# INTEGRATING CULTURAL TOOLS FOR WEED MANAGEMENT IN IRRIGATED SOYBEAN IN SOUTHERN ALBERTA

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## ABSTRACT

Soybean [*Glycine max* (L.) Merr.] is an important legume crop in western Canada. However, soybean exhibits delayed emergence and growth compared with many weeds in this region, resulting in greater reliance on herbicides. A field experiment was established near Lethbridge, Alberta, in 2020 and 2021 to determine how four cultural weed management practices [soybean row spacing (23 cm vs. 69 cm), target plant density (400,000 vs. 600,000 plants $ha^{-1}$) cultivar (slender vs. bushy) and fall rye cover cropping (with vs. without)] influenced soybean productivity and weed suppression. Overall, narrow compared with wide rows increased the ability for soybean to compete with and withstand competition from weeds. Increased target densities improved weed suppression, while bushy cultivars played a supporting role. The fall rye cover crop had inconsistent effects between years. Planting a bushy soybean cultivar in narrow rows at higher densities could improve irrigated soybean productivity and weed suppression in Alberta.

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| | |
|---|---|
| ANOVA | Analysis of Variance |
| GR | Glyphosate-Resistant |
| CHU | Corn Heat Units |
| MG | Maturity Group |
| ALS | Acetolactate Synthase |
| CPWC | Critical Period of Weed Control |
| HRC | Herbicide-Resistant Crops |
| PRS | Plant Root Simulator® |
| OM | Organic Matter |
| RCBD | Randomized Complete Block Design |
| AIC | Akaike Information Criterion |
| GDD | Growing Degree Days |
| PAR | Photosynthetically Active Radiation |
| LAI | Leaf Area Index |

# 1.0. INTRODUCTION

## 1.1. Background

Soybean [*Glycine max* (L.) Merr.] is among the most important oilseed crops grown globally. This crop was domesticated in Northern China and introduced into Canada in 1893 (Cloutier 2017). Canada is ranked as the seventh largest soybean-producing country, with 1.3% of global production (Masuda and Goldsmith 2009). Soybean varieties were first introduced into Manitoba in the 1990s (Cloutier 2017), but soybean production in the province increased only recently in the past decade due to the development of short-season soybean varieties (Hein 2018). The climate of Manitoba consists of adequate thermal time [e.g., Corn Heat Units (CHU) or Growing Degree Days (GDD)] and precipitation for soybean growth and development. In 2021, Manitoba had the largest soybean seeded area (about 532,900 ha) among the three Prairie provinces, whereas Saskatchewan had about 34,400 ha seeded to soybean (Soy Canada 2022). About 4,000 to 4,500 ha of soybean have been grown in Alberta in recent years (Statistics Canada 2021).

The high protein and oil content of soybean allow the crop to be used as food for human consumption, edible oils, as well as many industrial products. Soybean are not only a valuable crop used for human consumption, animal feed and industrial products, but also an important crop component for crop rotation and sustainable agriculture in western Canada. One beneficial aspect of legume crops is their ability to fix atmospheric nitrogen, thereby requiring less (or no) nitrogen in the form of fertilizer. Similar to many legumes, soybean plants develop specialized root structures called nodules, enabling a symbiotic relationship with *Bradyrhizobium japonicum* bacteria, which fix atmospheric dinitrogen

gas making it available to the plant in exchange for a carbon supply (Pratap et al. 2012). Their ability to fix atmospheric nitrogen as well as provide some residual nitrogen to subsequent crops, may help to reduce the carbon footprint associated with the production and transport of synthetic fertilizer, especially when soybeans are followed by non-leguminous nitrophilic crops, such as canola (*Brassica napus* L.) or wheat (*Triticum aestivum* L.).

Weeds are one of the most significant, but controllable, threats to soybean production globally (Soltani et al. 2017). Canada has the third-largest number of unique herbicide-resistant weed biotypes (weed species by herbicide mode of action) in the world, surpassed only by the United States and Australia (Heap 2020). Based on the global herbicide-resistant weed database as of 2020, British Columbia has one unique herbicide-resistant weed biotype, whereas Alberta has 26, Saskatchewan has 22, Manitoba has 30, Ontario has 38 and Quebec has five (Duckworth 2019; Heap 2020). Traditionally, application of a selective herbicide was the main weed management strategy in soybean (Bradley 2006). Glyphosate [N-(phosphonomethyl) glycine], is a non-selective, broad-spectrum herbicide that has simplified traditional weed management in soybean and other crops engineered to resist its application (Duke 2018). In 1996, a revolutionary new glyphosate use pattern commenced with the introduction of transgenic crops, such as soybean, corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and canola (Green and Owen 2011). Glyphosate can be applied to transgenic glyphosate-resistant (GR) crops as a post-emergence herbicide to control emerged weeds absent of crop damage (Powles 2008). GR canola, corn, cotton and soybean were commercialized in the mid-1990s (Reddy and Nandula 2012). GR soybean provide farmers with a cost-effective herbicide

option for broad-spectrum weed management post-emergence. In 2020, 59% of the soybean grown in the prairie region of Canada were GR, while 35% contained stacked traits conferring resistance to both glyphosate and dicamba [the remaining 6% of the soybean grown were either not specified (4%), non-herbicide-resistant (2%), glyphosate and 2,4-D resistant (<1%), or glufosinate-ammonium-resistant (<1%)] (Canadian Grain Commission 2021).

The evolution of glyphosate resistance in numerous weed species is an important global issue threatening crop production (Powles 2008). Heavy dependence on herbicides for weed control, particularly glyphosate, in many cropping systems results in high selection pressure for herbicide-resistant weed biotypes (Shaner 2000). GR weeds represent a significant risk to soybean growers in the Canadian prairies because most of the soybean grown in this region are genetically engineered to be GR. In 2011, GR kochia [*Kochia scoparia* (L.) Schrad.], was the first GR weed documented in western Canada (Hall et al. 2013). Recent findings indicate that waterhemp (*Amaranthus rudis* L.), a troublesome GR pigweed plant, has been discovered in Manitoba (Obeid et al. 2020). GR downy brome (*Bromus tectorum* L.) is another new problematic grassy weed biotype discovered recently in southern Alberta, Canada (Geddes and Pittman 2022).

Weeds interfere with crops in a variety of ways, which can lead to a reduction in crop yield. Weeds can compete with crop plants for essential resources, such as water, light and nutrients. This competition is the most critical in the initial stages of plant development. However, many weeds are adapted to compete well for available resources (Blackshaw et al. 2008), while most contemporary crops have been bred for maximum yield when resources are non-limiting (Jurado-Expósito et al. 2003). Many broadleaf

weeds, which produce foliage above the crop canopy, cause yield losses by competing for light (Wiles and Wilkerson 1991). In soybean cultivation, common cocklebur (*Xanthium strumarium L.*), giant ragweed (*Ambrosia trifida L.* ), jimsonweed (*Datura stramonium L.* ) and velvetleaf (*Abutilon theophrasti* Medik.) compete for light since they grow taller than the soybean and shade the crop late in the season, especially when they emerge at the same time as the soybean (Stoller and Woolley 1985). Soil moisture conditions can be a limiting but essential factor for soybean growth and production (Cloutier 2017). Precipitation and soil moisture strongly influence weed growth and competition (Griffin et al. 1989). When weeds compete with soybean for soil water, the amount of water available for crop growth is reduced. Yellow foxtail (*Setaria glauca* L.), Pennsylvania smartweed (*Polygonum pensylvanicum* L.) and velvetleaf resulted in greater soybean yield reduction when soil water was adequate early in the growing season compared with low early-season rainfall (Staniforth 1958; Staniforth and Weber 1956). Staniforth (1958) reported a 5% yield reduction in soybean due to weed competition under limited soil water conditions during the growing season. Another possible cause for yield losses due to weed competition is reduced nutrient uptake by the soybean crop. Nutrient competition is dependent on many weed characteristics, including weed species, density, and height. The capacity for absorption of nutrients, primarily nitrogen, phosphorus and potassium in plants depends on the magnitude and the morphology of the root system and its efficiency in absorption of nutrients (Blackshaw et al. 2008). In addition to direct competition for essential resources, weeds may also reduce crop yield by releasing secondary metabolites into the environment, which can impact neighboring plant growth (i.e., allelopathy) (Oudhia 2000). Soltani et al. (2017) reported that the potential soybean yield losses due to weed interference averaged 37% in North America.

Numerous cases of GR weeds have been reported worldwide due to the widespread use of glyphosate for weed control. The evolution of GR weeds has imposed new challenges in many cropping systems, and it is generally understood that integrating non-chemical weed management with herbicides can help mitigate and manage herbicide-resistant weeds (Knezevic et al. 2017). Among the many options of non-chemical weed management, the use of cover cropping (Proctor 2021), narrow row spacing (De Bruin and Pedersen 2008), increased seeding rates (Place et al. 2009) and growing competitive varieties (Knezevic 2014) have been shown to improve weed management in the United States and Canada.

Cultural weed management strategies such as row spacing, seeding rates, competitive varieties, or cover cropping are used to improve the ability for the crop to compete with weeds. Row spacing is considered as one of the major important management practices used to achieve the genetic potential of high yielding soybean (Wax and Pendleton 1968). In general, past studies have shown that, compared to narrow rows, wider rows lengthen the period of time that weeds must be controlled to prevent yield loss. This is largely due to differential light utilization between wide and narrow row soybean. A study conducted at Concord in eastern Nebraska showed that canopy closure is approximately 15 days earlier in narrow rows (38 cm) compared with wide rows (76 cm) (Knezevic et al. 2003). Soybean canopy closure earlier in the growing season results in greater light interception by the soybean crop, and higher soybean growth rate (De Bruin and Pedersen 2008).

The benefits of higher seeding rates, including weed suppression, has been well documented. Soybean seeded at high densities may have a competitive advantage over weeds because of rapid canopy closure (Weiner et al. 2001). Nice et al. (2001) found that

increasing soybean population from 245,000 to 481,000 plants $ha^{-1}$ caused a reduction in sicklepod (*Senna obtusifolia* L. ) density and growth. However, the economic cost of higher seeding rates (Thai 2018) must be considered along with potential weed management benefits.

Another important factor in soybean canopy closure can be the crop variety. Canopy closure can vary with soybean variety and early maturing varieties have the ability to close their canopies faster (Gulden, personal communication 2022), but the effect of this trait on weed control can vary among locations and years (King 2019).

A fall rye cover crop is often paired with soybean because it can provide several ecosystem services in addition to weed management, including: improved soil structure, reduced nitrogen losses from leaching, building of organic matter (OM), and reduced water and wind erosion (Reeves 2018). Blackshaw (2008) reported that, in western Canada, irrigated dry bean (*Phaseolus vulgaris* L.) following a fall rye cover crop terminated at planting suppressed weeds and increased yields under weedy conditions, while seed yields with the cover crop were comparable to those without under weed-free conditions. Thus, a fall rye cover crop grown before irrigated soybean in this same region could yield similar results as those observed for dry bean. Studies in eastern Canada (Blackshaw 2008; Mischler et al. 2010) and the United States (Loux et al. 2017), also indicate that the use of fall rye as a cover crop could be a viable practice to facilitate weed management in soybean, and that integrating fall rye cover cropping with increased soybean seeding densities can result in synergistic effects on weed management (Ryan et al. 2011), which could reduce selection pressure for GR weeds.

