegetative biomass, reproductive biomass, harvest index, germination percentage, and thousand seed weight by year, cultivar, treatment timing, and their interaction following crop-topping with a mower.

Covariance parameters	ndf/ddf[b]	3 WAA[b] plot biomass [a]	Total biomass [a]	Vegetative biomass [a]	Reproductive biomass [a]	Harvest index [a]	TSW[a,b]	Germination [a]	Viable seed production [a]
2019									
Trt[b]	2/6	0.4179	0.1206	0.1183	0.1562	**0.0173**	0.4548	0.1177	0.1389
Contrasts									
Control vs. early	1/6	0.9805	0.9971	0.9892	0.9745	0.2880	0.2857	0.5416	0.9419
Control vs. late	1/6	0.2596	0.0753	0.0733	0.0995	**0.0286**	0.2871	0.1277	0.0946
2020									
Trt[b]	3/9	**0.0017**	**0.0003**	**0.0016**	**<0.0001**	**<0.0001**	**0.0005**	**0.0016**	**<0.0001**
Clt[b]	2/24	**0.0251**	0.0823	0.2253	0.0218	0.2680	0.1594	**0.0047**	**0.0121**
Trt*Clt[b]	6/24	0.1454	**0.0089**	0.0917	**0.0014**	0.8985	**0.0243**	**<0.0001**	**0.0169**
Contrasts									
Semi-erect - Control vs. early	1/24	0.2802	0.3054	0.2983	0.5029	0.3736	0.7093	0.1070	0.0805
Semi-erect - Control vs. late	1/24	0.2335	0.5078	0.5787	**0.0021**	**<0.0001**	0.1886	0.1168	**0.0013**
Spreading - Control vs. early	1/24	0.9728	0.8637	0.6158	0.9423	0.1417	0.0763	0.2007	0.8563
Spreading - Control vs. late	1/24	**<0.0001**	**0.0002**	0.1326	**<0.0001**	**<0.0001**	**0.0020**	**<.0001**	**0.0004**
Upright - Control vs. early	1/24	0.1258	0.8553	0.9963	0.6052	0.4605	**0.0024**	**0.0285**	0.8330
Upright - Control vs. late	1/24	**0.011**	0.0598	0.9930	**<0.0001**	**<0.0001**	0.4014	0.2265	**<0.0001**

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

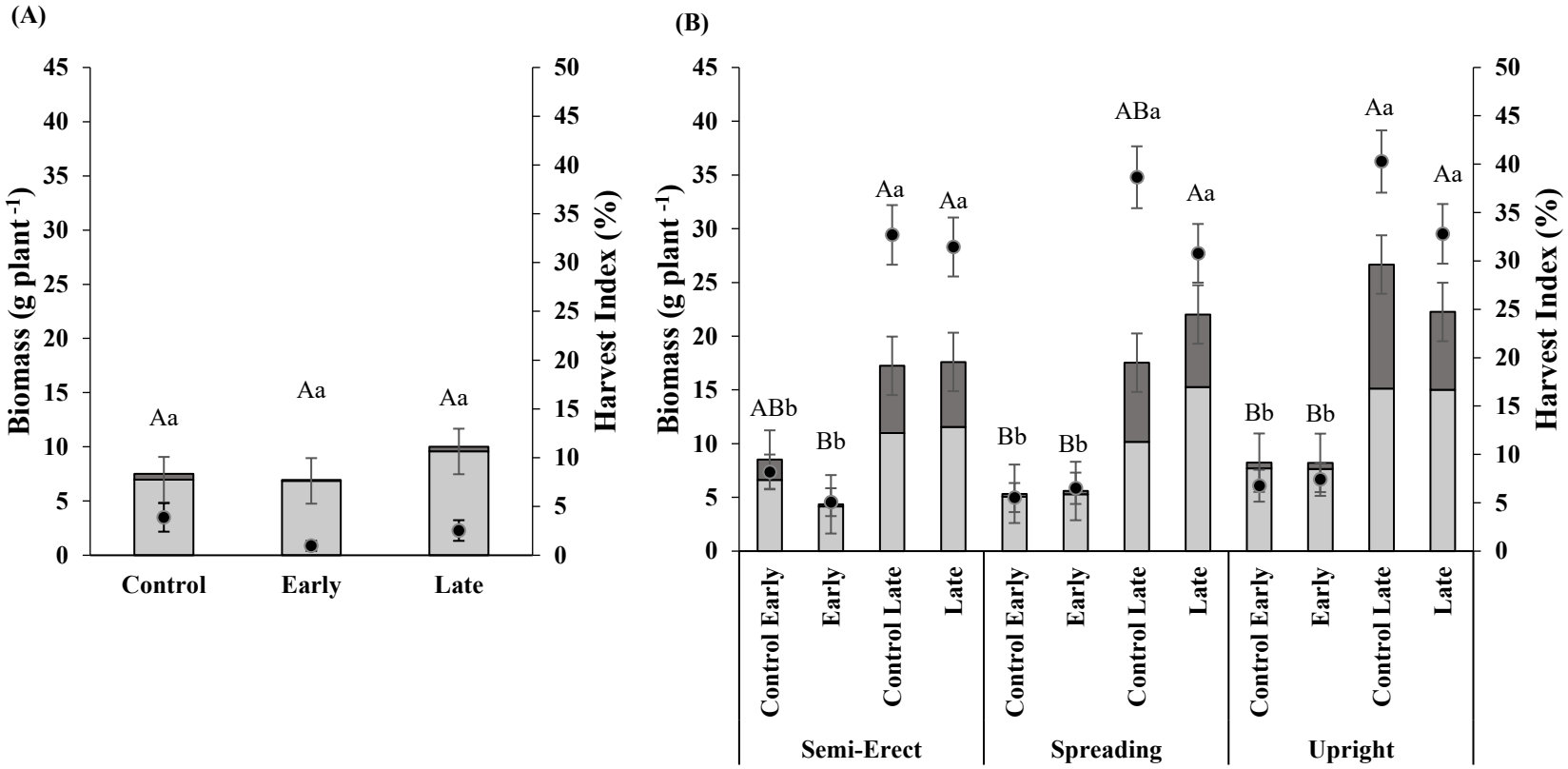

Figure 2.3. The effect of early and late crop-topping with a mower on common lambsquarters vegetative (light gray bars) and reproductive (dark gray bars) biomass allocation and harvest index (circles) in control, early and late in 2019 (A) and semi-erect, spreading and upright cultivars in 2020 (B) in Harrington PE. Data are least square means ± standard error of the mean of total biomass. Values not connected by the same letter are significantly different according to Tukey's honestly significant difference (α = 0.05). Pane A: 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. Pane B: Uppercase letters refer to the effect of treatment timing on total biomass (vegetative and reproductive) accumulation within potato cultivars, and lowercase letters refer to the effect of treatment timing on harvest index within potato cultivars.

Reproductive biomass of common lambsquarters was not affected by treatment timing in 2019 ($p=0.16$) (Table 2.2). Reproductive biomass was affected by treatment and cultivar interactions ($p<0.01$) in 2020 and decreased by 78% ($p<0.01$), 84% ($p<0.01$), and 76% ($p<0.01$) in the semi-erect, spreading, and upright cultivars, respectively following the late treatment (Table 2.2; Figure 2.3). Despite the limited changes to common lambsquarters biomass accumulation and allocation in 2019, early mowing was found to decrease common lambsquarters HI by 57%, while late mowing increased it by 140% ($p=0.03$) when compared to the control (Table 2.2; Figure 2.3). Similarly, the time of mowing also affected common lambsquarters HI in 2020 ($p<0.01$) and late mowing decreased the HI by 67% ($p<0.01$), 72% ($p<0.01$), and 70% ($p<0.01$) in the semi-erect, spreading, and upright cultivars, respectively (Table 2.2; Figure 2.3).

TSW ($p=0.45$), germination percentage ($p=0.12$) and VSP ($p=0.14$) were not affected by mow treatment timing in 2019 (Table 2.2; Figure 2.4). Common lambsquarters TSW was affected by mow timing ($p<0.01$) and the interaction between treatment timing and cultivar ($p=0.02$) in 2020 (Table 2.2). Contrast statements revealed early mowing increased common lambsquarters TSW by 26% ($p<0.01$) in the upright cultivar, and late mowing increased TSW in the spreading cultivar by 19% ($p<0.01$) in 2020 compared to the control (Table 2.2; Figure 2.4). Germination percentage and VSP was affected by mow timing ($p<0.01$), potato cultivar ($p\leq0.01$), and the interaction of mow timing and cultivar ($p\leq0.01$) in 2020 (Table 2.2). Early mowing in the upright cultivar and late mowing in the spreading cultivar increased common lambsquarters germination by 25% ($p<0.01$) and 160% ($p=0.03$), respectively (Table 2.2; Data not shown). Interestingly, late mowing decreased common lambsquarters VSP by 72% ($p<0.01$), 59% ($p<0.01$), and 72% ($p<0.01$) in the semi-erect, spreading, and upright cultivars, respectively

in 2020 (Table 2.2; Figure 2.4). The common lambsquarters germination percentage was positively correlated with TSW and increased as TSW increased (Figure 2.5).

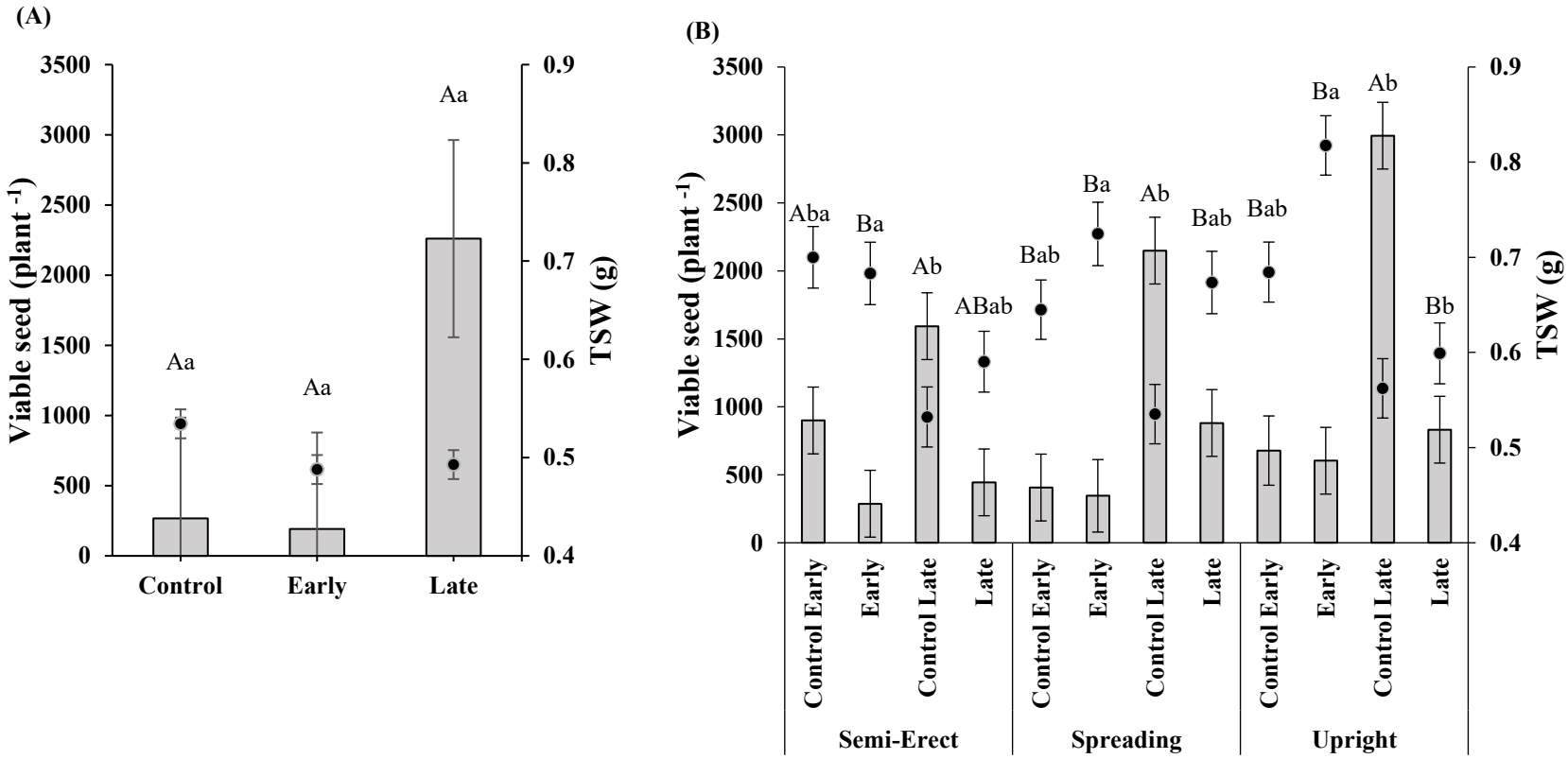

Figure 2.4. Effect of early and late crop-topping with a mower on common lambsquarters viable seed plant $^{-1}$ (bars) and thousand seed weight (TSW) (circles) in control, early and late in 2019 (A) and semi-erect, spreading and upright cultivars in 2020 (B) in Harrington PE. Data are least square means ± 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 seed plant $^{-1}$ and lowercase letters refer to the effects of treatment timing on TSW.