The depth and breadth of research conducted on the effects of various cultural weed management techniques in soybean dates back over 50 years, yet information on integrating all these practices together is much needed to help producers to develop systems that minimize the environmental impact of weed control without sacrificing profitability of crop production.

## 1.2. Research Problem Statement

All weed management practices implemented in irrigated soybean in southern Alberta are based on research from other areas of North America. Soybean producers in southern Alberta are in need of local information on sustainable weed management that helps mitigate and manage herbicide-resistant weeds in this important field crop.

## 1.3. Research Goal, Hypothesis and Objectives

### *1.3.1. Goal and Hypothesis.*

The goal of this research project is to enhance the productivity of irrigated soybeans in southern Alberta by integrating selected cultural practices that directly influence the crop competitiveness and weed suppression. It is hypothesized that planting competitive cultivars of irrigated soybean in narrow rows at higher densities into a fall rye cover crop could improve the ability for soybean to compete with weeds and withstand weed interference in southern Alberta.

### *1.3.2. Objectives.*

This study was designed to determine the impacts of soybean cultivar, row spacing, target plant density and fall rye cover cropping on soybean (1) productivity under weed-free conditions, (2) ability to compete with weeds, and (3) ability to withstand competition from weeds.

# 2.0. LITERATURE REVIEW

## 2.1. Soybean Production in Canada

Soybean is the third largest field crop grown in Canada based on seeded area (Soy Canada 2021), and its many end-uses make it a desirable commodity in export markets. In 2020, Canada exported about 4.4 million tonnes of soybean to 63 different markets worldwide (Soy Canada 2021). China imports approximately one-third of Canadian soybean exports, and other top destinations were Iran, Italy, Bangladesh and Japan (Soy Canada 2021). Most of Canadian soybean exports were non-processed/whole grains. The quantities of soybean flour, meal, oil and residues exported were much smaller than soybean grain exports, suggesting that much of the soybean processing takes place elsewhere (Pratap et al. 2012).

### *2.1.1. Soybean Production in Eastern Canada*

Corn, soybean and winter wheat are the three major crops grown in Ontario. Two thirds of Canadian soybean exports come from eastern Canada (Statistics Canada 2021). Among exported crops, soybean is the largest field crop exported from eastern Canada, with 53% of production exported each year. About 1.58 million metric tonnes of soybean are exported from Ontario to China, the European Union countries and the United States annually, while Japan, Malaysia, Vietnam and China represent other predominant export markets for food grade soybean (Ontario of Agriculture 2019). Together, these statistics show that a dominant portion of soybean exported from Canada originates from farms in Ontario.

Soybean have been cultivated on a small scale in Southwestern Ontario since 1920, however, seeded area in this region increased largely after the 1960s (Cloutier 2017). Ontario is the largest soybean growing province in Canada accounting for over 1.0 million ha of production annually (Follings et al. 2012). The majority of soybean in Canada was originally cultivated in the southern-most region of Ontario. However, efforts in agronomy and plant breeding resulted in expansion of soybean cultivation throughout the agricultural regions of Ontario, Quebec and the Maritime provinces (Cober and Voldeng 2012). In 2014, soybean cultivated area in eastern Canada reached over 1.21 million ha due to the development of early-maturing varieties, wider selection of herbicide options, and relatively low fertilizer requirements (OMAFRA 2017).

Farmer choice of soybean varieties is often based on CHU among other important factors such as yield. The CHU system provides an index to calculate plant development based on temperature. However, some reports indicate that this system is not accurate for predicting soybean maturity (Anonymous 2012). This is because soybean development is a function of both temperature and photoperiod, and not simply temperature alone (Jones et al. 1991). Minimum day length and adequate temperature are important parameters determining the initiation of soybean flowering (Major et al. 1975). Due to photoperiod sensitivity, most soybean varieties are adapted to growth in a narrow latitude range. In eastern Canada, most regions use a relative Maturity Group (MG) system to rank soybean cultivars instead of CHU (Ort et al. 2022). Soybean varieties are classified into MGs from 000 (shorter season) to IX (longer season). The MG classification system was established by the Regional Soybean Laboratory of the United States, Department of Agriculture (Jia et al. 2014). MG classification is based on the response to photoperiod or latitude, and

initially, the groups were ranged from MG I to VII. Later, MGs extended to VIII – X well-suited for lower latitudes of the America, southern Asia and Africa. However, this grouping system includes, MG 0, 00 and 000 soybeans, which are suited for growing in Canada and northern United States (Jia et al. 2014). Soybean with a relative maturity of 00 are considered adapted for Ontario and other parts of eastern Canada (OMAFRA 2009).

GR weeds hinder the production of GR soybean in many areas of the world, and eastern Canada is no exception. Many agro-chemical companies have developed multiple herbicide resistance traits in soybean to provide farmers with more options for management of herbicide-resistant weeds post-emergence (Soltani et al. 2016). Herbicide-resistant soybean traits available in eastern Canada include, Roundup Ready (RR; glyphosate-resistant), Roundup Ready 2 Yield (RR2Y; glyphosate-resistant), Roundup Ready 2 Xtend (RR2X; glyphosate- and dicamba-resistant), Enlist (glyphosate- and 2,4-D-resistant), Enlist E3 (E3; glyphosate-, glufosinate-ammonium- and 2,4-D-resistant) and Liberty Link (LL; glufosinate-ammonium-resistant) (Beckie 2013).

In recent decades, soybean producers in eastern Canada have shifted away from conventional tillage and toward conservation tillage systems in efforts to mitigate soil erosion (Derpsch 2003). From 1991 to 2006, the land area in Ontario under conventional tillage decreased from 78% to 44% whereas the no-till land area increased from 4% to 31% (Statistics Canada 2020). Overall, about two-thirds of soybean in Ontario are produced under conservation tillage systems (either no-till or reduced-till leaving most of the crop residue on the soil surface) (OMAFRA 2017).

Soybean performs well when grown in rotation with other crops. Growing soybean continually in the same field without practicing crop rotation may cause decreased yield, especially when using conventional tillage (Morrison et al. 2017). However, when both soybean and corn are grown in rotation, there is greater risk of selection for GR weeds because of similar herbicide resistance traits in both crops. Therefore, growers should diversify their weed management program and select herbicide chemistries with different modes of action. Winter wheat can help with weed management because growing a crop with an alternative life cycle can facilitate competition with summer-annual weeds and it requires alternative (non-glyphosate) herbicides for weed control post-emergence (Derksen et al. 2002).

### *2.1.2. Soybean Production in Western Canada*

Soybeans are a relatively new crop grown in western Canada due to a large increase in seeded area over the past decade in response to the development of shorter-season soybean varieties (MacMillan and Gulden 2020). Soybean were introduced to Manitoba in the 1990s (Cloutier 2017). During this period, soybean were grown mainly for livestock feed and human consumption. However, soybean seeded area in Manitoba has grown rapidly in the past decade. In 2021, soybean was grown on 532,890 ha in Manitoba compared with 465,226 ha in 2020 (Statistics Canada 2020; Statistics Canada 2021). Due to a suitable climate for soybean growth including sufficient accumulation of thermal time and precipitation, soybean production in Manitoba reached 1.16 million tonnes in 2020; making Manitoba the second largest soybean producing province in Canada (Statistics Canada 2020).

While most of the soybean production in western Canada takes place in Manitoba, soybean are also grown in Saskatchewan and Alberta to a lesser extent. In south eastern Saskatchewan, soybean seeded area comprised 68,800 ha in 2013 and 121,400 ha in 2014, but declined to 60,690 in 2019 (Soy Canada 2022; Statistics Canada 2020). In contrast, soybean were grown on 4,000-4,500 ha in Alberta in 2019 (Statistics Canada 2020). Soybean seeded area declines moving westward from Manitoba as the length of the growing season becomes shorter, and precipitation is more limited (Barker 2007). However, recent efforts to breed shorter-season soybean varieties have made soybean a viable option for farmers in Saskatchewan and Alberta, where production is likely to increase in the coming decades.

Current soybean varieties provide a diverse range of growth types and MGs that facilitate production over a wide geographical area. However, selection of an appropriate variety for a particular production region can depend on several factors. Soybean varieties are classified into three groups according to their growth: determinant, semi-determinant, and indeterminate. Determinant growth in soybean plants means when flowering begins, the terminal bud discontinues its vegetative activity. For semi-determinate growth, the terminal bud continues vegetative growth after flowering but ceases growth before indeterminate types. For indeterminate growth, the terminal bud continues vegetative activity throughout the growing season (CFIA 2022). Temperature is considered the main limiting factor to soybean growth and development (Soldati and Keller 2022). Most soybean varieties grown in western Canada are MG 00 or 000, which require about 2400 to 2500 CHU or < 2400 CHU, respectively (Gaultier 2019).

Herbicide-resistant weeds represent an immediate and growing threat to soybean cultivation in Canada and worldwide. Canada is home to the third largest number of unique herbicide-resistant weed biotypes among other countries (Heap 2022). In western Canada, 30 unique herbicide-resistant weed biotypes have been discovered in Manitoba, while 22 and 26 have been discovered in Saskatchewan and Alberta, respectively (Heap 2020). Herbicide-resistant traits were integrated into soybean varieties to provide cost-effective broad-spectrum and non-selective weed management post-emergence. In western Canada, these traits (grown in 2020) included: Roundup Ready (glyphosate-resistant), Xtend (glyphosate- and dicamba-resistant), Enlist (glyphosate- and 2,4-D-resistant), and Liberty Link (glufosinate-ammonium-resistant) (Canadian Grain Commission 2021). In 2020, most (59%) of the soybean grown in western Canada were resistant to glyphosate only, while 35% were glyphosate- and dicamba-resistant, <1% were glyphosate- and 2,4-D-resistant, <1% were glufosinate-ammonium-resistant, 2% were conventional (not herbicide-resistant) and 4% were not specified. Therefore, GR weeds represent a significant threat to soybean production in this region.

### 2.2. Problematic Weeds in Soybean Cultivation

A weed can be defined as an any plant growing where it is not wanted (Sutherland 2004). In an agricultural context, weeds often cause losses in crop yield or quality. Most weed species have characteristics that allow them to persist in agroecosystems, and compete with crops for available resources (Bastiaans and Kropff 2017). Many weeds produce abundant seeds that spread and germinate quickly or lie dormant and survive in harsh environments (Mohler et al. 2001). Many weeds also have an extensive root system and can spread rapidly below or above the soil. Weeds compete with crops for essential

resources required for growth and development, including: light, water, nutrients and space and this competition often leads to reduce crop yield (Swanton et al. 2015).

Over the past 65 years, herbicides have had a predominant role in weed control, thereby aiding in maintenance of crop yields. However, herbicidal weed control faces challenges, including environmental and safety issues, public opinion, and the evolution of herbicide-resistant weeds. The international herbicide-resistant weed database indicates that 267 weed species (154 dicots and 113 monocots) have evolved resistance to one or more herbicides worldwide. These numbers increase annually with new reports of novel herbicide-resistant weeds (Heap 2022).

Before the 1990s, herbicide-resistant weeds were a fundamental issue predominantly in developed countries because these countries depended on herbicides for weed control while some developing countries used predominantly non-chemical approaches such as hand weeding. However, this situation has changed in the last few decades as weed control in developing countries shifted toward chemical means of weed management; resulting in selection for herbicide-resistant weeds (Powles 2008).

The six “most troublesome" and "most common" weed species in the United States include Palmer amaranth (*Amaranthus palmeri* S.Wats.), commom lambsquarters *(Chenopodium giganteum* D.Don*.),* horseweed *(Erigeron canadensis* L.*),* morning glory (*Ipomoea purpurea L.*), common waterhemp (*Amaranthus tuberculatus* J.D.Sauer.) and giant ragweed (WSSA 2017). Among these species, Palmer amaranth was ranked as the most troublesome and difficult to control weed in 12 categories of broadleaf crops, including soybean. This is because Palmer amaranth has rapidly developed resistance to multiple groups of herbicides [e.g. microtubule, photosystem (PS) II, acetolactate

synthase (ALS), 5-enol-pyruvylshikimate-3-phosphate synthase (EPSPS), and hydroxyphenylpyruvate dioxygenase (HPPD) inhibitors] (Bomgardner 2019; Heap 2022). This weed species is native to the desert regions of the southwestern United States and northern Mexico and has gradually expanded to the southeast (USDA 2017), and many other areas of the United States. Palmer amaranth is a dioecious species capable of producing at least 100,000 seeds plant$^{-1}$ under crop interference and 500,000 seeds plant$^{-1}$ in the absence of interference (Berger et al. 2016). When farmers apply a single mode of action herbicides repeatedly, this weed species can adapt and spread herbicide resistance genes quickly (Ward et al. 2013).

Common lambsquarters is another problematic weed that has expanded in the United States soybean belt and was ranked as the most common weed species in sugar beets (*Beta vulgaris* L.), vegetable crops and pulse crops including soybean, lentils (*Lens culinaris* L.) and chickpeas (*Cicer arietinum* L.) (Mitich 1988). It can produce an average 72,000 seeds plant$^{-1}$ and these seeds exhibit different dormancy requirements. Generally, seed dormancy increase with increasing burial depth. About 50% of the common lambsquarters seedbank remained viable after 12 years in the soil (Buhler et al. 2001). Common lamsquarters is often one of the first summer annual weeds to emerge in the spring making it highly competitive with field crops (Fischer et al. 2004). This weed can result in up to 40% soybean yield losses (Teresa and Karen 1990). Common lambsquarters has evolved resistance to two different herbicide site of action including ALS inhibitors and Photosystem II inhibitors (Heap 2022). Common lambsquarters stems can cause problems during soybean harvest because they can plug combine harvesters (Harrison 1990).

Common waterhemp has become a most troublesome C4 broadleaf weed species in Nebraska and several other states in the Midwestern United States (Waselkov and Olsen 2014) due to its rapid growth rate averaging about 2.5 to 3.1 cm per day during the growing season. This helps waterhemp seedlings to obtain more sunlight more readily by competing with major crops. Hager et al. (2002) noted, 43% of yield loss in soybean when common waterhemp plants interfered up to 10 weeks after soybean unifoliate expansion. The first GR common waterhemp was identified in Missouri in 2008 (Legleiter and Bradley 2008). Waterhemp has evolved resistance to herbicides from six groups, including triazines like atrazine and simazine, ALS-inhibiting herbicides, PPO-inhibiting herbicides, glyphosate, HPPD-inhibiting herbicides, and 2,4-D (Schryver et al. 2017).

Giant ragweed is an annual broadleaf weed species of the Asteraceae family, which is native to the United States has expanded to several Midwestern areas (Ganie et al. 2016). Giant ragweed plants are found commonly in agricultural fields, orchards, roadsides, stream banks, drainage ditches, fence lines and other non-agricultural lands. Because of its allergenic pollen, it has high risk of causing hay fever (Abul-Fatih and Bazzaz 1979). Giant ragweed is one of the most problematic weeds in corn and soybean fields due to its early emergence, rapid growth rate and ability to germinate and survive in diverse environments. It has developed resistance to glyphosate and ALS inhibitors (Heap 2022).

Horseweed is a winter annual weed species that is competitive in no-till agricultural systems, and especially in soybean fields (Weaver 2001) located in southern Canada, tropical America and the United States (Sarangi and Jhala 2018). Bruce and Kells (1990) documented 71% to 98% soybean yield reduction caused by horseweed at a density of

100 to 212 plants $m^{-2}$. GR horseweed biotypes have been found in up to 38% of no-till soybean fields in some regions of Indiana (Davis et al. 2008). Some horseweed biotypes in the eastern corn belt are resistant to ALS inhibitors, PSI Electron Diverters and glyphosate (Heap 2022; Kruger et al. 2008).

A comprehensive 2016 survey of weed populations present after post-emergence herbicide application in 118 soybean fields in Manitoba, Canada showed that the top three most-abundant weeds in soybean were volunteer canola (*Brassica napus* L.), wild buckwheat (*Fallopia convolvulus* L.) and barnyard grass [*Echinochloa crus-galli* (L.) P.Beauv.] (Leeson et al. 2017). Volunteer canola was the fifth most abundant weed species after post-emergence herbicide application among annual field crops in Manitoba in 2016 (Leeson et al. 2017). Canola production has increased in the Canadian prairies with the introduction of herbicide-resistant canola in 1995/1996. Canola cultivars in the Canadian prairies can be resistant to either glyphosate, glufosinate-ammonium, imidazolinones, or glyphosate + glufosinate-ammonium (Beckie et al. 2006; Smith et al. 2011). Canola can return as a volunteer weed in years following canola production (Gulden et al. 2003) and may remain at low densities throughout three or four year rotations (Beckie et al. 2006). Considerable harvest losses in canola can result in volunteer canola interference in other important cash crops. Volunteer canola has high phenotypic plasticity and high efficiency of resource capture by strongly competing with less competitive crops grown in rotations such as sugar beet (Stachler et al. 2009), soybean (Beckie and Owen 2007) and field pea (Jhala et al. 2021). Gulden et al. (2003) reported that the most important step to reduce volunteer canola in a field is harvest management. Even a light soil disturbance after canola harvest can promote seed-soil

contact resulting in fall germination of canola seeds followed by winterkill of summer-annual genotypes in western Canada (Geddes and Gulden 2017). In western Canada, higher crop seeding rates, narrow row spacing, inter-row tillage (Geddes and Gulden 2018), or inter-row living mulches facilitate volunteer canola management in soybean (Geddes and Gulden 2021).

Green foxtail (*Setaria viridis* L. ) is native to Europe and was introduced to North America, spreading to the Canadian prairie provinces (Douglas et al. 1985). Green foxtail is the most abundant weed species in annual field crops sampled in Saskatchewan and Manitoba (Leeson et al. 2017). As a C4 plant, green foxtail is competitive under high temperatures. This species exhibits rapid growth through the vegetative stage to flowering, high phenotypic plasticity and is capable of producing a large number of seeds. Due to the above characteristics, management of green foxtail with herbicides can be variable. Green foxtail biotypes in Canada can exhibit resistance to including acetyl-CoA carboxylase (ACCase) inhibitors, dinitroanilines and ALS inhibitors (Heap 2022; Morrisson and Devine 1994).

Wild buckwheat, also known as black bindweed, is an annual broadleaf weed that has a fibrous root system capable of extracting water and nutrients from the soil at depths of 80 cm, making it highly competitive and drought tolerant (Beckie et al. 2012). Wild buckwheat has a vine-like growth habit which starts out as prostrate and trailing along the soil surface, branching, expanding, and finally creating its own large canopy (Raine 2015). This species can grow up to one meter tall by climbing through the crop canopy. Wild buckwheat seeds can contaminate small grains impacting both grain yields and also quality. These seeds can germinate throughout the growing season, but germination is

depend on soil moisture and typically takes place within the top 5 cm of soil. Prior to 2010, wild buckwheat was identified as being resistant to ALS inhibitors in Alberta.

Barnyard grass is a summer annual grassy weed commonly found throughout the Midwestern and southern soybean producing areas. It has thick, flat stems that branch from the base and spread over the ground. Jungle rice and awnless barnyard grass are two most-prevalent barnyard grass species found in the United States mid-south regions (Mitich 1990). Due to greater natural tolerance to post-emergence herbicides and prolonged emergence, it can be difficult to control barnyard grass. This weed is more tolerant of saturated soils and flooded conditions than most summer annual grass weeds that infest soybean (Maun 1977). Barnyard grass germinates from early spring to early summer and plants take about 42 days to mature, producing over 40,000 seeds plant$^{-1}$. This weed species has exhibited resistance to propanil, fenoxaprop and quinclorac and many resistant populations are resistant to more than one of these herbicide sites of action (Steckel 2019).

Kochia is a problematic tumbleweed species across western Canada and has become a significant threat for soybean cultivation in Manitoba, Saskatchewan and Alberta (Beckie et al. 2015). It is a C4 annual broadleaf weed that is native to Asia and central Europe and was introduced to North America as an ornamental plant by European immigrants (Friesen et al. 2009). Kochia continues to be sold by some seed companies and nurseries as an ornamental plant "burning bush". Kochia is capable of producing up to 100,000 seeds plant$^{-1}$ (Friesen et al. 2009). This tumbleweed exhibits efficient pollen- and seed-mediated gene flow, resulting in rapid spread of herbicide resistance traits (Beckie et al. 2016). For example, GR kochia increased from <1% to 58% of the kochia populations

sampled in Manitoba between 2013 and 2018 (Beckie et al. 2015; Geddes et al. 2021b) Similarly in Alberta, GR kochia increased from 4% to 50% of the populations sampled between 2012 and 2017 (Hall et al. 2014). Kochia germinates early in the spring (after as little as 50 GDD, Tbase = 0°C), making it highly competitive if left uncontrolled in field crops (Friesen et al. 2009; Geddes and Sharpe 2022; Schwinghamer and Van Acker 2008). Kochia is drought and saline tolerant, allowing it to thrive in unproductive areas of fields. Geddes and Sharpe (2022) reported, soybean yield losses of 52% on average due to kochia interference. GR kochia was the first GR weed identified in Canada in 2011, where it was discovered initially in chemical fallow fields located in Warner County, Alberta (Hall et al. 2014). A survey that was conducted across southern Alberta in 2012 identified that 4% of the 309 sites contained GR kochia (Hall et al. 2014). Surveys conducted in Alberta (2012), and Manitoba and Saskatchewan (2013) indicated glyphosate resistance in 4%, 5% and 1% of kochia populations in Alberta, Saskatchewan and Manitoba, respectively (Beckie et al. 2015). Unlike Alberta, the first GR kochia populations found in Manitoba were in GR soybean and GR corn fields (Geddes et al. 2019). The 2017 survey of Alberta also reported that 18% of the sampled kochia populations were resistant to the dicamba and 10% of kochia populations were triple-resistant to ALS inhibitors, glyphosate and dicamba (Beckie et al. 2020; Torbiak et al. 2021). Further research also identified fluroxypyr resistance in 13% of these populations bringing the percentage of triple-resistant kochia populations in Alberta in 2017 up to 16% (Geddes et al. 2021a). Due to high wind dispersal in southern Alberta, GR kochia has become a significant threat for crop producers, who practice chemical fallow, direct seeding, and grow GR corn, soybean, or canola (Hall et al. 2014). Therefore, alternative management practices are required to mitigate the impact that this weed can have on

soybean production in western Canada.