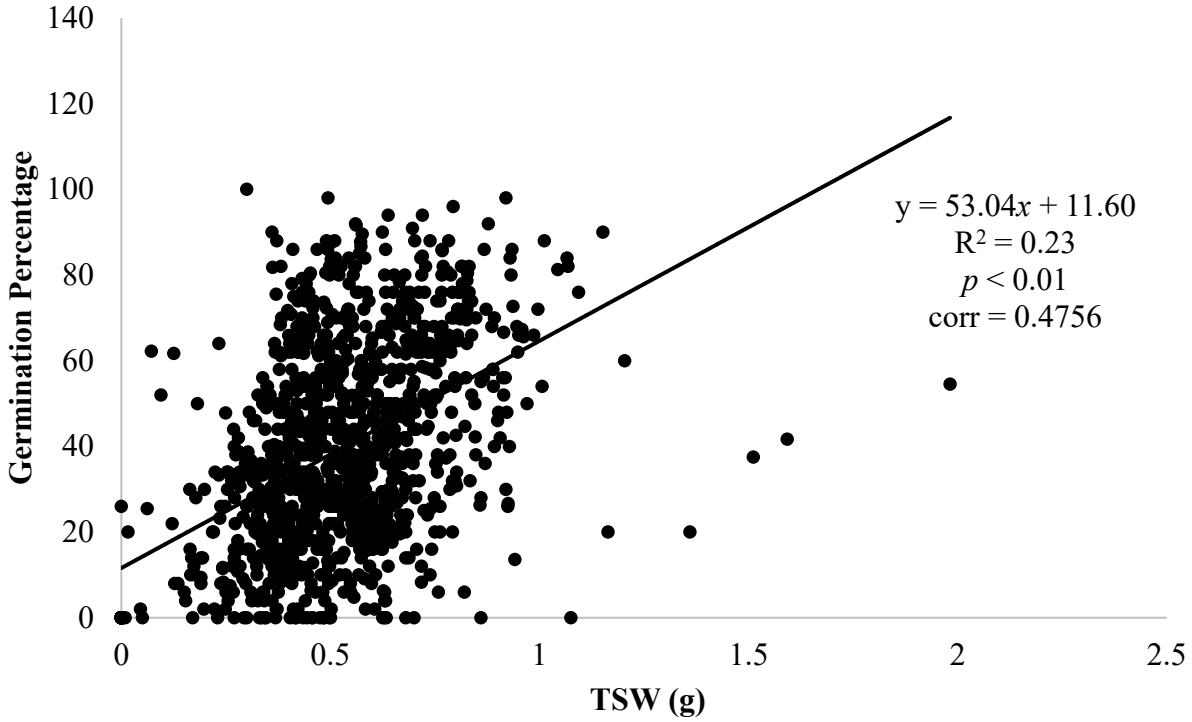

Figure 2.5. Relationship between thousand seed weight (g) and germination (%) of common lambsquarters seed following crop-topping with a mower or wick-applied glyphosate in 2019 and 2020. Black line represents linear regression between thousand seed weight to germination percentage (y=11.60+53.04*TSW) of sample size of 1119.

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 66) in our study is consistent with the findings of Hill et al. (2016), who 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 2019, mowing increased resource allocation to seed and increased HI with late mowing. In contrast, investment in common lambsquarters reproductive biomass dropped when mowed late in 2020 and resulted in reductions in HI and VSP. Several studies have documented rapid declines in seed number per plant and maintenance of seed weight in common lambsquarters response to crowding stress, decreased light intensity, and nitrogen availability (Colquhoun et al. 2001; 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 may have contributed to declines in VSP (AAFC 2023). The contrasting response of increased TSW and germination percentage with declines in viable seed produced in 2020 following mowing treatment may also be due to resource availability in that year, and resource allocation (AAFC 2023). As well, the R-selected life history strategy of *Chenopodium* species and the breaking of apical dominance may have allowed for an increased number of

inflorescences and increased seed production and germination but was paired with decreased viability (Albrechtova et al. 1994; Matzrafi et al. 2019). Together, these results suggest that crop-topping with a mower post-flowering can contribute to declines in VSP 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 was affected by the interactions of potato cultivar and treatment timing ($p=0.04$) in 2019 (Table 2.3). Marketable yield ranged from 17 to 30 T ha^{-1} in 2019 (Figure 2.6). In the semi-erect cultivar, early and late mowing treatment increased marketable potato yield by 57% ($p<0.01$) and 37% ($p=0.03$), respectively in 2019 (Table 2.3; Figure 2.6). Potato marketable yield was affected by potato cultivar in 2020 ($p<0.01$) and ranged from 13 to 24 T ha^{-1} in the semi-erect, spreading and upright cultivar, respectively (Figure 2.6). Potato cull yield was affected by the interactions of potato cultivar and treatment timing in 2019 ($p<0.01$) and 2020 ($p=0.01$). In 2019, potato cull yield ranged from 0.4 to 1.9 T ha^{-1} (Figure 2.6). Cull yield in 2019 decreased by 39% ($p=0.02$) and 41% ($p=0.02$) following early and late mowing in the semi-erect cultivar, respectively (Table 2.3; Figure 2.6). Cull yield increased by 68% ($p<0.01$) following the early treatment, but decreased by 47% ($p=0.01$) following the late mowing treatment in the spreading cultivar in 2019 (Table 2.3; Figure 2.6). In 2020, cull yield varied from a low of 0.4 T ha^{-1} to 1.2 T ha^{-1} (Figure 2.6). Early mowing in the spreading cultivar and late mowing in the semi-erect and spreading cultivars decreased cull yields by 41% ($p=0.01$), 30% ($p=0.05$), and 48% ($p<0.01$), respectively in 2020 (Table 2.3; Figure 2.6). The percentage of total yield lost to culls was affected by the interactions of potato cultivar and mowing timing in 2019 ($p<0.01$) and 2020 ($p=0.02$) (Table 2.3). The percentage of total yield lost to culls ranged from 3 to 5% in 2019 and was highest in the spreading (5%) and semi-erect

(4%) cultivars (Figure 2.6). By comparison, percentage of total yield lost to culls ranged from 4% to 5% in 2020 and remained highest in the semi-erect and spreading cultivars (Figure 2.6). Contrast statements revealed that early and late mowing decreased the percentage of yield lost to culls by 57% ($p<0.01$) and 45% ($p=0.01$) in the semi-erect cultivar, respectively in 2019 (Table 2.3; Figure 2.6). Conversely, early mowing increased the percentage of total yield lost to culls by 59% ($p=0.01$) in the spreading cultivar in 2019 (Table 2.3; Figure 2.6). In 2020, early and late mowing in the spreading cultivar resulted in reductions of percentage of yield lost to culls by 42% ($p=0.01$) and 54% ($p<0.01$), respectively (Table 2.3; Figure 2.6).

Table 2.3. 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.

Covariance parameters	ndf/ddf [b]	Marketable yield [a]	Cull yield [a]	Percentage yield lost to culls [a]
		2019		
Trt [b]	2/6	0.4784	0.0610	**0.0404**
Clt [b]	2/6	**0.0200**	0.1908	0.1932
Trt*Clt [b]	4/11	**0.0372**	**<0.0001**	**0.0016**
Contrasts				
Semi-erect - Control vs. early	1/11	**0.0029**	**0.0173**	**0.0021**
Semi-erect - Control vs. late	1/11	**0.0300**	**0.0179**	**0.0103**
Spreading - Control vs. early	1/11	0.6535	**0.0013**	**0.0123**
Spreading - Control vs. late	1/11	0.3667	**0.0167**	0.0602
Upright - Control vs. early	1/11	0.3239	0.2404	0.2488
Upright - Control vs. late	1/11	0.4734	0.6485	0.6603
		2020		
Trt [b]	2/6	0.2708	0.1573	0.1390
Clt [b]	2/6	**0.0002**	**0.0021**	0.0729
Trt*Clt [b]	4/48	0.3357	**0.0132**	**0.0217**
Contrasts				
Semi-erect - Control vs. early	1/48	0.2681	0.4592	0.9684
Semi-erect - Control vs. late	1/48	0.6768	**0.0524**	0.1339
Spreading - Control vs. early	1/48	0.1468	**0.0105**	**0.0099**
Spreading - Control vs. late	1/48	0.0874	**0.0028**	**0.0014**
Upright - Control vs. early	1/48	0.7301	0.5968	0.3895
Upright - Control vs. late	1/48	0.2732	0.2486	0.5683

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

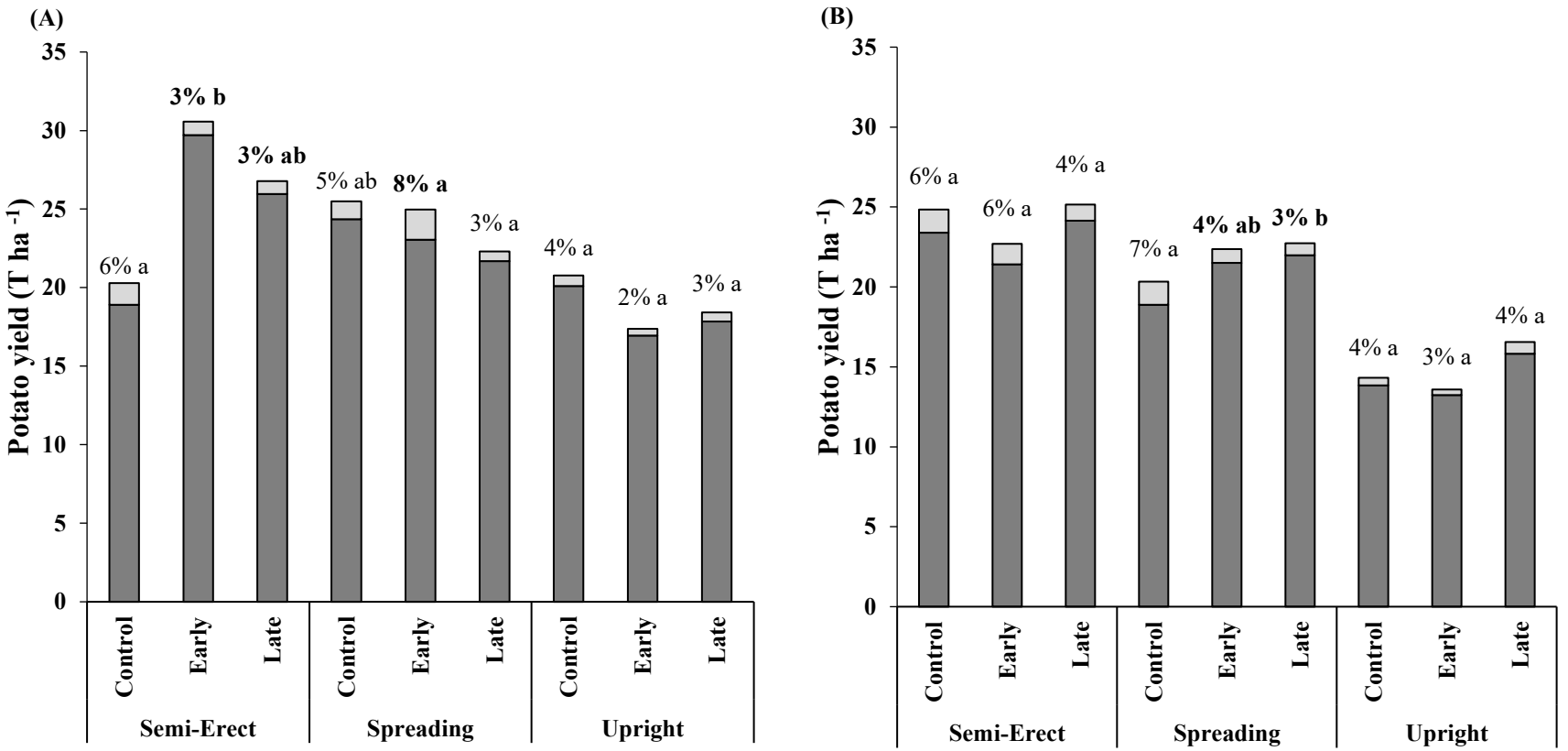

Figure 2.6. Effect of early and late crop-topping with a mower on yield of marketable tubers (dark gray bars) and culled tubers (light gray bars) in 2019 (A) and 2020 (B) of semi-erect, spreading, and upright potato cultivars. Data are least square means ± SEM. Values above bars indicate percentage of yield lost to culls, and letters refer to the effects of treatment timing on percentage of yields lost to culls. Boldface indicates that the effect was considered significantly different according to Tukey's honestly significant difference (α = 0.05).