## 2.3. Weed Interference in Soybean

Competition is any interaction between organisms that strive for the same resources in the same place. Weeds compete with field crops for nutrients, water and light that are essential to plant development, known as direct competition (Bastiaans and Kropff 2017). Weeds can also interfere with crops through indirect means such as allelopathy or shade avoidance (Rose et al. 1984). Inter-specific competition between weeds and crops can affect crop morphology and yields (Munger et al. 1987).

### *2.3.1. Critical Period of Weed Control*

The Critical Period of Weed Control (CPWC) is defined as the interval in the crop life cycle when the presence of weeds will cause unacceptable yield losses (Zimdahl 1980). The CPWC concept is the main theoretical framework in agricultural systems that helps to determine the most efficient time for post-emergence herbicide application (Arslan et al. 2006). The CPWC is affected by weed morphology, emergence timing, duration of emergence, density, crop competitiveness and environmental conditions (Knezevic et al. 2002). Under conventional tillage systems in Ontario, the CPWC in conventional soybean ranged from 9 to 38 days (V2 to R3 stages) after soybean emergence (Van Acker et al. 1993). Soltani et al. (2017) reported that on average, 52% soybean yield loss occurred due to weed interference in North America. Overall, the CPWC concept suggests that weed competition with soybean for available resources is most-critical between the V2 and R3 stages of growth and development (Mulugeta and Boerboom 2000).

### *2.3.2. Direct Competition*

#### **2.3.2.1. Light**

Light is an essential resource that is required for the growth and development of plants. Plants respond to the both light quality and quantity. Light quantity can be described as the number of photons capable of performing photosynthesis, while light quality refers the wavelength within the electromagnetic spectrum (Smith 1982). The 400-690 nm wavelength range is the highest quality of light for photosynthesis (Holmes and Smith 1977; Holt 1995). Light interception by the crop canopy depends on ground cover, which is a function of plant density, branching, height, leaf area, leaf distribution, leaf angle, dry mass accumulation, the time of day, cloudiness and latitude (Silva et al. 2013). Barnes et al. (2018) found that the interference of common ragweed in soybean was very high when there was direct competition for light.

Most weed species in soybean fields, especially ones that are tall, push through the soybean crop canopy and compete with soybean for light. Velvetleaf, jimsonweed, and common cocklebur grow taller than soybean and shade the crop for 8-10 weeks of the growing season. Competition for light can be even more severe when weeds emerge at the same time as soybean compared with later in the growing season (Stoller and Woolley 1985). Assembling many soybean nodes closer together is one key component to higher yield (Bechman 2021). Maun (1977) studied how soybean suppressed plant height, dry matter, and productivity of barnyard grass. Barnyard grass suppression remained low for the first five weeks of soybean growth. During this time, barnyard grass can directly influence soybean growth and development. From 6 to 11 weeks after soybean

emergence, soybean have sufficient ground cover to create a competitive environment capable of supressing barnyard grass.

#### 2.3.2.2.Water

Soybean require a large amount of water for optimal growth and development, and thus weed competition can be more severe under conditions where annual rainfall is low (Wijewardana et al. 2019). Sufficient precipitation is among the most-limiting factors for soybean expansion in Alberta and Saskatchewan, and thus, the crop is usually grown under irrigation in Alberta. Water availability is most-crucial to soybean growth and development during the periods between seed germination and seedling emergence, and from flowering to pod filling (Oya et al. 2004). Long-term unavailability of water can have detrimental effects on soybean plant morphology, including plant height, internode length, leaf area index (LAI), number of pods and seed weight (Desclaux et al. 2000). Under water stress condition, soybean plants lose water content causing leaf wilting and drooping; if soybean plants are exposed to a prolonged dry period, it could lead to plant death (Sheng et al. 2017).

Competition from major weeds, such as yellow foxtail, velvetleaf and Pennsylvania smartweed resulted in the greatest soybean yield reductions when soil water was adequate in the early growing season (Blair et al. 1989). Yellow foxtail is a very prominent C4 weed species in soybean fields in the eastern Canadian prairies (Leeson et al. 2017). Plant species, which exhibit C4 carbon metabolism are usually more efficient in their use of water, and produce more biomass per unit of water consumed (Chen and Blankenship 2021). Competition from Venice mallow (*Hibiscus trionum* L.) resulted in the greatest

soybean yield losses when soil water was adequate in the early growing season and limited in late summer (Eaton et al. 1973).

#### 2.3.2.3 Nutrients

Soil pH and nutrient availability also affect weed and crop competition. Nitrogen, phosphorous and potassium are three macro-nutrients, which are vital to plant growth. The magnitude of micro and macro-nutrient absorption in plants depends on the morphology of the root system and its capability in absorption of these nutrients (Procopio 2004). Soybean are less-dependent on nitrogen fertilizer due to their ability to fix plant-available nitrogen from atmospheric dinitrogen gas via symbiotic association with *Bradyrhizobium japonicum* (Meena et al. 2018; Song et al. 2021). However, early stages of soybean growth and development require nitrogen uptake from the soil because this symbiotic relationship may not fully establish until the V2 growth stage (Patterson 1995). However volunteer canola was more competitive in soybean following the addition of a small amount of nitrogen fertilizer (Geddes and Gulden 2018), suggesting that growing soybean in nitrogen-limited environments could improve its competitive ability with weeds.

### *2.3.3. Indirect Competition*

Indirect plant interference can take place through the production of allelopathic chemicals (Rose et al. 1984) or by altering the immediate environment surrounding neighboring plants. Plant interference may occur as result of abiotic or biotic stresses with the release of secondary metabolite chemicals (allelopathic effect) into the environment resulting in the inhibition of neighboring plant species (Anand 2013). Schreiber and Williams (1967)

found that decaying roots of giant foxtail (*Setaria faberi* L.) inhibited corn root growth. Bhowmik and Doll (1982) observed that common lambsquarters, redroot pigweed (*Amaranthus retroflexus* L.) and yellow foxtail residues reduced the productivity of greenhouse-grown soybean by 19%. Verma and Rao (2006) identified the allelopathic effect of extracts of four weed species; billygoat weed (*Ageratum conyzoides* L.), scutch grass [*Cynodon dactylon* (L.) Pers.], black nightshade (*Solanum nigrum* L.) and Parthenium hysterophorus (*Parthenium hysterophorus* L.) on seedling growth, seed germination and protein quality of six soybean varieties in the Tarai region of India and results indicated that the seed germination was decreased in all soybean varieties in extracts of all four weed species.

#### 2.3.3.1. Allelopathic Interactions

Allelopathic interactions are species-specific and may impact soybean production in some instances but not in others which could be exploited to manage weeds in soybean. In many agricultural systems, allelopathy is considered as a secondary weed management strategy. Organic farming and minimum or no-tillage agricultural systems are often problematic for weed control, and often allelopathy plays more important role in these systems (Scavo and Mauromicale 2021). However, information on the allelopathic potential of different crop species and their effects on common weeds is limited in western Canada (Geddes et al. 2015).

Cover crops can have potential benefits for weed suppression in soybean cultivation. For example, the aqueous extracts of fall rye and winter wheat mulch tissues suppressed kochia seed germination and radical elongation. Geddes et al. (2015) reported that the allelopathic potential of aboveground biomass of fall rye, hairy vetch (*Vicia villosa* L.)

and winter wheat was significantly higher on canola, kochia, wild oat (*Avena fatua* L.), lambsquarters and wheat than that of belowground biomass. Winter wheat and fall rye have been shown to suppress seed germination and radical elongation of several weed species due to the release of allelochemicals, such as benzoxazinoids (Schulz et al. 2013).

#### 2.3.3.2. Shade Avoidance

Shade avoidance is another indirect plant interference method. Shade avoidance is defined as the response of plants to shade by increasing the elongation of vertical stems and petioles, which locates leaf blades higher in the canopy profile, suppress branch formation, accelerate flowering and causes changes in biomass accumulation (Zekri and Parsons 1999). Soybean convey shade avoidance in response to low Red:Far Red (R:FR) light reflected from neighbouring plants. This response is expressed as an integral component of competition (Green-Tracewicz et al. 2011). However, these shade avoidance responses depend on the crop phenotypic plasticity. Most studies have shown that soybean exhibit both vegetative and reproductive plasticity (Carpenter and Board 1997; Vega et al. 2000). Green-Tracewicz et al. (2011) found that soybean seedlings initiated a shade avoidance response when the R:FR light ratio was reduced and it caused reduced branching and increased plant to plant variability in biomass accumulation. Since the presence of weeds can alter reflected light quality, these responses (which ultimately reduce seed yield) may also manifest during early soybean establishement in weedy environments.

## 2.4. Integrated Weed Management Strategies in Soybean Cultivation

Integrated weed management is the coordinated use of multiple weed control strategies in a single weed management program while enhancing control of specific weed problems (Jabran and Chauhan 2018; Knezevic et al. 2017). Four major categories of weed management that may be combined to implement an integrated weed management program are biological, mechanical, cultural and chemical weed control. Biological tools refer to the use of biological organisms, such as livestock or insects to manage weeds. Cultural tools include, for example, time of seeding, extended crop rotation, improved fertility management, crop row spacing, seeding rate, cover cropping and competitive cultivars which can be used to improve the ability for the crop to compete with weeds and withstand weed interference. Chemical tools refer to the use of agro-chemicals, such as herbicides to control weeds, while mechanical tools can be defined as the use of machinery to physically disrupt weed life cycles (Owen et al. 2015).

Historically, many crop producers have depended heavily on a few dominant weed management tools, such as herbicides, thereby causing weeds to adapt and avoid management using these tools. Due to the high diversity and strong survival strategies present in many weed species, the use of a single weed control tactic is not feasible or sustainable. Some of the general principles of an integrated weed management program include: (i) the proactive use of appropriate agronomic tools to prevent weeds before they start to grow (ii) help the crop to compete with weeds, and (iii) use appropriate practices that keep weeds off balance (Knezevic et al. 2017). In contemporary agriculture, the evolution of herbicide-resistant weeds pose a significant issue in many agricultural fields due to over usage of herbicides that have only short-term success. Therefore, sustainable

and integrated weed management is required to overcome severe weed-crop competition and achieve effective long term weed management (Kruger and Vieira 2017). This is perhaps even more important in relatively uncompetitive crops like soybean.

### *2.4.1. Chemical Tools*

Since the mid-1900s, the use of herbicides has been the predominant means of weed control, particularly in developed countries. Introduction of Herbicide-Resistant Crops (HRCs) further expanded herbicide options for non-selective weed control post-emergence in several field crops. As an example, many HRCs, including soybean, corn, and canola, are resistant to glyphosate and/or glufosinate-ammonium (Takano and Dayan 2020) and most crop producers in the United States and Canada have willingly integrated HRCs into their weed management portfolios. The use of herbicides can have many advantages, including mitigating weed infestations through pre-emergence application, activity on a wide range of weed species, reduced risk of damage to crop roots via physical disturbance, translocation to root systems resulting in effective perennial weed control, reduced labour, and increased time efficiencies (Timmons 1970). Regardless of these benefits, herbicide resistance evolution in weeds represents a significant threat to effective chemical weed control (Powles 2008). Therefore, the use of herbicides alone would not be an ideal solution for an effective weed management strategy for soybean cultivation.