The impacts of mowing on potato marketable yield in our study are similar to several studies that have documented improvements to yields in tuber crops following crop-topping. For example, 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 coincided with sweet potato tuber bulking, whereby water, nutrients, and carbohydrates shifted from above-ground vegetative production to below-ground reproductive development. By removing the fruits of a tuber-producing crop, resources required for sexual reproduction can be reallocated to the asexual reproductive structures, thus improving tuber quality and marketable yields. Such a response has been observed in several potato cultivars and wild tuber-forming plants (Jansky and Thompson 1990; Van Drunen and Dorken 2012). Among cultivars in the present 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 to marketable yield and the incongruences with previous studies. The decrease in cull yield and percentage of yield lost to culls observed in both years show potential for reallocation of resources into existing tubers rather that development of new ones, though further data are required. Together our results suggest that potato marketable yields are dependent on cultivar selection and environment. An improved understanding of shifts in biomass allocation in response to crop-topping in potato is required to elucidate the potential positive effects of mowing on yield.

2.3.2 Impact of Wick Weeding Timing on Common Lambsquarters and Potato

Wick weeding timing had no impact on common lambsquarters total ($p=0.56$) or vegetative ($p=0.54$) biomass in 2019 ($p=0.54$) (Table 2.4). There was an effect of potato cultivar ($p=0.03$) on common lambsquarters total plot biomass in 2020 at 3 WAA whereby common lambsquarters biomass was 114% ($p<0.01$) and 93% ($p<0.01$) lower in the semi-erect and spreading cultivars compared to the upright, respectively (data not shown). There was an effect of wick weeding treatment timing ($p<0.01$) and potato cultivar ($p<0.02$) on common lambsquarters total plant biomass and vegetative biomass in 2020 (Table 2.4). Within the spreading cultivar, late wick weeding increased common lambsquarters vegetative biomass by 50% ($p=0.02$) in 2020 compared to the control (Table 2.4; Figure 2.7).

Table 2.4. ANOVA table of common lambsquarters 3 WAA plot biomass, total biomass, vegetative biomass, reproductive biomass, harvest index, germination percentage, and thousand seed weight by year, cultivar, treatment timing, and their interaction following crop-topping with wick-applied glyphosate.

Covariance parameters	ndf/ddf [b]	3 WAA plot biomass [a]	Total biomass [a]	Vegetative biomass [a]	Reproductive biomass [a]	Harvest index [a]	TSW [a]	Germination [a]	Viable seed production [a]
				2019					
Trt [b]	2/6	0.8518	0.5632	0.5422	0.4182	0.1828	0.4999	0.4687	0.3745
				Contrasts					
Control vs. early	1/6	0.8744	0.8512	0.9678	0.2192	0.0766	0.2925	0.2848	0.1786
Control vs. late	1/6	0.7074	0.4221	0.3615	0.7331	0.4790	0.8760	0.3187	0.4339
				2020					
Trt [b]	3/9	0.0983	**<0.0001**	**0.0003**	**<0.0001**	**<0.0001**	0.1116	**0.0014**	**0.0005**
Clt [b]	2/24	**0.0342**	**0.0192**	**0.0143**	0.1935	0.5519	**0.0057**	**0.0007**	0.1096
Trt*Clt [b]	6/24	0.8006	0.2317	0.5338	0.1742	0.6950	**0.0005**	**<0.0001**	**0.0403**
				Contrasts					
Semi-erect - Control vs. early	1/24	0.9040	0.2817	0.2630	0.3163	0.1827	0.7056	**0.0382**	0.2494
Semi-erect - Control vs. late	1/24	0.9391	0.9252	0.7947	0.9025	0.7733	**0.0431**	**0.0409**	0.4670
Spreading - Control vs. early	1/24	0.3058	0.9516	0.9191	0.9825	0.6658	0.5255	0.2229	0.9760
Spreading - Control vs. late	1/24	0.8337	0.2456	**0.0215**	0.7235	0.0785	**0.0041**	**0.0006**	0.2364
Upright - Control vs. early	1/24	0.1851	0.9966	0.9851	0.9885	0.7799	0.8698	0.7553	0.9533
Upright - Control vs. late	1/24	0.2667	0.0827	0.9542	**0.0127**	0.0972	0.5939	**0.0034**	**<0.0001**

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

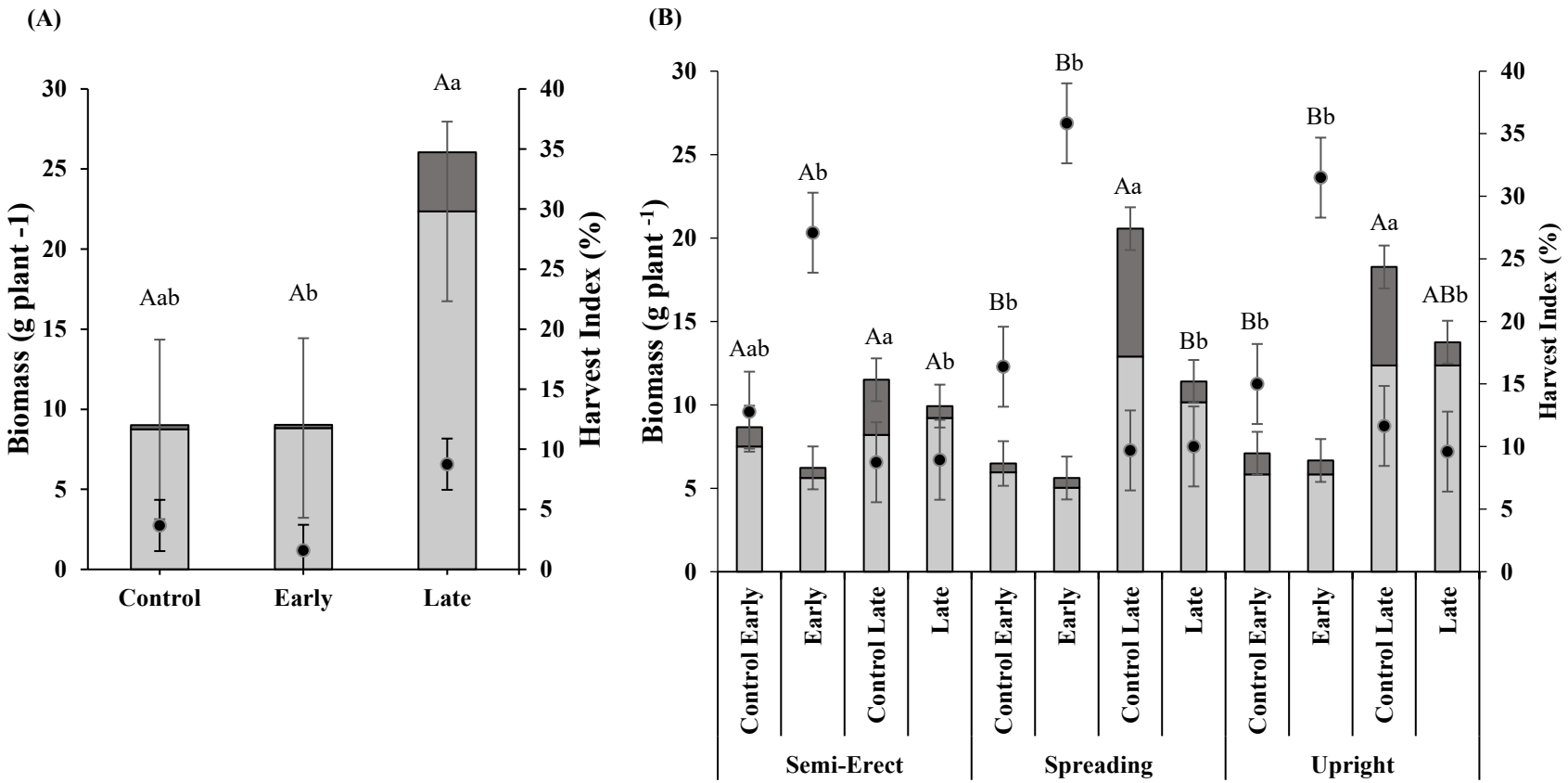

Figure 2.7. The effect of early and late crop-topping with wick-applied glyphosate on common lambsquarters vegetative (light gray bars) and reproductive (dark gray bars) biomass allocation and harvest index (circles) in control, early and late in 2019 (A) and semi-erect, spreading and upright cultivars in 2020 (B) in Harrington PE. Data are least square means ± standard error of the mean of total biomass. Values not connected by the same letter are significantly different according to Tukey's honestly significant difference (α = 0.05). Pane A: 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. Pane B: Uppercase letters refer to the effect of treatment timing on total biomass (vegetative and reproductive) accumulation within potato cultivars, and lowercase letters refer to the effect of treatment timing on harvest index within potato cultivars.

Common lambsquarters plants were considerably larger and had greater biomass in the late treatment in 2020 compared with 2019 and may have contributed to differences in the responses to wick-applied glyphosate (Figure 2.7). 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 translocated glyphosate more rapidly through basipetal movement, which can be attributed to their larger carbohydrate sinks (Schuster et al. 2007). In the present study late glyphosate applications in 2020 were made to common lambsquarters at 120 cm in height and the observed increases in biomass accumulation may be due to the enhanced translocation within the mature plants compared with earlier treatment timings made to plants < 84 cm. Hormetic effects, including stimulation of biomass productivity by low doses of glyphosate, have been reported in several crop and weed species, including common lambsquarters (Nadeem et al. 2016; Brito et al. 2018). Nadeem et al. (2016) observed a stimulatory effect of glyphosate on common lambsquarters seedling shoot length and seedling biomass up to a concentration of 16 g ae ha^{-1}. Despite the high concentration of glyphosate used in the present study, 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 late wick treatments.

Common lambsquarters reproductive biomass was not affected by wick weeding treatment timing ($p=0.42$) in 2019, but was in 2020 ($p<0.01$) (Table 2.4). Late wick weeding reduced common lambsquarters reproductive biomass by 37% ($p<0.01$) in the upright cultivar in 2020 compared to the control (Table 2.4; Figure 2.7). Late wick weeding reduced reproductive

biomass by 3% ($p=0.90$) and 8% ($p=0.72$) but was not significantly different from the control (Table 2.4; Figure 2.7).

Wick weeding treatment timing had no effect on common lambsquarters HI ($p=0.18$), TSW ($p=0.50$), nor germination percentage ($p=0.47$) in 2019 (Table 2.4). HI in 2020 was affected by wick weeding treatment timing ($p<0.01$), but no significant differences were observed across timings in each cultivar (Table 2.4; Figure 2.7). In addition to changes in biomass allocation and HI, wick treatment timing impacted common lambsquarters seed viability in 2020. TSW of common lambsquarters in 2020 was affected by potato cultivar ($p<0.01$) and the interactions between potato cultivar and wick weeding treatment timing ($p<0.01$) (Table 2.4). Late wick weeding of common lambsquarters decreased TSW in 2020 in the semi-erect and spreading cultivars by 21% ($p=0.04$) and 31% ($p<0.01$), respectively (Table 2.4; Figure 2.8). Wick weeding treatment timing ($p<0.01$), potato cultivar ($p<0.01$), and their interactions ($p<0.01$) affected common lambsquarters germination percentage (Table 2.4). Early wick weeding of common lambsquarters decreased germination by 30% ($p=0.04$) in the semi-erect cultivar (Table 2.4; data not shown). Similarly, late wick treatment reduced common lambsquarters germination by 32% ($p=0.04$), 63% ($p<0.01$) and 56% ($p<0.01$) in the semi-erect, spreading and upright cultivars, respectively (Table 2.4; Figure 2.8). The overall common lambsquarters germination percentage was highly variable and ranged from 12 to 52% across treatments and years (data not shown).

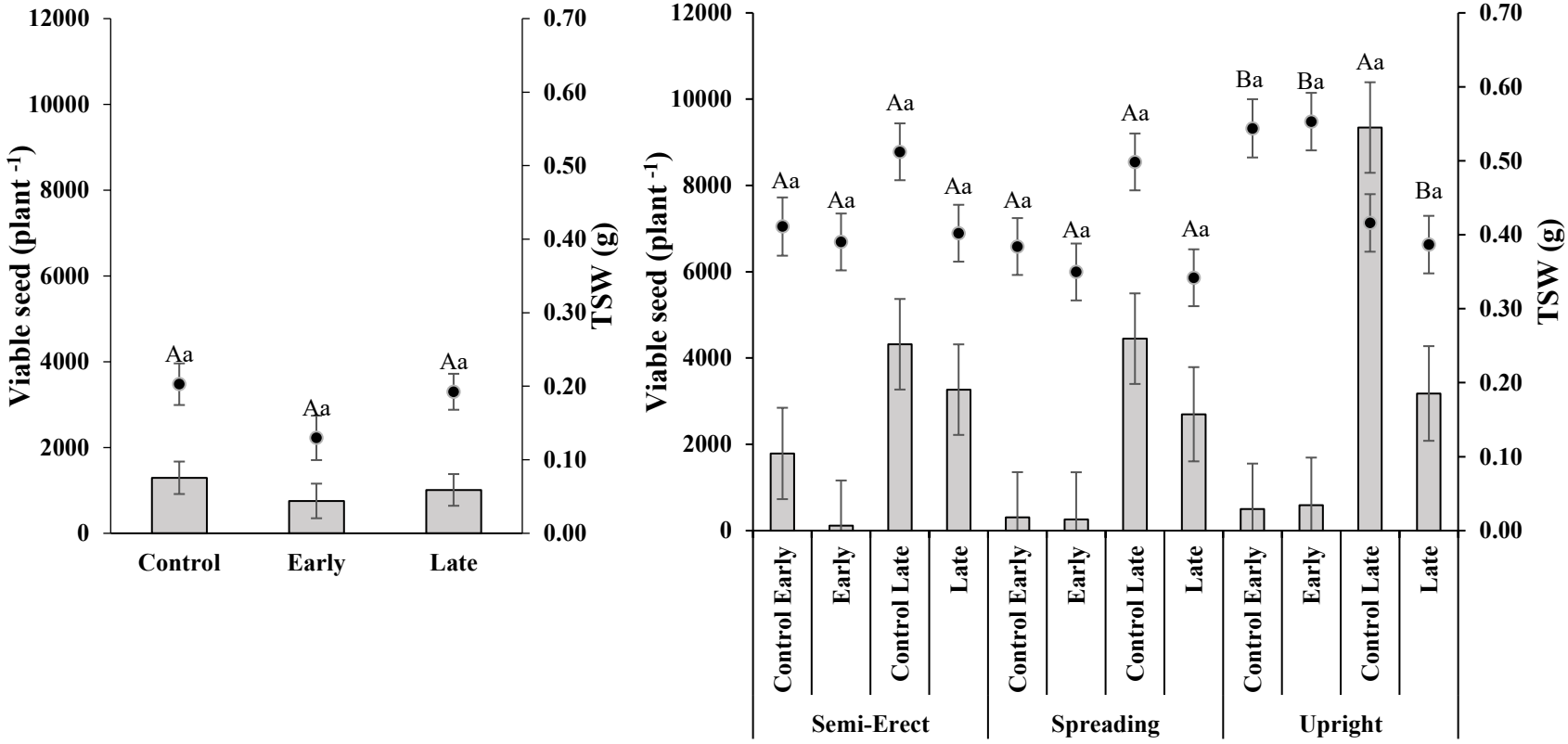

Figure 2.8. Effect of early and late crop-topping with wick-applied glyphosate on common lambsquarters viable seed plant $^{-1}$ (bars) and thousand seed weight (TSW) (circles) in control, early and late in 2019 (A) and semi-erect, spreading and upright cultivars in 2020 (B) in Harrington PE. Data are 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 seed plant^{-1} and lowercase letters refer to the effects of treatment timing on TSW.

Wick weeding treatment timing had no effect on common lambsquarters VSP in 2019 ($p=0.37$) (Table 2.4; Figure 2.8). VSP was affected by wick weeding treatment timing ($p<0.01$) and the interaction between wick weeding treatment timing and potato cultivar ($p=0.04$) in 2020 (Table 2.4). Contrast statements revealed that late wick weeding in the upright cultivar reduced common lambsquarters VSP by 66% ($p<0.01$) (Table 2.4; Figure 2.8). 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 late wick application made during flowering and fruit set may be due to increased glyphosate translocation to sink tissues and disruption of subsequent flower and seed production. Considering the greater glyphosate rates used in 2019, it is unclear why wick weeding treatment effects were so great in 2020 compared with 2019, but it may be due to the extended drought period in 2020 exasperating treatment effects compared to the cold, long spring of 2019 (AAFC 2023). Therefore, although wick-applied glyphosate may provide a hormetic effect on common lambsquarters biomass production, doses may also 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 contribute to seedbank reductions.

The different response of common lambsquarters to wick-applied glyphosate treatments between cultivars may be related to morphological features of each potato cultivar. Many potato cultivars do not vary in their ability to suppress weeds (Colquhoun et al. 2009; Conley et al. 2001). However, common lambsquarters biomass, HI, TSW, germination percentage, and VSP were consistently greatest amongst the upright potato cultivar and the same or lower amongst the spreading and semi-erect cultivars. Early-emerging, short stature, and highly branched cultivars have been shown to provide superior weed suppression over erect, less leafy potato cultivars (Barbaś et al. 2020). Interestingly, the upright cultivar was the tallest variety at treatment application timing, followed by the spreading and semi-erect in both 2019 and 2020. Although our results vary in effectiveness between years, environmental differences between these years may have influenced potato emergence and early canopy development across cultivars. These differences may have affected wick treatment interception and subsequently common lambsquarters growth and seed production.

Potato marketable yield was affected by potato cultivar ($p<0.01$) in 2019 and ranged from 16 to 27 T ha^{-1} (Table 2.5; Figure 2.9). Potato marketable yield in the semi-erect and spreading cultivars decreased by 12% ($p=0.06$) and 14% ($p=0.04$), respectively, following the early wick-applied glyphosate compared to the control in 2019 (Table 2.5; Figure 2.9). Potato marketable yield was affected by potato cultivar in 2020 ($p<0.01$) and ranged from 10 to 22 T ha^{-1} (Table 2.5; Figure 2.9).

Table 2.5. 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 wick-applied glyphosate.

Covariance parameters	ndf/ddf [a,b]	Marketable yield [a]	Cull yield [a]	Percentage yield lost to culls [a]
		2019		
Trt [b]	2/6	0.2372	**0.0001**	**<0.0001**
Clt [b]	2/6	**0.0019**	0.1133	0.3057
Trt*Clt [b]	4/12	0.1127	0.1732	0.4227
Contrasts				
Semi-erect - Control vs. early	1/12	0.0607	**<0.0001**	**<0.0001**
Semi-erect - Control vs. late	1/12	0.4641	**0.0011**	**0.0003**
Spreading - Control vs. early	1/12	**0.0376**	**<0.0001**	**<0.0001**
Spreading - Control vs. late	1/12	0.9070	**0.0010**	**0.0002**
Upright - Control vs. early	1/12	0.2238	**0.0010**	**<0.0001**
Upright - Control vs. late	1/12	0.7617	**0.0144**	**0.0005**
		2020		
Trt [b]	2/6	0.1555	0.3204	0.5327
Clt [b]	2/6	**0.0020**	0.2190	0.4996
Trt*Clt [b]	4/12	0.5113	0.2447	0.1814
Contrasts				
Semi-erect - Control vs. early	1/12	0.8113	0.4242	0.7892
Semi-erect - Control vs. late	1/12	0.1358	**0.0181**	**0.0278**
Spreading - Control vs. early	1/12	0.1248	0.3921	0.9150
Spreading - Control vs. late	1/12	0.3309	0.9750	0.7059
Upright - Control vs. early	1/12	0.2694	0.7274	0.7515
Upright - Control vs. late	1/12	0.9704	0.9973	0.9541

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

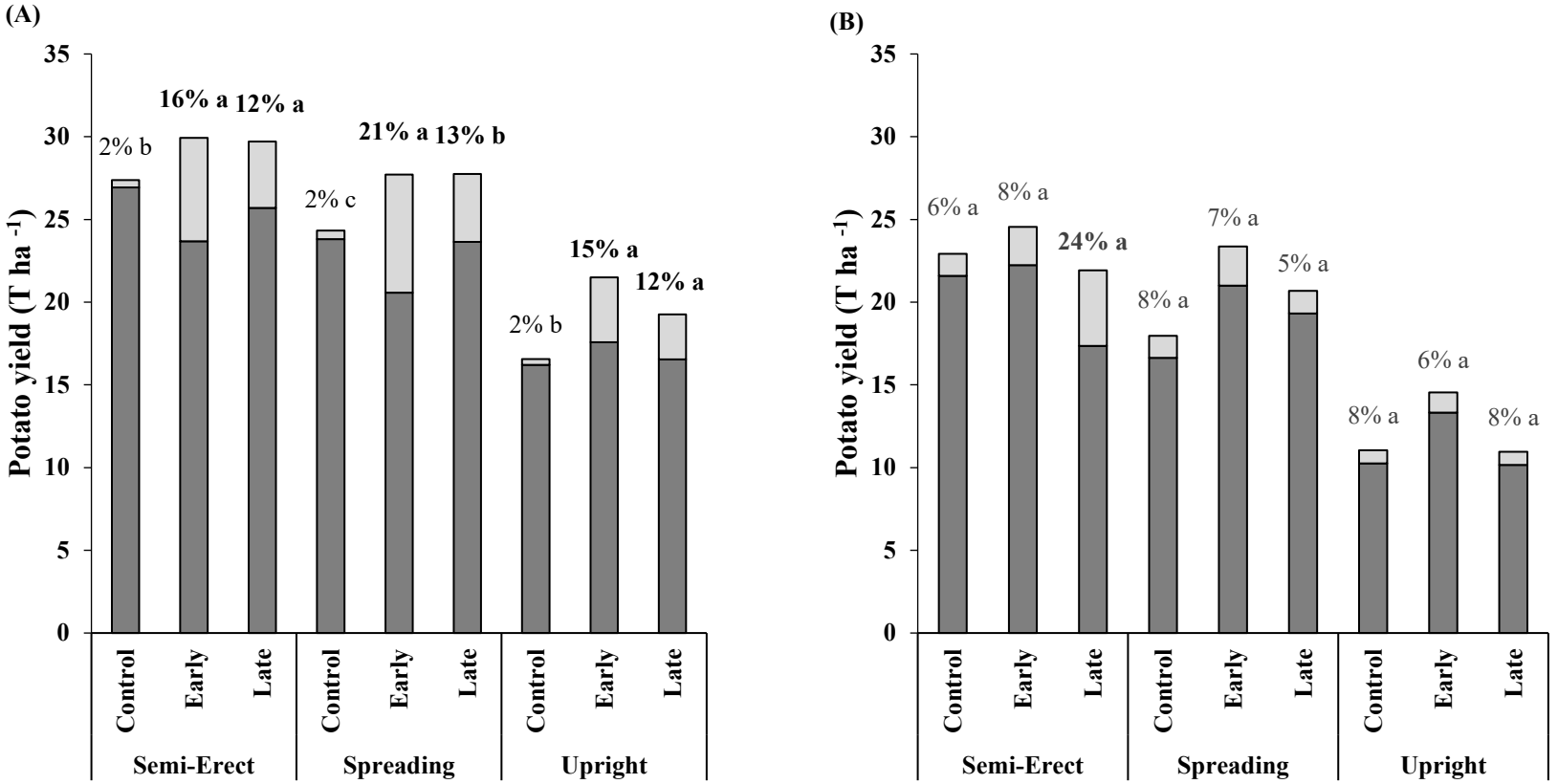

Figure 2.9. Effect of early and late crop-topping with wick-applied glyphosate on yield of marketable tubers (dark gray bars) and culled tubers (light gray bars) in 2019 (A) and 2020 (B) of semi-erect, spreading, and upright potato cultivars. Data are least square means ± SEM. Values above bars indicate percentage of yield lost to culls, and letters refer to the effects of treatment timing on percentage of yields lost to culls. Boldface indicates that the effect was considered significantly different according to Tukey's honestly significant difference ($\alpha = 0.05$).

Potato cull yield was affected by wick-applied glyphosate timing ($p<0.01$) in 2019 and increased by 11- to 13-fold and 7- to 8-fold in the early and late applications, respectively in each cultivar (Figure 2.9). In 2019, potato cull yield ranged from 2.7 T ha^{-1} in the upright cultivar to 6.3 T ha^{-1} in the semi-erect cultivar (Figure 2.9). Potato cull yield was not affected by wick-applied glyphosate timing ($p=0.32$), potato cultivar ($p=0.22$), nor their interactions ($p=0.24$) in 2020, but contrast statements revealed that late treatment in the semi-erect cultivar increased cull yield 2-fold (Table 2.5). In 2020, potato cull yield ranged from 0.8 T ha^{-1} in the upright cultivar to 4.6 T ha^{-1} in the semi-erect cultivar (Figure 2.9). The percentage of total yield lost to culls was affected by wick-applied glyphosate treatment timing ($p<0.01$) in 2019 and was 10-fold ($p<0.01$), 8-fold ($p<0.01$), and 7-fold ($p<0.01$) greater following early wick weeding in the semi-erect, spreading, and upright cultivars, respectively (Table 2.5; Figure 2.9). Similarly, late treatment in 2019 resulted in cull increases by 7-fold ($p<0.01$), 5-fold ($p<0.01$), and 5-fold ($p=0.01$) in the semi-erect, spreading, and upright cultivars (Table 2.5; Figure 2.9). The percentage of total yield lost to culls was not affected by potato cultivar ($p=0.31$) but ranged from 12 to 21% in 2019 and was highest in the spreading cultivar (Figure 2.9). The percentage of total yield lost to culls was not affected by wick-applied glyphosate treatment timing ($p=0.53$), cultivar ($p=0.50$), nor their interactions ($p=0.18$) in 2020 but similarly ranged from 5 to 24% yet was highest in the semi-erect (24%) and lowest in the spreading (5%) cultivar (Table 2.5; Figure 2.9). Similar to cull yield, percentage of total yield lost to culls increased 3-fold in the semi-erect cultivar following late treatment (Table 2.5; Figure 2.9).