### *2.4.2. Cultural Tools*

Cultural weed control can be simply defined as any technique that supports field conditions in which weeds are less likely to establish and continue their development. This form of non-chemical weed management covers a wide range of agronomic practices from crop variety selection to land preparation to harvest and post-harvest processing (Gunsolus 1990). Cultural weed management is commonly implemented among most crop producers (knowingly and unknowingly) and, thus it plays a pivotal role in weed management. As soybean is a less competitive crop, weed management is very important to attain full yield potential. The critical period of weed removal was earlier in soybean, which were planted in 76 cm rows compared with 19 cm rows (Knezevic et al. 2003). Therefore, post-emergence herbicide application potentially can be more effective in soybean grown in narrow rows compared with wide rows (Knezevic et al. 2003).

Cultural practices include, crop rotation and the manipulation of crop variety, row spacing, or seeding date to improve the competitive ability of a crop over weeds (Rosset 2020). Soybean row spacing affects nutrient uptake, and results in greater light interception earlier in the season, plant growth, dry matter accumulation and yield (De Bruin and Pedersen 2008). A study which assessed the interference of redroot pigweed and green foxtail with soybean at different densities and row spacing showed that under weedy conditions, soybean growth and yield were increased and weed growth was decreased in narrow rows compared with wide rows (Orwick and Schreiber 1979). Narrow row grown soybeans can reduce growth of weed seedlings by inhibiting seed germination of later emerging cohorts (Batlla and Benech-Arnold 2014) and providing less light to weeds beneath the crop canopy. This resulted in less growth of velvetleaf,

spurred anoda [*Anoda cristata* (L.) Schltdl.] and Rhodes grass (*Chloris gayana* Kunth.) by decreasing aboveground biomass, leaf area and seed production (De Bruin and Pedersen 2008). Crotser and Witt (2000) identified that Eastern black nightshade (*Solanum Ptycanthum* Dun.) growth and fruit production decreased by 50% when soybean was grown in narrow rows (38 cm) compared with wide rows (76 cm). Soybean grown under high densities in wide rows creates non-uniform soybean spatial arrangement, which can result in intraspecific competition and self-thinning. Self thinning in wide row soybean can result in reduced stand densities and lower yield (Van der Werf et al. 1995). However, soybean production in narrow rows more-readily maintains stand uniformity resulting in greater yield.

Appropriate seeding rates are an important cultural tool which helps to produce a healthy, vigorous, uniform soybean crop, thereby facilitating competition with weeds. Greater plant densities help to increase soybean LAI resulting in greater light interception (Edwards and Purcell 2005). Lower plant densities diminish the competitiveness of soybean with weeds creating greater reliance on herbicides for effective weed management (Arce et al. 2009). This tool can lead to diminished herbicide effectiveness through greater selection pressure for herbicide-resistant weed biotypes. Increasing soybean plant density helped to decreased weed density and biomass production, and this effect was more pronounced with wider row spacing. For example, Rich and Renner (2007) reported that increasing soybean population density from 185,000 to 432,000 seeds $ha^{-1}$ in wide rows (76 cm) decreased Eastern black nightshade density and aboveground biomass by 57% and 68%, respectively, but the effect was not significant in narrow-seeded (19 cm) soybean. Geddes and Gulden (2018) also reported that increased

soybean plant density from 420,000 and 630,000 plants $ha^{-1}$ had no significant effect on aboveground biomass of volunteer canola when soybean were grown in narrow (19 cm) rows.

Most producers opt for reduced soybean seeding rates due to the high cost of soybean seed (DeWerff et al. 2014). Norsworthy and Frederick (2002) observed that the recommended seeding rate of GR soybean can be decreased without negatively affecting seed yield under weed-free conditions. Kratochvil et al. (2004) observed that increasing seeding rate from 345,000 to 432,500 plants $ha^{-1}$ had no significant effect on seed yield in soybean under weed-free conditions, and the lower seed cost increased profit ranging from \$14 to \$28 $ha^{-1}$. The competitive ability of soybean can vary among cultivars, suggesting that cultivar selection can be an important component of an integrated weed management program. In soybean, maturity group is the only trait identified historically as having a direct impact on weed competition (Place et al. 2011). Prior to using chemical herbicides, crop producers in the southern United States used late maturing soybean cultivars with a long growing season to maintain ground cover. The ability for soybean to grow vegetatively for a long duration helps shade weeds beneath the crop canopy resulting in delayed weed seed production (Place et al. 2011; Rose et al. 1984). Nevertheless, breeders could potentially select soybean genotypes which have desirable characteristics such as LAI, plant height, and canopy volume that are also related to weed suppression (Norsworthy and Shipe 2006). Faster soybean groundcover results in greater weed suppression by reducing light interception to lower ground levels (Norsworthy and Shipe 2006).

Crop producers may use cover crops to reduce soil erosion and post-season capture of plant available nutrients, and this practice can also aid in weed suppression. Cover crops supress weeds by directly competing for space, light, water and nutrients, and indirectly by releasing allelopathic compounds or providing a physical barrier to weed establishment (Proctor 2021). However, weed suppression by cover crops is not always consistent and depend on environmental factors, biomass of the cover crop, presence of weed species, and the management practices used (Proctor 2021). Cover crops can be established with or without a main crop in different ways as a living mulch or smother crops, shoulder season cover crops (between cash crops) and full season cover crops (in place of a cash crop). In each case, cover crops provide ground cover when the main crop is not present, which can improve soil quality parameters, supress weeds through competition, shading or releasing allelopathic chemicals, and also protecting the soil surface from water or wind erosion (Sarrantonio and Gallandt 2003).

Fall rye is often grown as a cover crop prior to soybean production due to the complementary nature of the crop cover and soybean growth and development. It has been identified as a good cover crop in cool season production systems due to its winter hardiness and ability to regrow in the spring resulting in high early spring biomass (Ateh and Doll 1996). Fall rye is often planted in early fall, and seedlings grow, in general, up to 15-20 cm prior to winter freeze-up. During the winter period, the belowground plant parts (roots including crown region) remain alive. With increasing temperatures the following spring, the fall rye begins to regrow and accumulate biomass prior to termination of the cover crop before planting the cash crop. Under this system, the fall rye cover crop will remain alive and will help to directly compete with winter annual weeds

(Cornelius and Bradley 2017). Fall rye mulches have the ability to inhibit weed growth by intercepting light before it reaches weeds near the soil surface, resulting in a physical barrier to weed development (Teasdale and Mohler 2000). Teasdale and Mohler (1993) demonstrated that a rye cover crop limits both light and temperature that weed seeds often require for initiation of germination. A fall rye cover crop releases allelochemicals to the rooting zone that help to suppress neighboring weeds (Barnes and Putnam 1987). Phytotoxic benzoxazinones are major allelochemicals that accumulate in young tissues of fall rye, and their amount varies depending on the environment and fall rye cultivar (Tabaglio et al. 2013). Furthermore, there is a direct relationship between the amount of rye cover crop biomass and weed suppression, and Teasdale and Mohler (2000) described that most annual weeds can be suppressed up to 75% when rye mulch biomass exceeds 8,000 kg $ha^{-1}$ with a mulch thickness of >10 cm. However, the method and timing of rye cover crop termination have considerable impact on the effectiveness of weed suppression in no-till cropping systems (Creamer and Dabney 2002). Mirsky et al. (2011) identified that a delay in cereal rye termination caused increased cover crop biomass and decreased annual weed density.

Growing a fall rye cover crop for weed suppression prior to soybean production has been the focus of several research studies. Cornelius and Bradley (2017) demonstrated that the effects of eight winter annual cover crops, including fall rye, on winter and summer annual weed emergence in soybean cultivation in Columbia and Moberly, Missouri. Their results suggested that fall rye reduced early season waterhemp emergence by 35% compared to without a cover crop (Cornelius and Bradley 2017). One potential, yet understudied, mechanism through which a fall rye cover crop can supresses weeds is

through uptake of soil nitrogen, making it less available to nitrophilic weeds (Wells et al. 2013). Since rye mulch has a high C:N ratio, it can promote nitrogen immobilization in low nitrogen environments, leaving nitrophilic weeds nitrogen-deprived (Wells et al. 2013). Smith et al. (2011) reported that high rye biomass reduced weed competition in roller-crimped soybean due to nitrogen immobilization driven by the rye mulch residue. Therefore, nitrogen immobilization by the rye cover crop could play a role in weed suppression through nitrogen deprivation.

Crop rotation is the cultural tool of growing a sequence of plant species over time on the same land (Bullock 1992). Crop rotations may be diversified by growing different plant species, such as grasses and broadleaves, and also different life cycles, such as annuals, biennials, perennials and winter annuals (Bullock 1992). However, the diversity of crops grown in rotation has been reduced in most parts of the North America over the past 50 years due to the introduction of chemical fertilizers, herbicides and other pesticides. These shorter crop rotations have led to decreased soil Kratochvil OM, degraded soil physical characteristics like soil aggregate stability, bulk density, increased soil erosion and reduced water infiltration rate (Bullock 1992).

Soybean is a nitrogen fixing legume and when grown in rotation with other crops, such as corn and wheat, it contributes to increased crop yield, improved soil structure, maintenance of soil moisture and crop residue breakdown (Bhowmik and Doll 1982). The soybean-corn rotation is one of the most common rotations in the Midwestern United States. From a 10-year crop rotation study in Minnesota, Crookston et al. (1991) found that the 3$^{rd}$ year of continuous soybean monoculture showed a significant decrease in seed yield (16-19%) compared to that of soybean rotated annually with corn. Results also

showed that the seed yields of the 2nd year continuous soybean were equal to the yields of soybean that rotated annually with corn, suggesting that a reduction in soybean seed yield occurs after two years of continuous production of the crop. However, soybean-corn rotations have high risk of selection for herbicide-resistant weeds due to similar herbicide resistance traits integrated into these crops. Increasing the diversity of crop rotations with non-HRCs could help reduce selection pressure for the development of resistance to non-selective herbicides like glyphosate or glufosinate-ammonium.

*2.4.3. Mechanical Tools*

Mechanical weed control can be defined as the physical removal or disruption of weeds by mechanical equipment before planting the main crop or during the crop growing season (Hussain et al. 2018). Mechanical practices include tillage, hoeing, hand weeding, digging, mowing, burning, flooding, mulching, inter-row cultivation and harvest weed seed control (Rueda-Ayala et al. 2010).

Hand weeding can also be carried out by physical removal or pulling out of weeds by hands or knives. However, many weed species can regrow from root segments that are left in the soil. Therefore, for this method to be effective the entire root system should be removed from the soil (Mohler et al. 2001). With the size of contemporary farming operations in North America, the use of hand weeding across broad-acre crops is labor intensive and not economical.

Mowing can be used to suppress weeds in a variety of crop and non-crop areas. Repeated mowing helps to minimize the competitive ability of weeds, diminish carbohydrate

reserves in the roots, and can mitigate seed production (Hussain et al. 2018). However, successful mowing depends on the target weed species, timing and frequency.

Mulching can be used over relatively small areas to cover the soil with materials, such as straw, saw dust, bark dust, paper, plastic sheets or polyethylene. However, most perennials cannot be controlled using mulching because it can provide a favorable environment for weed growth (Kviklys et al. 2004).