These results suggest that wick weeding negatively impacts potato yield and quality. The greater negative impact of wick applied glyphosate on potato yield in 2019 compared to 2020 may be due to greater interception of glyphosate by potato 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 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 on to potato plants (Harrington and Ghanizadeh 2017).

2.4 Conclusion

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 in common lambsquarters and timing crop-topping applications to this period may provide greater reductions in viable seed return (Geddes and Davis 2021). Furthermore, combining mow or wick 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.

Chapter 3: Effects of Cover Crop and Termination Method on Common Lambsquarters (*Chenopodium Album* L.) Seedbank Dynamics in Potato

3.0 Abstract

Common lambsquarters (*Chenopodium album* L.) is one of the most troublesome weeds in Atlantic Canadian potato (*Solanum tuberosum* L.) production systems. A high proportion of common lambsquarters in this region have been identified as resistant to commonly used herbicides and have become increasingly difficult to control with existing management practices. Atlantic potato producers have increasingly adopted cover crops into their rotations for soil conservation and nutrient cycling benefits, as well as suppression of crop pests including weeds. Four cover crops and termination methods were evaluated for their ability to suppress common lambsquarters populations in a potato rotation at Harrington, PE and Fredericton, NB from 2018 to 2020. Brown mustard, buckwheat, Timothy, and a mixture of hairy vetch, annual ryegrass and crimson clover, were spring-sown and terminated by mowing, roller crimping, discing, or glyphosate in fall. Effects of cover crops and termination treatments were consistently greater at Fredericton than Harrington and is attributed to lower initial common lambsquarters seedbank pressure. Buckwheat and brown mustard cover crops established rapidly and reduced common lambsquarters densities in the subsequent potato crop by over 46%. Termination via discing and glyphosate improved marketable yields, yet the soil-incorporation through discing buckwheat maximized the weed suppressive effects and reduced common lambsquarters seedbank germination by 64% when compared to glyphosate. Our results illustrate the significance of cover crops and termination methods on the common lambsquarters lifecycle and potato yields. This paper demonstrates how termination method can influence cover crop residue management

and verifies the importance of proper cover crop selection for management of herbicide-resistant common lambsquarters in potato production systems.

3.1 Introduction

Potato (*Solanum tuberosum* L.) is the most economically important vegetable crop grown in Canada with table-stock potato exports worth CAD$330 million in 2021 (CATSNet 2021). The Atlantic Canadian provinces account for 38% of Canada's potato production area, with potatoes contributing to over 42% of total farm cash receipts in Prince Edward Island (PE) and 18% in New Brunswick (NB) (CATSNet 2021). Potatoes are intensively managed and require expensive inputs to sustain production and yields. Potato producers in PE attributed 26% of their input costs to fertilizer and chemical crop protectants, both of which have increased in cost by 6% and 20%, respectively since 2014 (PE Potato 2019). Potato crops are slow to establish, often requiring greater than 14 days to emerge, and are poor competitors with weeds, which if left uncontrolled can result in 12 to 61% yield loss (Ganie et al. 2023). Producers in Atlantic Canada have few in-season broadleaf herbicide options and often rely on a single application of a pre-emergent photosystem II (PSII)-inhibiting herbicides to provide season-long weed control. These herbicides include either metribuzin, a group 5 triazinone, or linuron, a group 5 substituted urea and are known to be applied to over 75% of potato acreage in the Atlantic region (WSSA 2021; L MacKinnon, personal communication 2019). In recent years, Atlantic producers have reported reduced efficacy of these herbicides and weed resistance has been confirmed in the region (McKenzie-Gopsill et al. 2020). As such, research into alternative management approaches in potato that do not rely on broadcast herbicide applications are required.

Common lambsquarters (*Chenopodium album* L.) is a summer annual broadleaf weed that emerges and establishes early in various crops throughout North America (Bajwa et al. 2015; Williams 1963). Its continuous emergence pattern allows it to compete for resources with spring-planted crops for the duration of the growing season (Bassett and Crompton 1978; Brown et al. 2022). Common lambsquarters is considered one of the most economically significant weeds in potato production systems and has been shown to reduce potato yields by up to 85% (Eberlein et al. 1997; Parks et al. 1996). Common lambsquarters sets seed in late summer and early fall and can produce an average of 72,000 seeds per plant (Stevens 1932). The small black seeds have little endosperm and can persist in the soil seedbank for over 20 years (Lewis 1973; Stevens 1932). A high proportion of common lambsquarters in Atlantic Canada have been identified as resistant to PSII-inhibiting herbicides and are increasingly difficult to control in potato with existing conventional management tactics (McKenzie Gopsill et al. 2020).

The integration of cover crops into cash crop rotations has been considered for their ability to increase cropping system diversity, provide residues that suppress early emerging weeds in-crop and reduce weed biomass thereby reducing competition and the intensity of herbicide resistance selection pressure (Norsworthy et al. 2012; Owen et al. 2014). Producers in Atlantic Canada that incorporate cover crops in their potato rotations identify the soil building properties and the breaking of pest cycles as the main benefits for their use (Mann et al. 2021). A cover crop is a crop grown between periods of regular cash-crop production and provides numerous benefits to agroecosystem health (Sarrantonio and Gallandt 2003). Cover crops have been shown to suppress weeds in-season, decrease the reliance on herbicide applications and improve potato productivity (Kumar et al. 2020; McKenzie-Gopsill et al. 2022; Nyiraneza et al. 2021). Cover crop species vary in their ability to suppress weeds in-season. For example, cover

crops with high biomass production have been found to out-compete weeds in-season, thus limiting their reproductive success and lessening weed competition for the subsequent crop (Adeux et al. 2023; Christina et al. 2021). Soil-incorporating these nutrient-rich residues can alter carbon and nitrogen levels and nutrient availability within the soil, as well as alter the soil microbiome and can provide weed-suppressive effects and hinder germination (Khan 2021; Kumar et al. 2011; Mohler et al. 2018). As cover crops degrade and breakdown, the release of allelopathic chemicals can further suppress weed seed germination following soil incorporation (Bajwa et al. 2015; Duke 2015; Galon et al. 2021). Pittman et al. (2020) found that cover crops with high biomass and high C:N ratio provided a lasting mulch for light interference and subsequently increase the level and duration of weed suppressive effects and have been correlated to increased crop yield in the subsequent year. Buckwheat's aggressive spring growth, high productivity, and allelopathic effects have been found to hinder weed establishment (Iqbal et al. 2003; Falquet et al 2015; McKenzie-Gopsill et al. 2022). Furthermore, McKenzie-Gopsill et al. (2022) found monocultures of buckwheat were more weed suppressive than when using a cover crop mixture. Buckwheat is known to provide weed suppressive effects through the release of allelopathic compounds (including gallic acid) and is highly competitive with annual weeds including common lambsquarters (Creamer and Baldwin 2000; Iqbal et al. 2003; Xuan and Tsuzuki 2004). Campiglia et al. (2009) demonstrated the weed suppressive potential of incorporating fall seeded rapeseed (*Brassica napus*) and ryegrass cover crops in herbicide-free potato systems including their high growth potential, competitive ability for nitrogen uptake, as well as their release of allelopathic compounds. To date, cover crop research has focused on species effects on weed populations, however limited work has been done to investigate the effects of their termination methods and its varying impact on weed suppression.

Selecting the appropriate cover crop termination method is critical for maximizing a species' weed suppressive potential (Wortman et al. 2013). Cover crops can be terminated chemically, through use of herbicides, or mechanically, through use of plowing, rolling, mowing, discing, or roller crimping. Depending on the desired outcome and specific weed species, termination timing, method and soil disturbance can influence the weed suppressive ability of the cover crop from increased soil ground cover (Morse 1999; Mirsky et al. 2010; Wortman et al. 2013). Incorporating cover crop residues following mechanical termination can bury weed seeds and block light to inhibit weed emergence in the subsequent crop (Lehman and Blum 1997; Shaner and Beckie 2014). Similarly, Schmidt et al. (2019) found that incorporating cover crop mulch via chisel ploughing prior to potatoes reduced common lambsquarters seedbank by 15% in the top 15 cm of soil when compared to conventional moldboard ploughing. The dead cover crop mulch was applied and spread directly after potato emergence and provided nearly 100% soil cover from May until June, thus hindering common lambsquarters emergence. Furthermore, mechanical termination of cover crops by roto-tilling has been found to improve soil seed bed uniformity, thus improving tuber seeding, and resulted in increased potato marketable yield (Mehring et al. 2016). Use of non-selective chemical herbicide for cover crop desiccation can effectively terminate the crop while also providing rapid and broad-spectrum weed control (Whalen et al. 2019). Furthermore, glyphosate application does not require physical soil disturbance and allows for direct seeding of the subsequent crop (Kornecki 2020). As such, termination methods that maximize surface residue and minimize soil disturbance have been shown to provide the greatest potential for inhibiting weed emergence (Teasdale 2007).

In Atlantic Canada potatoes are generally grown in 2-year cereal/legume-potato or 3-year cereal/legume-forage-potato rotations. The incorporation of annual cover crops is often

introduced to this rotation to improve soil health, reduce nutrient leaching and erosion, and to break pest cycles for disease management. The objective of the present study was to evaluate several cover crops and termination methods to suppress common lambsquarters populations in a potato rotation. We hypothesized that (1) cover crops with higher stand densities will decrease common lambsquarters seed germination, density, and contributions towards the weed seedbank, (2) cover crops terminated with methods that increase soil ground cover will decrease the germinable fraction of the common lambsquarters seedbank, and (3) the cover crops terminated with methods that soil-incorporate biomass will increase potato yield and quality.

3.2 Materials and Methods

3.2.1 Experimental Design

A multi-year field experiment was established at the Harrington Research Farm (46°20’37.020’’ N, 63°10’11.050’’ W) in Harrington, PE, Canada and the Fredericton Research Farm (45°55’22.530’’ N, 66°36’29.490’’ W) in Fredericton, NB, Canada in 2018, 2019, and 2020. Local site restrictions prevented access to the Fredericton research site in 2020 and resulted in reduced site years from this location. Soil at Harrington, PE is characterized as a fine sandy loam (Ferro-Humic Podzol, OM 3%, pH 6.6) and at Fredericton NB as a coarse sandy loam (Gleyed Humo-Ferric Podzol, OM 3%, pH 6.2). The experiment was established as a randomized strip-plot design with Latinization and three replications (n = 27). Cover crop species was the whole-plot factor and termination method the strip-plot factor. Brown mustard (*Brassica juncea* L.), buckwheat (*Fagopyrum esculentum* M.), Timothy (*Phleum pretense* L.)), and a mixture consisting of annual ryegrass (*Lolium multiflorum* Lam.), hairy vetch (*Vicia villosa* L.), and crimson clover (*Trifolium incarnatum* L.) were selected as cover crops to

evaluate the effects of cover crop species with varying growth habits and their ability to suppress common lambsquarters.

In the cover crop phase, fields were moldboard ploughed, spring-toothed harrowed twice, rolled, and fertilizer broadcast according to provincial recommendations (PE Potato Agronomy 2017). Cover crops were seeded with a small plot seeder (Plotseed XL, Wintersteiger AG Ried im Innkreis, Austria) in 2018 and 2019. Seeding rates for brown mustard, buckwheat, and Timothy were 11.2 kg ha^{-1}, 44.8 kg ha^{-1}, and 5.6 kg ha^{-1}, respectively. The seeding rate of the cover crop mixture was 3.0 kg ha^{-1}, 36.0 kg ha^{-1}, and 12.0 kg ha^{-1}, for the ryegrass, hairy vetch, and crimson clover, respectively. Seeding rates were chosen based on local recommendations (McKenzie-Gopsill et al. 2022). Cover crops were sown in 6 × 12 m plots. The early-flowering species, buckwheat and brown mustard, were flail mowed at flowering in mid-August and replanted within 7 days as is common in the region (McKenzie-Gopsill et al. 2022). To evaluate the effects of different termination methods on common lambsquarters seedbank persistence and potato quality, cover crops were terminated with 1 of 4 methods in mid-September: 1) mowing, 2) roller crimping, 3) discing, or 4) glyphosate. Mowing was conducted using a Woods PRD6000 rear-mounted 1.83 m flail mower (Woods Equipment, Oregon, IL, USA) to mow cover crops to an approximate height of 5 cm. Roller crimping was conducted with a roller crimper (I & J Manufacturing 10.5', Gordonville, PA, USA) filled with approximately 400 L of water for a total weight of 1195 kg. Cover crops were rolled twice, bi-directionally. Discing was to an approximate depth of 10 cm with a 1.83 m Land Pride DH1572 disc harrow (Land Pride, Salina, KS, USA). Glyphosate (Roundup WeatherMAX, Monsanto, Winnipeg, Canada, 540 g a.e. L^{-1}) was applied at a rate of 2.33 L ha^{-1} (1258.2 g a.i ha^{-1}) using a CO_2-pressurized research plot sprayer in 2018 and a CO_2-pressurized back-pack sprayer in 2019. Both sprayers were

calibrated to deliver 200 L ha^{-1} at 210 kPA with TP 8802VS nozzles (TeeJet Technologies, Springfield, MA, USA). Mechanical termination methods were applied at a travel speed of approximately 5 km h^{-1}.

In Year 2, potato plots consisting of four, 5 × 1 m rows were sown into cover crop plots from Year 1. Fields were chisel ploughed to a depth of 5 cm and spring-tooth harrowed to incorporate cover crop residues. At planting, rows were formed and fertility banded according to local recommendations in order to provide 185, 200, and 135 kg ha^{-1} of nitrogen, phosphorus and potassium, respectively (Burton et al. 2018). Untreated Elite 1 potato sets (cv Russet Burbank) were hand-planted at 38 cm spacing with 91 cm between rows. Rows were closed mechanically and imidacloprid (Admire 240, Bayer Crop Science, Calgary, Canada, 240 g a.e L^{-1}) was applied at a rate of 2.33 L ha^{-1} (1258.2 g a.i ha^{-1}) in-furrow. Potatoes were hilled at ground-crack, approximately 4 weeks after planting (WAP). Additional pest management for insects and diseases was conducted as required in accordance with provincial recommendations. At maturity, potatoes were top killed with diquat (Reglone, Syngenta Canada, Guelph, ON, Canada, diquat ion 240 g a.i L^{-1}) at a rate of 300 g a.i ha^{-1} on September 20, 2019 and August 27, 2020 at Harrington, and on Sept 17, 2019 at Fredericton. Potato plots were harvested at physiological maturity on October 11, 2019 and October 7, 2020 in Harrington, and on October 9, 2019 in Fredericton.

3.2.2 Data Collection

3.2.2.1 Cover Crop Phase

To determine early-season cover crop and common lambsquarters density, cover crop and common lambsquarters counts were made in three randomly placed 0.5 × 0.5 m quadrats per plot

at four WAP. Cover crop establishment was computed using calculated seedings rates, seed lot germination factors, and cover crop TSW.

3.2.2.2 Potato Phase

To evaluate the effect of cover crop and termination method on the germinable fraction of the common lambsquarters seedbank, composite rhizosphere soil cores (0-15 cm) consisting of three, 8 cm diameter samples were collected prior to cover crop termination and at potato hilling and stored at 4°C until processing (Gross 1990). 1 L sub-samples were mixed and sieved through a 4000 µm sieve to remove large debris and concentrated using an elutriation system (Gillison's Variety Fabrication Inc., Benzonia, USA) affixed with 840 µm mesh screen at the top of each chamber (Ter Heerdt et al. 1996; Gross 1990; Smucker et al. 1982). Sub-samples were run for approximately four minutes and the contents within the cylinders and mesh screens were then washed into a 250 µm mesh sieve. Samples were spread into trays containing moistened sterilized play sand (Home Depot, Charlottetown, Canada). Trays were placed in a greenhouse with a 16/8 h light/dark photoperiod and 22/16 °C day/night temperature cycles. High pressure sodium lights provided supplemental lighting when natural light conditions fell below a PPFD of 2000 µmol m^{-2} s^{-1}. A watering spike was placed in each tray which supplied 150 ml of water day^{-1}. Trays were monitored regularly for seedlings. Germinated seedlings were identified, tallied, and removed until germination ceased (Ter Heerdt et al. 1996).

To evaluate the effects of cover crop termination method on soil C:N a sub-sample was taken from all soil samples. Soil samples were analyzed for %C and %N using high temperature combustion with the Vario MAX Cube Organic Elemental Analyzer (Elementar Americas Inc., Ronkonkoma, NY, US).

To evaluate carry-over weed suppressive effects of cover crops in potato, common lambsquarters density was determined at 4 and 8 weeks after hilling (WAH) within one 0.5 m × 0.5 m quadrat randomly placed within each plot. At physiological maturity, potatoes were mechanically harvested to determine carry-over effects of cover crops and termination method on yield. Potatoes were graded in accordance with the CFIA potato grading scale (CFIA 2015b) using an optical grader (Celox-*P*-UHD, New Tec, Odense, Denmark) and sorted into cull or marketable potatoes. Small (<3.8 cm), large (>8.9 cm), misshapen and sunburnt potatoes were removed and counted as culls. The sum of small (3.8–5 cm) and Canada #1 (5–8.9 cm) class sizes were calculated as marketable yield.

3.2.3 Statistical Analysis

All statistical analyses were performed using SAS v9.4 (SAS Institute, Cary, USA) and a Type I error rate of $\alpha = 0.05$. Following preliminary testing, all data from the cover crop phase was combined across cover crop year (2018 and 2019) and location (Harrington and Fredericton). Cover crop establishment and common lambsquarters density were analyzed with a generalized linear mixed effect model using PROC GLIMMIX and a Poisson distribution with a log link function. The whole-plot factor (cover crop), strip-plot factor (termination treatment), location, and their interactions were treated as fixed effects. Replication, year, and its interaction with cover crop were treated as random effects. Due to significant location by treatment interactions, results were presented separately for Harrington and Fredericton. Potato phase common lambsquarters density was analyzed with a generalized linear mixed effect model with repeated measures through time (WAH) using PROC GLIMMIX and a Poisson distribution with a log link function. The whole plot factor (cover crop), strip-plot factor (termination treatment), location, WAH, and their interactions were treated as fixed effects. Replication by year and its

interaction with location were treated as random effects. Potato phase common lambsquarters density was analyzed with a generalized linear mixed effect model with repeated measures through time (WAH) using PROC GLIMMIX and a Poisson distribution with a log link function. The whole plot factor (cover crop), strip-plot factor (termination treatment), location, WAH, and their interactions were treated as fixed effects. Replication by year and its interaction with location were treated as random effects.

The effect of cover crop and termination method on the common lambsquarters seedbank was analyzed with a generalized linear mixed effects model using PROC GLIMMIX and a Poisson distribution with a log link function. To account for initial differences between plots, the common lambsquarters seedbank prior to planting cover crops was used as a covariate in the analysis. Soil C, N and C:N ratio was analyzed with generalized linear mixed effects model using PROC GLIMMIX and a Gaussian distribution with an identity link function. Whole plot factor (cover crop), strip-plot factor (termination treatment), and their interaction were treated as fixed effects, and replication by year was treated as a random effect.

Marketable potato yield was analyzed using a generalized linear effects model using PROC GLIMMIX and a Gaussian distribution with an identity link function. In all cases, least square means and standard error of the mean were generated for presentation and mean separation was conducted with a Tukey's HSD test and a Type I error rate of $\alpha = 0.05$. Linear regression was used to investigate relationships between cover crop density and common lambsquarters density in the cover crop phase, and for soil C:N and common lambsquarters density in the potato phase using PROC REG and PROC CORR using Pearson's correlation coefficient.

3.3 Results and Discussion

3.3.1 Cover crop phase

Cover crop density varied by location ($p<0.01$), cover crop ($p<0.01$), and their interaction ($p<0.01$). Total average cover crop density was 42% greater in Fredericton than in Harrington ($p<0.01$). At both locations, the cover crop densities were reflective of seeding rates whereby the mixture and the Timothy had the highest cover crop densities and the buckwheat was the lowest (Table 3.1). Cover crop establishment varied by location ($p=0.02$), cover crop ($p<0.01$), but not their interaction ($p=0.07$). Establishment at both locations was similar for brown mustard, buckwheat and the mix, and averaged 82-190% greater than Timothy (Table 3.1). Common lambsquarters density was impacted by location ($p<0.01$) and the cover crop by location interaction ($p=0.04$). Common lambsquarters density did not vary by cover crop ($p=0.66$), but populations were 159% greater in Harrington than Fredericton (Table 3.1). Combined, these results demonstrate that cover crop density and establishment was greater in Fredericton and may be a result of lower common lambsquarters seedbank pressure at that location. For example, weed seedbank size, among other characteristics, can affect in-season weed establishment and the success of the weed management tactics utilized within the system (Buhler et al. 1997; Benvenuti and Mazzoncini 2021). Benvenuti and Mazzoncini (2021) suggest that soil texture and seedbank size may influence a weed's degree of invasiveness. Buhler et al. (1997) found that initial weed seedbank density of common sunflower was positively corelated to the density of surviving seedlings after a weed control treatment. This suggests that a high seedbank density may reduce a cover crop's ability to establish and suppress weeds, similar to what we found between locations in the present study. Furthermore, common lambsquarters density displayed a negative relationship with cover crop density and declined as cover crop

density increased ($p<0.01$; $R^2 = 0.087$) (Figure 3.1). These findings suggest that more densely seeded cover crops provided suppression of common lambsquarters but may also be attributed to differences in cover crop phenology and increased competition amongst species within the cover crop mix.

Table 3.1. Cover crop establishment and common lambsquarters density (plants m^{-2}) 4 weeks after planting in Harrington PE and Fredericton NB in 2018 and 2019.

Location	Cover Crop	Cover crop density [a,b]	Cover crop establishment [a,b]	Common lambsquarters density [a,b]
		plants m^{-2}	%	plants m^{-2}
Harrington	Brown mustard	167 AB	43.4 A	291 A
	Buckwheat	88 B	58.3 A	270 A
	Mix	249 A	55.1 A	246 A
	Timothy	274 A	20.1 B	214 A
	SEM	±28	±5.9	±63
Fredericton	Brown mustard	248 B	64.4 A	33 A
	Buckwheat	84 C	55.6 A	37 A
	Mix	658 A	58.5 A	23 A
	Timothy	455 AB	30.6 B	25 A
	SEM	±52	±5.9	±8

[a] Data are least square means.
[b] Means followed by different letters are significantly different with a Type I error rate of $\alpha=0.05$ according to a Tukey's HSD test within each location.

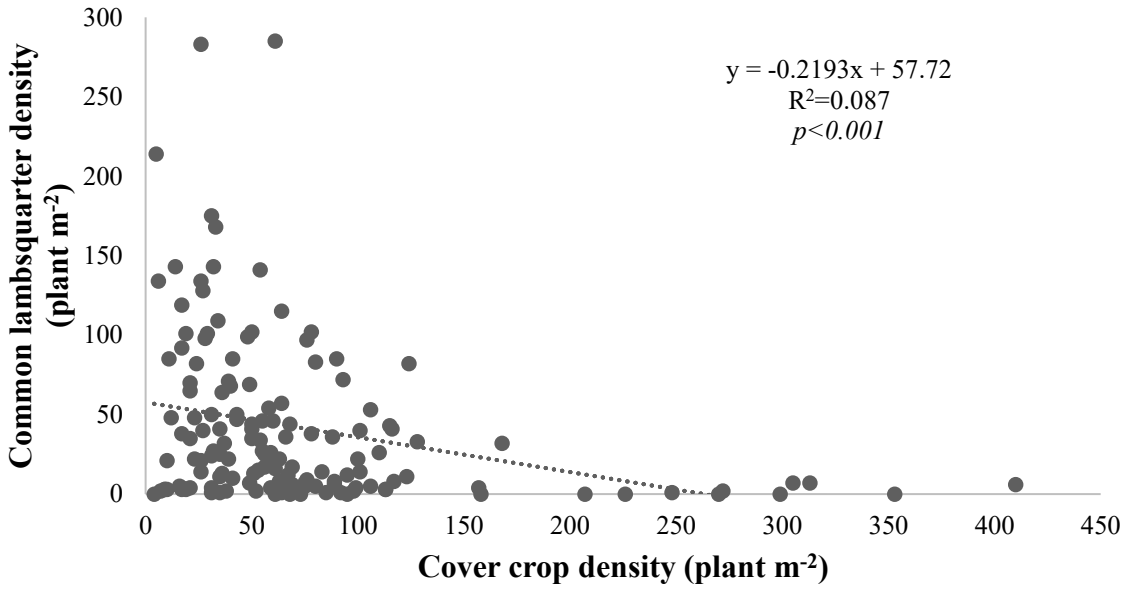

Figure 3.1. Relationship between cover crop density (plants m^{-2}) and common lambsquarters density (plants m^{-2}) at 4 WAP in the cover crop phase at Harrington PE and Fredericton NB in 2018 and 2019. Black line represents linear regression between cover crop density to common lambsquarters density (y=-0.2193x + 57.72) of sample size of 142.

3.3.2 Potato phase

In the potato phase of the rotation, common lambsquarters density differed by the interaction between cover crop, location, and time ($p<0.01$), but was not impacted by termination method ($p=0.92$). Overall, common lambsquarters density remained higher at Harrington than Fredericton and can be again attributed to differences in seedbank density. Forcella et al. (1993) demonstrated that high seedbank loads of >1000 seeds m^{-2} would produce populations so great that mechanical means of seedbank preparation were not sufficient to control seedlings and chemical herbicide intervention was required to prevent crop yield losses. Similarly, Mirsky et al. (2010) investigated the influence of soil disturbance through tilling and cover cropping on the germinable common lambsquarters seedbank and found that seedbank recruitment was not influenced by soil disturbance or cover cropping and attributed the lack of response to a high initial seedbank population. These findings are similar to ours in that common

lambsquarters populations remained higher at Harrington, where densities were initially high and were less responsive to cover crop treatments (Table 3.2).