Another successful mechanical weed control method is harvest weed seed control (Walsh et al. 2018). It involves collecting or destroying weed seeds at the time of grain harvest and preventing their entry back into the soil seedbank through various methods of destruction, removal or concentration. This control strategy is only successful for weeds that retain most of their seeds at the time of crop harvest (Broster et al. 2016).

Tillage remains the most implemented strategy of mechanical weed management. There are several production systems implemented in North America that vary in the degree to which tillage is implemented, including: conventional tillage, minimum tillage, and zero/no-tillage. With conventional tillage, most or all of the plant residues on the soil surface are buried within the soil, often leaving the soil exposed to wind and water erosion. In reduced tillage, about 30% of the soil remains covered with plant residues. In no-tillage, no soil disturbance takes place outside that of the seeding operation (Heatherly 2020). No-tillage systems often increase reliance on herbicides for pre-plant weed control, which can lead to greater selection for herbicide-resistant weeds. Farmer et al. (2017) compared the effect of three tillage systems on season-long emergence of *Amaranthus* species in glufosinate-resistant soybean and showed 62%, 67% and 73% of *Amaranthus* species reduction in conventional, minimum and no-tillage systems,

respectively. Weed dry matter absent of rotary hoeing was 1859 kg $ha^{-1}$ while soybean yield was 955 kg $ha^{-1}$, however, timely rotary hoeing reduced weed development to 529 kg $ha^{-1}$and increased soybean yield to 1096 kg $ha^{-1}$ (Lovely et al. 1958).

Kochia can be one of the major problematic weeds in western soybean production, and tillage can help to reduce kochia populations (Sbatella et al. 2019). Kochia emerges from shallow depths in the soil and is most commonly found in no-till fields. Tillage can bury kochia seeds at soil depths from which the species fails to emerge, resulting in reduced emergence of kochia plants. However, soil disturbance, as a result of tillage, can also bring new weed seeds near the soil surface resulting in a stimulation of weed emergence (Knezevic et al. 2017). For example, spring soil disturbance promoted the emergence of volunteer canola on average from 3% to 11% of the spring seedbank (Geddes and Gulden 2017).

Tillage can increase soil erosion and result in higher fuel and labour costs (Lowrance 1989). There are many advantages of conservation tillage systems including, reduce soil erosion and water run-off, increased soil OM, water holding capacity, water infiltration and soil organisms (Baumhardt and Lascano 1996; Bruce et al. 1992). Therefore, crop producers should weigh all of the potential risks, costs and benefits before making a decision on the implementation of tillage for weed management.

### *2.4.4. Biological Tools*

Biological weed control comprises the use of biological agents or natural predators to control weeds. There are two types of biological weed control methods: (i) classical and (ii) inundative biological control (Andres 1982). Classical biological control uses natural enemies of the pest that originate from the pest's native range. This strategy can be used to control weeds in areas with low intensity management, such as preserved natural areas, some waterways, forests and rangelands. Often the intensity of crop production can disrupt the life cycles of biocontrol agents, rendering classical biological control less effective in these disturbed agroecosystems. Inundative biological control uses natural enemies or agents applied directly to the target pest (e.g., a bio-herbicide) often aiding in rapid reduction in the pest population (Frick 2005). With modern technology, pathogens may also be used to alter specific genes to control growth, seed set, flowering and competitiveness of weeds in the future (Bruckart 2020).

Biocontrol is not used often for weed control in Canadian soybean fields, because most biological control agents cannot survive the cool climate. Moreover, some biological agents can attack other important non-target species. For example, Canada thistle [*Cirsium arvense* (L.) Scop.] is a weed species that is closely related to other native thistles and biological agents can feed on Canada thistle and also attack other native (and perhaps beneficial) thistle species (Fleury 2007 ).

## 2.5. Developing an Integrated Weed Management System for Irrigated Soybean in Alberta

Historical production of soybean in Alberta has remained low, however, recent development of early maturing soybean varieties may facilitate production of this crop in some regions of the province. Soybean is a warm-season C3 crop and it takes about 110-125 days or 2300 CHU to reached maturity (Thai 2018). Thus, the length of the growing season in many areas of Alberta is a predominant barrier to expansion of soybean production in the province. Soybean production under irrigation in southern Alberta recently increased from 1495 ha in 2011 to 8000 ha in 2020 due to the development of very early maturing, glyphosate-resistant and cold-tolerant varieties (MG 00 and 000) (Thai et al. 2019). Alberta Agriculture and Forestry's Crop Diversification Centre (CDCS) in Brooks evaluated new varieties for their productivity and adaptability to irrigated lands in southern Alberta in recent years (King 2017). When comparing soybean production with other Canadian provinces, including Manitoba and Ontario, these newly introduced soybean genotypes have helped to conquer shorter growing seasons and lower heat units prevailing areas in southern Alberta (Statistics Canada 2022).

Changes in the production area of crops within a region can also cause changes in weed pressures. In southern Alberta, weeds grow more rapidly and compete aggressively to obtain water and nutrients compared with soybean. Since soybean exhibit low competitive ability compared with other crops grown in this region, increased production of the crop and reliance on herbicides for weed control could risk increased selection pressure for herbicide-resistant weeds (Thai 2018). Application of cultural weed management tools, such as increased seeding density, growing competitive varieties,

implementing cover crops and using narrow row spacing can help improve the performance of other weed management tools like tillage or herbicides (Stoller et al. 1987).

Most soybean producers in southern Alberta grow short season soybean cultivars at recommended seeding densities (400,000 target plants $ha^{-1}$) (Geddes and Gulden 2018), and at narrow row spacing (Blackshaw et al. 2008). Soybean canopy closure can be hastened with narrow row spacing (De Bruin and Pedersen 2008; Wax and Pendleton 1968), increased seeding rates (Norsworthy and Shipe 2006) and selection of soybean varieties with traits that have rapid canopy development (Bussan et al. 1997). Due to the significant increase in soybean seed prices, most crop producers tend to grow lower soybean rates than those that are optimal for weed competition. Previous studies clearly showed that soybean cultivated at low seeding density (400,000 plans $ha^{-1}$) did not affect soybean yield in weed-free environments (Norsworthy and Frederick 2002). This scenario was supported by Norsworthy and Oliver (2001), who suggested that the savings in seed costs were greater than the expense for an extra glyphosate application. Past studies have demonstrated the potential of a fall rye cover crop for weed management in soybean. Fall rye is a competitive cover crop that is often paired with soybean production in the United States. Fall rye mulch can create a weed suppressive mat that helps minimize weed infestations in soybean but the efficacy of this tool is often dependent on the local environment (De Bruin et al. 2005).

Integrating multiple cultural, mechanical, and biological weed management practices can result in additive or synergistic efficacy for weed control. This approach has been associated with using many little hammers for ecological weed management that, if done

right, can be equivalent to one big hammer (i.e., herbicides) (Liebman et al. 1997). Therefore, based on previous research, it is hypothesized that integrating a competitive (bushy-type) soybean cultivar grown in narrow (23 cm) rows at high (600,000 plants $ha^{-1}$) target plant densities following a fall rye cover crop will increase the ability for soybean to compete with and withstand competition from weeds under irrigated conditions in southern Alberta compared with industry standard production practices.

# 3.0. MATERIALS AND METHODS

## 3.1. Experimental Sites

The effects of soybean row spacing, target plant densities, cultivar and cover crop on the ability for soybean to compete with and withstand competition from weeds were evaluated at the Agriculture and Agri-Food Canada, Lethbridge Research and Development Centre located near Lethbridge, AB. The experiment was conducted in 2020 (49.69°N, −112.84°W; 917 m Elevation), and repeated in 2021 (49.62°N, -112.82°W; 917 m Elevation). Soils of the first experimental site were classified as dark brown chernozem with clay loam texture, 3.7% OM content and pH 7.8, while the second experimental site was classified as dark brown chernozem with clay loam texture, 2.6% OM content and pH 8.2 (Table 3.1).

Table 3.1: Soil characteristics and nutrient status in spring prior to seeding of soybean at each experimental site near Lethbridge, AB in 2020 and 2021.

| Year | Cover crop | Sample depth | Soil characteristics[a] | | | | |
|---|---|---|---|---|---|---|---|
| | | | N | P | K | Organic matter | pH |
| | | cm | | kg/ha | | % | |
| 2020 | Fall rye | 0-15 | 8 | 280 | 1633 | 3.7 | 7.8 |
| | | 15-60 | 13 | | | | |
| | Absent | 0-15 | 10 | 247 | 1636 | 3.6 | 7.7 |
| | | 15-60 | 62 | | | | |
| 2021 | Fall rye | 0-15 | 9 | 15 | 562 | 2.9 | 7.6 |
| | | 15-60 | 18 | | | | |
| | Absent | 0-15 | 12 | 16 | 603 | 2.6 | 7.8 |
| | | 15-60 | 24 | | | | |

[a]Abbreviations : N, $NO_3$-N ; P, $P_2O_5$ ; K, $K_2O$ .

### 3.2. Experimental Design and Treatment Structure

The field experiment consisted of a full factorial treatment structure including five factors. The main plots consisted of all combinations of four factors, including soybean row spacing [23 cm (9") vs. 69cm (27")], target plant densities [400,000 vs. 600,000 plants $ha^{-1}$ (equivalent to 100% and 150% of recommended soybean seeding rates for this region, respectively)], soybean cultivar (Slender vs. Bushy) (cultivar names not provided to protect identification according to material transfer agreements), and fall rye cover crop (presence vs. absence) (Table 3.2). These sixteen treatments were arranged in a Randomized Complete Block Design (RCBD) with four replications at each of two different irrigated sites in 2020 and 2021. The main plots (17 m × 2.5 m) were split in half (front vs. back half of each experimental replication) creating a "split-block" or "strip-plot" design.

In certain treatments, a fall rye cover crop was seeded in early September in 2019 and late September in 2020 after harvesting of the preceding spring wheat crop (Table 3.3). The fall rye (cv. 'Daniello') was seeded at a rate of 400 viable seeds $m^{-2}$ in rows spaced 19 cm apart using a double disc seeder (Fabro Ltd., Swift Current, SK). Starter fertilizer equivalent to 6 kg N $ha^{-1}$ and 30 kg $P_2O_5$ $ha^{-1}$ was applied as monoammonium phosphate within the fall rye cover crop seed rows to facilitate fall establishment. Immediately prior to cover crop termination and soybean seeding in late May, fall rye aboveground biomass was estimated by harvesting 1 m of two adjacent rows in two locations (back and front) of each plot. The fall rye biomass data were collected only from treatments 1 and 5.

Table 3.2: Treatment combinations that included in the study excluding the weedy vs. weed-free split blocks.

| Treatment number | Soybean cultivar[a] | Row spacing | Target plant density (plants ha$^{-1)}$ | Cover crop[b] |
|---|---|---|---|---|
| 1 | Slender | 23 cm | 400,000 | Fall rye |
| 2 | Slender | 23 cm | 400,000 | Absent |
| 3 | Slender | 23 cm | 600,000 | Fall rye |
| 4 | Slender | 23 cm | 600,000 | Absent |
| 5 | Slender | 69 cm | 400,000 | Fall rye |
| 6 | Slender | 69 cm | 400,000 | Absent |
| 7 | Slender | 69 cm | 600,000 | Fall rye |
| 8 | Slender | 69 cm | 600,000 | Absent |
| 9 | Bushy | 23 cm | 400,000 | Fall rye |
| 10 | Bushy | 23 cm | 400,000 | Absent |
| 11 | Bushy | 23 cm | 600,000 | Fall rye |
| 12 | Bushy | 23 cm | 600,000 | Absent |
| 13 | Bushy | 69 cm | 400,000 | Fall rye |
| 14 | Bushy | 69 cm | 400,000 | Absent |
| 15 | Bushy | 69 cm | 600,000 | Fall rye |
| 16 | Bushy | 69 cm | 600,000 | Absent |

[a]Bushy = highly branched, round leaf structure, relative maturity 00.3, CHU 2375; [a]Slender = fewer branches, lanceolate leaf structure, relative maturity 000.9, CHU 2275. [b] fall rye (cv. Daniello).