The reduction in common lambsquarters observed in the potato phase at both locations suggest that brown mustard and buckwheat had carry over suppressive effects (Table 3.2). Campiglia et al. (2009) reported the incorporation of fall seeded rapeseed and ryegrass cover crops in herbicide-free potato systems resulted in the lowest proportion of weed biomass in the cover crop year and further reduced weed emergence in the subsequent potato crop. These findings were attributed to the crop's high growth potential, competitive ability for nitrogen uptake and the release of allelopathic compounds (Campiglia et al. 2009). Common lambsquarters density in potato was consistently lower at both locations following brown mustard and buckwheat than when following Timothy or the cover crop mixture at both 4 and 8 WAH (Table 3.2). Further, common lambsquarters density was 46-65% lower following buckwheat than all other cover crops in Harrington at 8 WAH ($p<0.01$; Table 3.2) and 77-81% lower following brown mustard and buckwheat in Fredericton at 8 WAH ($p<0.01$; Table 3.2). The reduction in common lambsquarters populations observed at 4 and 8 WAH in Fredericton and 8 WAH in Harrington could be due to suppressive allelopathic effects of buckwheat and brown mustard (Iqbal et al. 2003; Xuan and Tsuzuki 2004; Campiglia et al. 2009; Björkman et al. 2015). For example, brassica crops contain glucosinolates which can form volatile compounds known as isothiocyanates which have been shown to inhibit the germination and growth of many weeds including common lambsquarters (Teasdale and Taylorson 1986; Brown and Morra 1997; Haramoto and Gallandt 2004). The use of *Brassicaceae* seed meals with biologically active isothiocyanates has also been shown to reduce common lambsquarters biomass by over 87% (Rice et al. 2007). Similarly, buckwheat produces exudates and shoot

extracts known to have plant growth inhibiting effects on various weeds (Iqbal 2003; Kumar et al. 2009a). In the cover crop phase, we found buckwheat, brown mustard and the mixture to be the best-established cover crops and this may be due to their rapid growth. In combination, we find support for our first hypothesis, that cover crops would vary in their ability to suppress common lambsquarters, as observed in both the cover crop and potato phases. The cover crop mixture contained annual ryegrass, a quick to establish grass species that is known to improve early season weed suppression (Wagg et al. 2021). The inclusion of annual ryegrass in the mixture may have further reduced common lambsquarters densities due to its production of allelopathic root exudates known to have suppressive effects on common lambsquarters (Amini 2009). Together, planting cover crops with rapid growth and establishment show good potential to suppress common lambsquarters in subsequent cropping years. Cover crops with high growth potential, ground cover and first year establishment, combined with allelopathic effects have demonstrated strong effects on the common lambsquarters suppression. As such, buckwheat and *Brassicaceae* species can provide adequate suppression of common lambsquarters in potato production systems.

Table 3.2. Least square mean and standard error of the mean (SEM) of common lambsquarters density (plants m^{-2}) at Harrington PE and Fredericton NB, 4 and 8 weeks after hilling (WAH) in the potato phase in 2019 and 2020.

Location	Cover Crop	4 WAH [a,b]		8 WAH [a,b]	
		plants m^{-2}			
Harrington	Brown mustard	148	A	303	A
	Buckwheat	133	A	165	B
	Mix	173	A	378	A
	Timothy	223	A	472	A
	SEM	±61		±115	
Fredericton	Brown mustard	45	B	57	B
	Buckwheat	39	B	56	B
	Mix	291	A	294	A
	Timothy	192	AB	246	A
	SEM	±74		±85	

[a] Data are least square means.
[b] Means followed by different letters are significantly different with a Type I error rate of $\alpha=0.05$ according to a Tukey's HSD test within each location.

3.3.3 Impact of Cover Crops and Termination Method on Soil Seedbank and C:N

Common lambsquarters seedbank was affected by cover crop type and differed by termination method ($p<0.01$; Table 3.3). Buckwheat terminated with discing resulted in 64% fewer common lambsquarters seedlings emerging from the seedbank compared to glyphosate ($p<0.01$; Table 3.3). Thus, we find support for our second hypothesis that cover crop termination method would influence the common lambsquarters seedbank. Similar to Björkman and Shail (2013), our results show buckwheat incorporated through discing provided adequate soil disturbance and tillage to inhibit common lambsquarters seed germination. Discing promotes the breakdown of residues and can thereby alter soil nutrient availability, release allelopathic compounds, and alter common lambsquarters germination and growth (Dyck et al. 1995). In contrast, Timothy terminated with glyphosate resulted in 58% and 62% fewer germinating common lambsquarters in the seedbank compared to mowing and roller crimping, respectively

($p<0.01$; Table 3.3). These findings suggest that the weed suppressive effects of cover crops can alter based on residue management type. Timothy is a perennial bunchgrass with slow regrowth and is generally perceived as a poor competitor with annual weed species (Malik 1990). The poor establishment of Timothy in the cover crop year (Table 3.1) compounded with the high common lambsquarters densities observed in the potato year (Table 3.3) indicate Timothy generates insufficient residue to inhibit the common lambsquarters lifecycle via low mechanical termination methods such as mowing or roller crimping alone. Together, these results suggest that termination method can have varying effects on the common lambsquarters seedbank depending on cover crop species planted and should be selected with the cover crop phenology in mind.

Table 3.3 Least square mean and standard error of the mean (SEM) of common lambsquarters seedbank densities based on cover crop and termination treatment in the potato phase at Harrington PE in 2019.

Cover Crop	Termination Treatment	Common lambsquarters [a,b]	
		plant L soil^{-1}	
Brown mustard	Mow	16	A
	Roller crimp	13	A
	Disc	11	A
	Glyphosate	11	A
	SEM	±3	
Buckwheat	Mow	19	AB
	Roller crimp	18	AB
	Disc	10	B
	Glyphosate	26	A
	SEM	±4	
Mix	Mow	24	A
	Roller crimp	28	A
	Disc	32	A
	Glyphosate	34	A
	SEM	±6	
Timothy	Mow	68	A
	Roller crimp	75	A
	Disc	53	AB
	Glyphosate	28	B
	SEM	±12	

[a] Data are least square means.
[b] Means followed by different letters are significantly different with a Type I error rate of $\alpha=0.05$ according to a Tukey's HSD test within each cover crop.

Soil carbon was affected by cover crop ($p<0.01$), but was not impacted by termination method ($p=0.95$), or their interaction ($p=0.99$) (Table 3.4). In the potato phase, soil carbon following buckwheat was 4-6% lower than following the other cover crops. By comparison, soil nitrogen and C:N was not affected by cover crop ($p>0.05$), termination method ($p>0.69$), or their interaction ($p>0.67$) (Table 3.4). Despite cover crop species having negligible impact on soil C:N, a relationship between common lambsquarters emerging from the seedbank in the potato

phase and soil C:N was found. The common lambsquarters' seedbank declined with increasing soil C:N ($p<0.05$; R^2= 0.20) (Figure 3.2). The addition of nitrates to soil can help break common lambsquarters dormancy and stimulated seed germination (Williams and Harper 1965; Fawcett and Slife 1978). Our results demonstrate cover crops that increase the soil C:N had lower common lambsquarters germination and may be due to the lower nitrogen availability for seed germination. Similar to our findings, Kumar et al. (2009b) observed buckwheat and brown mustard to have relatively low C:N biomass levels and rapid residue decomposition rates, suggesting structural plant compounds may also influence their breakdown. McKenzie-Gopsill and Farooque (2023) found cover crops can interfere with weed germination when residues are soil incorporated and cause soil disturbance, as well as by means of nutrient tie-up and release of allelopathic compounds. Thus, termination method may further influence the weed suppressive ability of a cover crop and should be selected based on the establishment rate and biomass composition of the species.

Table 3.4. Least square mean and standard error (SE) of percent carbon (C), nitrogen (N) and carbon-to-nitrogen ratio (C:N) of soils collected at hilling in the potato phase at Harrington PE in 2019 and 2020.

Location	Cover Crop	%C [a,b]	%N [a,b]	C:N [a,b]
Harrington	Brown Mustard	1.67 A	0.18 A	9.31 A
	Buckwheat	1.65 B	0.18 A	9.22 A
	Mix	1.74 A	0.19 A	9.38 A
	Timothy	1.70 A	0.18 A	9.33 A
	SE	±0.03	±0.00	±0.37

[a] Data are least square means.
[b] Means followed by different letters are significantly different with a Type I error rate of $\alpha=0.05$ according to a Tukey's HSD test.

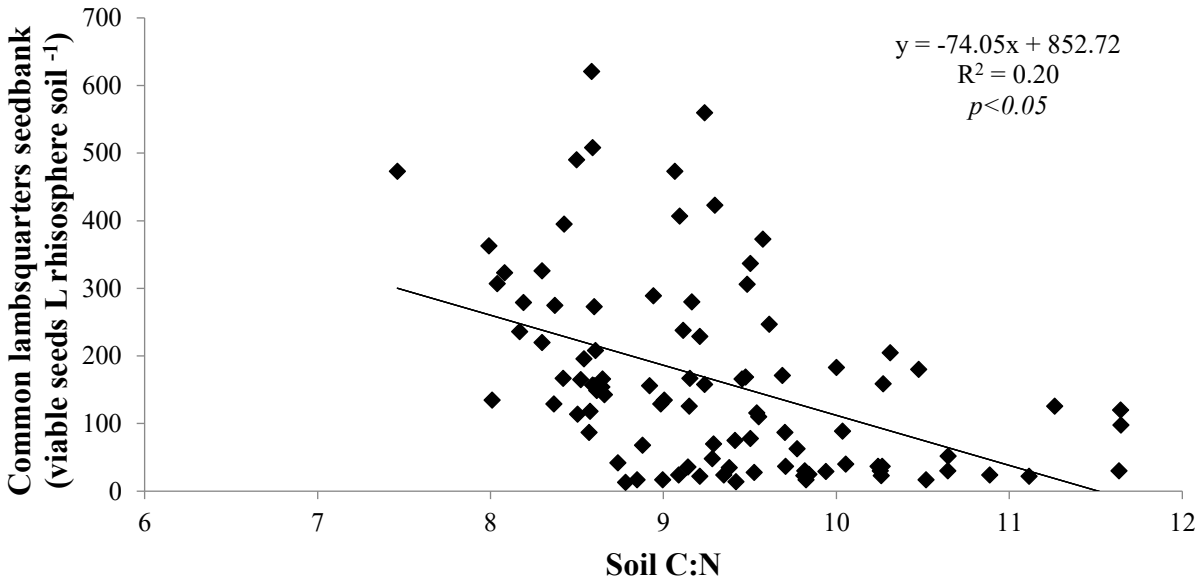

Figure 3.2. Relationship between the soil C:N and common lambsquarters density (plant m^{-2}) at 4 and 8 weeks after hilling (WAH) in the potato phase at Harrington PE in 2019 and 2020.

3.3.4 Impact of Cover Crops and Termination Method on Potato Yield

Potato marketable yield was affected by location ($p=0.02$), termination method ($p<0.01$), cover crop ($p<0.01$) and the interactions of location x termination method ($p<0.01$) and termination x cover crop ($p=0.04$). Marketable potato yield was consistently higher in Fredericton than in Harrington and may be due to reduced common lambsquarters seedbank

populations in Fredericton (Figure 3.3). Similarly, Buhler (1999) found the efficacy of control tactics on weeds and yield varied by initial weed density and noted that weed control and crop yield diminished in areas with high initial weed density. In the present study, marketable potato yield at Fredericton increased by 29% and 31% when following cover crops that were terminated via discing or glyphosate, respectively (Figure 3.3). This supports our third hypothesis, that cover crop termination method would influence potato yield and quality. Similarly, Mehring et al. (2016) found potato marketable yield was highest following cover crops terminated by roto-tilling, a high soil-disturbance method. Termination of cover crops by discing or roto-tilling improves seedbed conditions for potato planting and establishment and increases available nutrients from decaying cover crop residues and promotes crop yields (Wortman et al. 2013). Glyphosate is a systemic herbicide and is known as an effective cover crop terminator that can provide further control of weeds along with crop desiccation (Kumar et al. 2023). By comparison, mowing and rolling terminate cover crops by chopping and crimping the stems of the cover crop, respectively. These methods do not incorporate residues into the soil and were found to have less impact on potato yield. Therefore, termination by glyphosate and discing may improve seedbed conditions and nutrient availability for potato establishment in the subsequent cropping year, contributing to increased marketable yields.

Marketable potato yield was greater following the buckwheat and brown mustard which may in part be due to the decreased common lambsquarters density observed following these species early in the season (Table 3.2; Figure 3.3). The added pest suppressive benefits of these cover crops may have also contributed to these observed increases in potato yields. For example, Mehring et al. (2016) found potatoes grown under irrigation had 93% weed control following a spring-seeded rye/canola (*Brassica napus* L.) cover crop at 14 days after planting and attributed

this to their allelopathic effects. Further to cover crop effects on weed suppression and potato yield, *Brassica spp.* have been shown to suppress potato pests and provide increases in yield following incorporation (Davis et al. 1996). This includes suppression of pests like wireworm, or diseases like verticillium wilt (*Verticillium dahliae*), as well as parasitic nematodes (Davis et al. 1996; Ploeg 2008). Jiang et al. (2022) found that potatoes in rotation with buckwheat had increases in marketable tuber yield by 16% compared to other barley and red-clover rotations which was similarly attributed to its in-season mineralization in the subsequent potato crop year. Furthermore, brown mustard has been found to increase soil pH and soil phosphorus and potassium (Khan et al. 2021). Soil pH alters nutrient availability to a crop which alters biomass potential and yield (Neina 2019).