Table 3.3: Dates of major cultural practices conducted at the two experimental sites near Lethbridge, AB in 2020 and 2021.

| | Important dates | | |
|---|---|---|---|
| | Year | Seeding | Emergence |
| Fall rye | 2019 | 6,September | - |
| | 2020 | 21,September | - |
| | 2021 | - | - |
| Soybean | 2020 | 27,May | 12,June |
| | 2021 | 31,May | 17,June |

During the growing season, herbicides were applied both pre-plant and post-emergence. Pre-plant herbicide treatment included 900 g ae $ha^{-1}$ glyphosate (Roundup Weather MAX®, Bayer CropScience Canada Inc., Calgary, AB) + 28 g ai $ha^{-1}$ carfentrazone (Aim® EC , FMC of Canada Limited, Mississauga, ON) applied to the entire experiment area one or two days prior to seeding of the crop. The pre-plant herbicide treatment served to manage existing weeds and also terminate the fall rye cover crop. The weed-free sub/strip-plots received two post-emergence applications of glyphosate at 900 g ae $ha^{-1}$, whereas the weedy sub/strip plot received no post-emergence herbicide. This created weedy and weed-free split-blocks (7.5 m × 2.5 m sub-plots) used to assess the treatments in the presence and absence of weed competition (factor 5). The first and second rounds of post-emergence herbicide were applied at soybean stage VC–V1 and V3–V4, respectively.

In 2020 only, canola (cv. 'DKTF92SC'; seed treated with Acceleron®; Bayer CropScience Canada Inc., Calgary, AB), representing volunteer canola, was broadcasted on the surface of the weedy sub/strip-plots, perpendicular to the soybean rows at a density of 80 seeds $m^{-2}$ to establish a uniform weed pressure. A consistent density of volunteer canola was broadcasted to ensure even weed infestation throughout the experimental area. This was not repeated in 2021 for reasons outlined in Section 4.

Soybean final plant density is defined by the seeding rate, but other factors could affect the plant establishment and survival. Thus, seed quality (viability and germination rate) and emergence mortality (determined by soil temperature, moisture, weather conditions as well as pest and management practices) affect the relationship between the achieved and the target plant density. Two soybean target densities were adjusted based on seed

viability and germination rate based on petri dish seed germination tests, assuming soybean survival rate was 75%. A Fabro double disk drill (Fabro Ltd., Swift Current, SK) was used to seed soybean at a depth of 2–3 cm.

The soybean seed was pre-treated with Acceleron®; (Bayer CropScience Canada Inc., Calgary, AB) and liquid inoculant (*Bradyrhizobium japonicum*), and it was double inoculated with TagTeam® granular soybean inoculant (10.6 kg $ha^{-1}$ for 23 cm rows and 4.0 kg $ha^{-1}$ for 69 cm) placed with the seed. Soybean were seeded on May 27 and 28, 2020 and May 31, 2021 (Table 3.3). No fertilizer was added during soybean planting.

All plot were sprinkler irrigated with a linear move irrigation system (Valley 3000; Valmont Industries, Inc., Valley, NE) based on rainfall and evapotranspiration rates. The irrigation system delivered 25 mm of irrigation evenly over the experiment area during each use (Table 3.4).

Table 3.4: Mean monthly precipitation and air temperature during the growing season at two experimental sites near Lethbridge, AB in 2020 and 2021.

| Month | Precipitation[a] (mm) | | | Mean air temperature[a] (°C) | | | Irrigation (mm) | |
|---|---|---|---|---|---|---|---|---|
| | 2020 | 2021 | 30-Yr Avg[y] | 2020 | 2021 | 30-Yr Avg [y] | 2020 | 2021 |
| May | 64.1 | 27.2 | 23 | 11.7 | 10.4 | 11.1 | | |
| June | 109 | 11.7 | 84 | 15.1 | 18.4 | 15.4 | 50 | 100 |
| July | 25.2 | 6.6 | 41 | 17.7 | 21.2 | 18.4 | 50 | 125 |
| August | 16.8 | 29.2 | 41 | 18.5 | 18 | 17.9 | 75 | 125 |
| September | 23.1 | 15 | 41 | 13.7 | 14.7 | 13 | | 50 |
| October | 18.8 | 24.8 | 21 | 4.4 | 7.7 | 6.6 | | |

[a] Data was collected from Alberta Climate Information Service (ACIS, 2016); [y] 30-yr average (1981– 2010).

## 3.3. Data Collection

All data were collected during the soybean phase of the experiment.

### *3.3.1. Soil Sampling*

Soil samples were collected from both fall rye present and absent treatments prior to planting the soybean crop (Treatments 1, 2, 5 and 6 in Table 3.2). These treatments were sampled because they included the combination of the two factors most likely to impact soil nutrient composition (i.e., cover crop and soybean row spacing). They also matched those sampled for the other environmental measurements (Sections 3.3.2.1, 3.3.2.2, and 3.3.2.3). Soil samples were analyzed separately for soil nutrient status. One soil sample was collected in each of the four replicate plots per treatment at two depths (0–15 cm and 15–60 cm). The soil samples collected from each replicate were composited for each combination of treatment and depth, and soil macro-nutrients (N, P, and K), OM, pH and texture were analyzed by Down to Earth Labs (https://downtoearthlabs.com/; Lethbridge, AB) (Table 3.1).

### *3.3.2. Environmental Measurements*

Surface soil temperature, volumetric water content, and nitrate-nitrogen supply rates were evaluated in treatments 1, 2, 5 and 6 only (see Table 3.2). These variables were evaluated as supplemental information that could be used to explain the impact of fall rye cover cropping and soybean row spacing on weed suppression. Availability of funds, and extensive labor requirements for these supplemental measurements, warranted their implementation in a subset of the treatment combinations.

*3.3.2.1. Soil Temperature*

Soil temperature was measured within the seed row at 5 cm soil depth using DS1921G-F5 Thermocron iButton® data loggers (Embedded Data Systems, LLC, Lawrenceburg, KU) scheduled to record temperature every two hours from soybean seeding (late-May) to harvest (mid-October). The iButtons® were installed immediately after seeding of the crop. A single iButton® was installed in the center of the weed-free sub-plots (treatments 1, 2, 5 and 6 in Table 3.2) in each of the four replicates. These treatments were chosen because the fall rye cover crop and soybean row spacing factors were expected to have greater influence on soil temperature than soybean cultivar and plant density. A soil knife was used to place each iButton® at 5 cm depth, then the soil and surface residue were replaced around the installation site. The iButtons® were removed after soybean harvest and temperature data were downloaded using the "OneWireViewer" software (Embedded Data Systems, LLC, Lawrenceburg, KU).

*3.3.2.2. Soil Moisture*

Soil moisture was measured as volumetric water content ($m^3$ water $m^{-3}$ soil) using a PR2/4 Profile Probe connected to a DL6 data logger for continuous measurement, and a HH2 Readout Meter for point estimates (Delta-T Devices Ltd., Cambridge, UK). The PR2/4 Profile Probe uses capacitance sensors to measure volumetric water content at 10, 20, 30 and 40 cm depths in the soil profile. Volumetric water contents were measured only in the weed-free sub-plots to provide an estimate of water that would otherwise be available for uptake by weeds (treatments 1, 2, 5 and 6 in Table 3.2). One PR2/4 access tube was installed in the centre of each weed-free sub-plot (all four replicates of the four treatments) centered between two soybean rows using the installation kit and following

the installation instructions described by Delta-T Devices Ltd (https://deltat.co.uk/product/pr2/, Cambridge, UK). Beginning at seeding, and at 2-week intervals thereafter, the profile probe was detached from the DL6 data logger and used along with the HH2 Readout Meter for point estimates of volumetric water content in all 16 sub-plots (4 treatments × 4 replicates). Point estimates consisted of taking four readings per access tube (one in each cardinal direction) of each sub-plot and averaging the four measurements for each combination of soil depth, sub-plot, and measurement timing. The PR2/4 Profile Probe was reinstalled back in the control plot (Treatment 2) for continuous measurement following each point estimate timing.

*3.3.2.3. Surface Soil Nutrient Availability*

The nutrient availability in surface soil was measured using Plant Root Simulator (PRS®) Probes (Western Ag Innovations, Saskatoon, SK). PRS® probes consist of ion-exchange resin membranes held in plastic supports that are easily inserted into soil. The probes absorb nutrients from the soil with minimum soil disturbance. There are two types of PRS® probes, those that are positively charged to absorb anions, and negatively charged to absorb cations. Examples of nutrient anions include nitrate ($NO_3^-$), phosphate ($H_2PO_4^-$) and sulfate ($SO_4^{-2}$), while exampled of cations include ammonium ($NH_4^+$), potassium ($K^+$), calcium ($Ca_2^+$) and magnesium ($Mg_2^+$). PRS® probes were designed to be inserted vertically into the uppermost soil layer because this is arguably the most dynamic soil layer that can provide nutrients to plants of all sizes. Eight PRS® probes (four cation and four anion) were installed between the crop rows in each weed-free sub-plot for treatments 1, 2, 5, 6 in replicates one to three. The probes were exchanged every two weeks for the first 10 weeks after soybean seeding. After removing from the soil, PRS®

probes washed thoroughly with deionized water and shipped to the Western Ag Innovations (https://www.westernag.ca/innovations/; Saskatoon, SK) for nutrient analysis. While the PRS® probe were analyses covered a range of macro- and micro-nutrients, the primary interest for this research was the supply of $NO_3^-$ in the surface soil. This was based on previous research documenting an impact of a fall rye cover crop on nitrogen availability to weeds growing in subsequent soybean crops (Wells et al. 2013).

### *3.3.3. Soybean Measurements*

#### *3.3.3.1. Soybean Emergence*

The first soybean data collection took place at the VE stage. The date of soybean emergence was considered when 80–90% of the soybean cotyledons have emerged through the soil. This date was recorded and used to determine soybean emergence timing for each treatment in days after seeding.

#### *3.3.3.2. Light Interception by the Crop Canopy*

Light interception data were collected using a Line-Quantum Sensor (Model LI-191 Line Quantum Sensor, Li-Cor® Environmental Inc., Lincoln NE) at soybean stages V3, R3, and R5 in 2020, and stages V3, V5, R1, R3, and R5 in 2021. Data were collected between 1:00 and 3:00 pm, when there were no clouds in the sky to interrupt the incoming solar radiation. Photosynthetically active radiation (PAR) was measured ($\mu mol \cdot m^{-2}\ s^{-1}$) perpendicular to the soybean rows above the standing vegetation and beneath the standing vegetation at the soil surface in two spots in each weed-free sub-plot. This provided a value for total incoming PAR and PAR penetrating through the plant canopy, which would otherwise be available to weeds. Using these two measurements, light interception

data were expressed as the percentage of PAR that penetrated through the crop canopy within each weed-free sub-plot.