Double cropping of the brown mustard and buckwheat crops and the impact of residue breakdown on soil C:N ratios must also be considered in vegetable production systems. The observed reduction in soil carbon following buckwheat cover crops and lower soil C:N may promote residue decomposition and allow for greater nutrient availability or subsequent increases in tuber production (Creamer et al. 1997; Teasdale and Abdul-Baki 1998). Buckwheat is a phosphorus-efficient crop that increases soil phosphorus for the subsequent crop if soil-incorporated (Teboh and Franzen 2011; Posslinger et al. 2013). Combined, these findings demonstrate the benefits of soil incorporating buckwheat cover crop residues and produce yields comparable to chemical termination methods.

Cull yield varied by location ($p<0.01$), termination treatment ($p<0.01$) and the interaction of termination treatment x location ($p<0.01$). Cull yield in Harrington did not differ by termination treatment (Figure 3.3), however, in Fredericton was 52% and 88% greater following discing and rolling, respectively, than when following cover crops terminated by mowing (Figure

3.3). Mehring et al. (2016) noted that disc cultivators may not be able to position soil above the tubers when the previous cover crop is grown on fine-textured soils. Furthermore, Bellinder et al. (1996) found increased cultivation to be the solution for treating tuber greening because it buried potato sets deeper and reduced sunlight exposure. These results suggest that cover crop termination method can impact cull potato yield in the subsequent year, and termination via mowing will provide enhanced ground cover so to produce fewer culls.

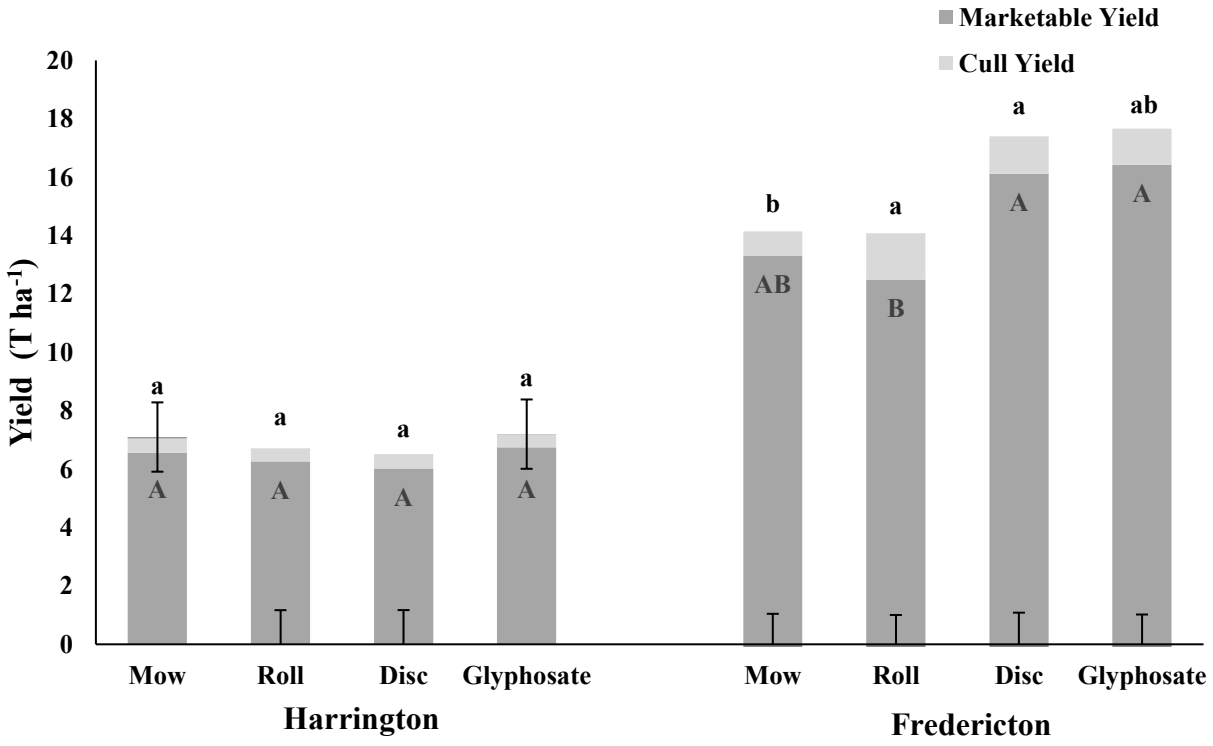

Figure 3.3. Effect of cover crop termination method on yield of marketable (Canada #1 and small) and cull yield (T ha^{-1}) weights in Harrington and Fredericton in 2019 and 2020. Standard error of the mean of total potato yield (T ha^{-1}). Datasets are least square means ± SEM. Bars with different letters are significantly different with a Type I error rate of $\alpha = 0.05$ according to a Tukey's HSD test. Letters refer to bars directly below them; uppercase letters refer to marketable yield, lowercase letters refer to cull yield.

3.4 Conclusion

This study evaluated the efficacy of buckwheat, brown mustard, a cover crop mix, and Timothy on common lambsquarters in potato production systems in Atlantic Canada. Further, four cover crop termination methods, mowing, rolling, discing and glyphosate, were evaluated for their impact on the common lambsquarters seedbank, soil nutrient status, and potato yield. We found that effects of cover crops and termination methods had different impacts based on location and were better integrated in Fredericton where the common lambsquarters seedbank was lower. Our data support the incorporation of cover crops with rapid establishment and allelopathic effects into potato rotations to provide common lambsquarters suppression, aid in the long-term exhaustion of the weed seedbank, and improve marketable potato yield and support sustainable potato production. Further work to explore optimal cover crop phenological stages for termination and their effects on soil C:N and the weed seedbank may also be beneficial to optimize these IWM tactics. Future research should also investigate cover crop biomass nutrient content and analysis of its ground-cover and mulch potential, as well as decomposition effects on the soil. This study contributes to the development of weed seedbank management tactics for common lambsquarters and demonstrates the viability of integrating cover crops as part of an integrated weed management plan.

Chapter 4 – Conclusion

Research Summary:

The major goal of this thesis was to investigate common lambsquarters biology and seedbank dynamics to identify IWM control strategies that could increase mortality, deplete the weed seedbank, and decrease viable seed shed. We explored a combination of mechanical, chemical and cultural management tactics. In Chapter 2 we conducted a crop-topping experiment involving above-canopy mowing and wick-applied glyphosate to evaluate in-season control of common lambsquarters overtopping the potato canopy. It was hypothesized that crop-topping semi-erect and upright potato cultivars will increase potato damage and negatively impact yield. Contrary to this, the semi-erect cultivar exhibited an increase in marketable yield and decrease in percentage of yield lost to culls when mowed at either timing in 2019. Wick-applied glyphosate had marginal effects on marketable yield in either year, but did show increases in cull yield, particularly in 2019 which supported our hypothesis. This increase could be due to increased glyphosate concentration, as well as exasperated effects from drought-like weather conditions throughout summer 2019. It was also hypothesized that early crop-topping will increase common lambsquarters control and maximize reductions in viable seed production but will reduce potato yield. Minimal support was found for this hypothesis since post-flowering treatments had a greater reduction in common lambsquarters seed viability. For instance, mowing common lambsquarters pre-flowering at a height of 25% of the crop canopy reduced common lambsquarters HI, while mowing post-flowering caused the opposite response. When applied at a 10 cm weed:crop height differential in 2020, mowing post-flowering successfully reduced overall plant reproductive biomass and resulted in lower reproductive biomass, HI and VSP across all cultivars in 2020. Both early and late mowing at 25% of the crop canopy increased

marketable potato yields of the semi-erect cultivar and decreased the percentage of yield lost to culls in the semi-erect and spreading cultivars. While effects to marketable yields were minimal, these reductions in common lambsquarters seed viability and cull yields indicate seasonal differences between 2019 and 2020, and subsequent plant resource availability and allocation. Moreover, our data indicates that mowing can successfully be applied to semi-erect, spreading and upright potato cultivars with minimal impact to potato yield while reducing common lambsquarters viable seed production. Similar weather effects on common lambsquarters size were observed in the wick-applied glyphosate experiment, whereby common lambsquarters were larger and potato yields were greater in 2020. Consistent reductions in common lambsquarters seed viability were observed across all cultivars when wicked post-flowering at a 10 cm weed:crop height differential. This included reductions in reproductive biomass, TSW and VSP. Similar to the mowing experiment, the upright cultivar exhibited reductions in VSP when treated post-flowering. Combined, this experiment demonstrated that crop-topping in potato production systems can be a viable method of late-season common lambsquarters control and can be incorporated into an IWM program to reduce viable seed shed. The marginal effects on potato yield in 2020, and drastic increases in cull yields in 2019 indicate further investigation required involving varying rates of wick-applied glyphosate and timing of application within varying stages of potato growth. Furthermore, a combination of late-season mowing and wick-applied glyphosate should be investigated. Late season wick-applied glyphosate decreased TSW, germination, and VSP of common lambsquarters and had minimal impact on potato yield in 2020, thus, a combination of late-season mowing paired with ultra-late wick-applied glyphosate has the potential to control common lambsquarters and protect potato yield potential.

The objective of Chapter 3 was to evaluate various cover crops and termination methods to suppress common lambsquarters populations in a potato rotation. A combination of cover crops including brown mustard, buckwheat, Timothy, and a mixture containing hairy vetch, annual ryegrass, and crimson clover were spring-sown and fall-terminated by mowing, roller crimping, discing or glyphosate. It was hypothesized that cover crops with higher stand densities will decrease common lambsquarters seed germination, seedbank density, and contributions towards the weed seedbank. In the more densely-seeded Timothy and cover crop mixture we observed lower common lambsquarters density in the cover crop year. A carry-over suppressive effect of buckwheat and brown mustard was observed on common lambsquarters populations in the subsequent potato year. The combination of high growth potential, competitive ability for nitrogen, and the exudation of allelopathic chemicals from these crops better suppressed common lambsquarters than did Timothy or the cover crop mixture. It was also hypothesized that cover crop termination methods that increase soil ground cover will decrease the germinable fraction of the common lambsquarters seedbank. Our data supports this hypothesis and suggests that the weed suppressive effects of cover crops can alter based on residue management strategies. Discing has been shown to alter common lambsquarters germination and growth by breaking down cover crop residues and alter soil-nutrient availability as well as release allelopathic compounds (Dyck et al. 1995). Our data demonstrates how buckwheat terminated via discing resulted in 64% fewer common lambsquarters seedling emerging than if terminated via glyphosate (Table 3.3). By comparison, termination of Timothy via glyphosate better reduced common lambsquarters seedbank germination than by other mechanical means. While Timothy is a poor competitor with slow regrowth and low residue production, and thus a poor cover crop, it relied on the broad-spectrum control of glyphosate to hinder common lambsquarters

germination. Thirdly, we hypothesized that cover crops terminated with methods that soil-incorporate biomass will increase potato yield and quality. Marketable potato yield increased when following cover crops terminated via discing or glyphosate compared to rolling. High soil-disturbance termination methods have been shown to increase marketable potato yields as they improve soil seedbed conditions for planting, establishment and nutrient availability (Wortman et al. 2013; Mehring et al. 2016). Cull yields were increased following cover crops terminated via discing and rolling when compared to mowing and is attributed to inadequate soil-incorporation and residue ground cover. Together, these results provide support for incorporation of cover crops for suppression of common lambsquarters in potato production systems and exemplify how termination methods should be selected with consideration of cover crop species competitive and allelopathic effects. The differences in common lambsquarters seedbank densities and greater cover crop effects observed between Harrington and Fredericton were significant and further research into effects of seedbank densities on the success of cover crop effects and IWM tactics overall is required. In the present study, buckwheat and brown mustard proved successful at suppressing common lambsquarters and were, in essence, double-cropped. The mowing and replanting of these crops would provide increased soil ground cover and soil disturbance when compared to the other cover crops and may have enhanced their positive effects. Future work should investigate the impacts of terminating at the same time as other cover-crop species, as well as flail mowing and not re-planting the crops in order to better compare management tactics.

This thesis demonstrates the potential benefits and viability of incorporating crop-topping and cover cropping IWM tactics into Atlantic potato rotations. Combined, we have demonstrated how wick-applied glyphosate and above-canopy mowing can deplete diminish common lambsquarters viability, and how incorporating cover crops can outcompete and suppress

common lambsquarters germination in subsequent potato years. This is preliminary research for potato cropping in the Atlantic Canadian region and future projects should include more Canadian potato-growing locations so to better understand the effects of these tactics on potato yields. As the occurrence of herbicide-resistant species continue to rise in Canadian potato cropping systems, future work should also assess the impacts of the IWM tactics investigated in the present study, as well as focus efforts on understanding the species seedbank dynamics.

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