*3.3.3.3. Soybean Density*

Soybean density was determined at the V2 soybean stage by counting all soybean plants in 1 m length of two adjacent rows in two places diagonally across the front and back of each main plot. Soybean densities were converted to plants $m^{-2}$ based on the crop row spacing.

*3.3.3.4. Soybean Biomass*

The aboveground biomass of soybean was determined at the R5 stage by removing biomass above the soil surface from two 0.5 m lengths of soybean in each sub-plot. The number of rows sampled varied based on the soybean row spacing, where 0.5 m of three rows were sampled for the 23 cm row spacing, and 0.5 m of one row was sampled for the 69 cm row spacing. This was repeated in two spots per sub-plot located diagonally across the front and back half of each sub-plot. The two biomass collections from each sub-plot were composited, dried at 40°C, and dry weights were determined.

*3.3.3.5. Soybean Days to Maturity.*

The date of soybean maturity was recorded for each weedy and weed-free sub-plot at soybean stage R8. Soybean stage R8 referred to when soybean plants had senesced, 95% of pods were brown, seeds rattled in pods, and all leaves were abscised from the plant. The date of maturity was used to determine the number of days from soybean planting to maturity for each treatment.

*3.3.3.6. Soybean Grain Yield.*

At soybean maturity, the plots were harvested using a Wintersteiger Delta Plot Combine with direct harvest header (concave clearance 10 mm, cylinder speed 690 rpm, fan speed 1110 rpm, 12 mm sieve, Wintersteiger Inc, Saskatoon, SK). Seed samples were collected in cotton bags and dried at 40°C until weights reach equilibrium. The dried grain samples were cleaned using a Clipper O.T. seed cleaner [Lewis M. Carter Mfg. (Canada) Ltd, Saskatoon, SK]. The cleaner was equipped with a 4.76 mm by 19.05 mm slotted sieve on top and a 3.97 mm by 19.05 mm slotted sieve below the top sieve. The cleaned soybean grain samples were weighed and yield measurements were adjusted to 13.0% moisture content.

*3.3.4. Weed Measurements*

*3.3.4.1. Weed Density by Species*

Weed density was determined at soybean stage V2 by counting all weeds in each of two 0.5 $m^2$ (0.71m × 0.71 m) quadrats in front and back areas of each weedy sub-plot. The quadrats were aligned with the edge of a soybean row. Weeds were counted by species to determine the most abundant weed species present within each treatment.

*3.3.4.2. Weed Biomass*

Total weed aboveground biomass was determined following similar methodology as described for soybean aboveground biomass. The weed biomass area, however, included two 0.25 $m^2$ (0.5m × 0.5 m) quadrats within each weedy sub-plot taken from the same areas as the soybean biomass samples. The weed biomass samples from each sub-plot were composited, dried at 40°C, and dry weights were determined.

*3.3.4.3. Weed Seed Dockage*

When harvesting field plots using a combine harvester, the grain sample includes both crop grain and other contaminants. These contaminants are referred to as "dockage" because they result in dockage of the sale price for seed products based on the level of grain contamination. The total number of weed seeds collected with soybean at harvest was termed "weed seed dockage". Weed seeds were separated from soybean seed and other contaminants during cleaning of the soybean grain samples (described above). The weed seed samples were weighed to provide an estimate of weed seed production within each treatment.

### 3.4. Statistical Analysis

Data were statistically analyzed using the 'lme4' package of R version 4.0.4 [R Development Core Team 2020 (Chow et al. 2016)]. Soybean density, biomass, yield loss, and grain yield data were collected from all treatment combinations, but weed density, biomass, and seed dockage were collected only from the weedy sub-plots. Soil temperature, soil moisture, surface soil $NO_3^-$ supply rates and light penetration through the crop canopy were determined only in weed-free sub-plots. Among these measurements, soil temperature, soil moisture, and surface soil $NO_3^-$ supply measurements were conducted only in treatments 1, 2, 5 and 6, but these measurements were repeated over time.

All data were analyzed by site and by split-block (weedy vs. weed-free) due to the number of interactions included in the five-way full factorial treatment arrangement present at each site, and because initial data exploration showed significant ($P < 0.05$)

interactions with site for most response variables. For the analysis of soybean density, soybean biomass, soybean yield, soybean yield loss, weed density, weed biomass and weed seed dockage, the fixed factors were soybean target plant density, cover crop, soybean row spacing and soybean cultivar while experimental block was a random factor.

The fall rye biomass data were collected only from treatments 1 and 5 because these treatments coincide with the environmental measurements where the fall rye cover crop was present. Therefore, the linear mixed model used to analyze these data considered treatment, site, and their interaction as fixed factors and replicate nested within site as a random factor.

Soybean canopy light penetration, soil volumetric water content, and soil $NO_3^-$ supply rates were measured over time, and therefore these data were analyzed using repeated measures Analysis of Variance (ANOVA) in the MIXED procedure of SAS Studio v. 3.81 (Littell et al. 1998). Soybean canopy light interception was evaluated at specific soybean growth stages (V3, R3, and R5 in 2020, and V3, V5, R1, R3, and R5 in 2021), considering soybean cultivar, row spacing, target density, fall rye cover crop, soybean growth stage and their interactions as fixed factors and replicate as a random factor. Light penetration measurements were repeated over soybean growth stage using a first-order anti- dependence covariance structure based on minimization of the Akaike Information Criterion (AIC). Soil volumetric water content and $NO_3^-$ supply were measured every two weeks and only in treatments 1, 2, 5 and 6. Therefore, the analysis of soil volumetric water content included soybean row spacing, fall rye cover crop, soil depth, time (in weeks after planting) and their interaction effects as fixed factors while replicate was a random factor. The volumetric water content measurements were repeated over time

using a first-order autoregressive covariance structure according to minimization of the AIC. A similar model was used with a compound symmetry covariance structure to analyze the soil $NO_3^-$ supply data, but absent of the soil depth factor.

All data were examined for the assumptions of ANOVA including conformation of residuals to the normal distribution and heterogeneity of residuals. The Shapiro-Wilk test was used to assess the assumption of normality while visual inspection of residuals versus predicted values were used to assess homogeneity of variance. The "*ggstatsplot"* package in R studio used to determine whether extreme outliers were present and required further examination and/or removal.

Weed density data did not conform to the assumptions of ANOVA. Therefore, a log transformation was used to produce data with residuals that were normally distributed with homogeneity of treatment variances, and means were back transformed for presentation. *Post hoc* multiple mean comparisons were conducted using Tukey's Honest Significant Difference (HSD) ($\alpha = 0.05$).

Cumulative GDD were calculated as a measure of thermal time by subtracting the lower base or threshold temperature for soybean (10°C) (Irmak et al. 2013) from the average daily soil temperature at 5 cm depth and then summing for each day of growth using equations 1 and 2, respectively:

$$GDD_{\text{daily}} = [T_{\max} + T_{\min}/2] - T_{\text{base}} \quad [1]$$

$$Cumulative\ GDD = \sum_{i=1}^{n} GDD_{\text{daily}} \quad [2]$$

Where $T_{\max}$ is the maximum daily soil temperature, $T_{\min}$ is the minimum daily soil temperature, and $T_{\text{base}}$ is the base temperature for soybean growth and development

(10°C); $n$ is the number of days elapsed since soybean seeding, and $GDD_{\text{daily}}$ was bound to nonnegative numbers.

# 4.0. RESULTS AND DISCUSSION

## 4.1. Growing Conditions

Weather conditions varied between the years of study (Table 3.4). In 2020, precipitation during soybean establishment in June was almost ten-fold greater than 2021, and consequently greater supplementary irrigation was added in 2021. The mean air temperature in 2020 was 0.4°C lower than the 30-yr average (1981-2010) in June, and 0.6°C warmer in August, while in 2021 June was 3°C, July 2.8°C and August 0.1°C warmer than the 30-yr average (Table 3.4). Overall, the 2021 growing season was 1.8°C warmer than 2020 growing season.

## 4.2. Fall Rye Cover Crop

### *4.2.1. Biomass at Termination Timing*

Fall rye is a cold tolerant cereal grain crop that can grow well under conditions of low temperature, optimum to low fertility and low moisture (Moore et al. 2014). It grows best with ample moisture but excessive rainfall can supress subsequent vegetative growth (De Bruin et al. 2005). In this study, fall rye was selected as a cover crop by considering its winter hardiness and high biomass potential (De Bruin et al. 2005) and temporal compatibility of biomass accumulation by the time of soybean seeding. Fall rye is often paired as a cover crop with soybean because of its ability to produce high biomass by the planting of the soybean crop in early spring and also because of high allelopathic potential for weed suppression (Putnam et al. 1983). In 2019, fall rye was seeded in early September, while in 2020 it was seeded in late September (Table 3.3). In 2020, twenty times greater fall rye biomass was present at the time of cover crop termination compared

with that produced in 2021 (Figure 4.1). The main reason for lower biomass production in 2021 was likely due to water stress caused by very low precipitation in late fall and early spring when the irrigation was not available. In Pennsylvania, Mischler et al. (2010) reported that delaying of cereal rye cover crop termination by 5 to 15 days in the spring could remunerate for a delay of 30 days in cereal rye planting in the fall. They observed that when delaying termination by 10 to 20 days in the spring, cereal rye biomass doubled. Mirsky et al. (2011) further, reported that rye biomass accumulation at cover crop termination was 7,880 kg $ha^{-1}$ at the earliest planting date and 5,069 kg $ha^{-1}$ at the later planting date. Other potential reasons for lower fall rye biomass in 2021 than 2020 in the current study could be the later fall rye planting date or lower soil macro-nutrient status overall (Tables 3.1 and Table 3.3).

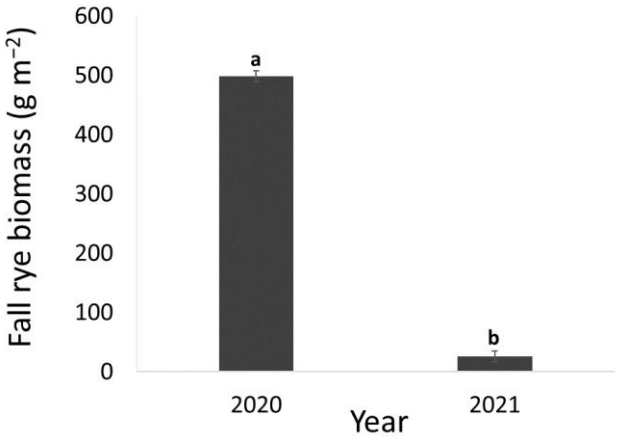



Figure 4.1: Aboveground biomass production of fall rye cover crop at termination in spring of 2020 and 2021. Different letters indicate significant differences based on Tukey's HSD ($\alpha = 0.05$). Error bars indicate ± one standard error of the means.

## 4.3. Impact of Row Spacing, Cultivar, Target Plant Density, and Cover Crop on Soybean Seedling Emergence, Biomass Accumulation, Soybean Density, Soybean Yield Loss and Seed Yield

### *4.3.1. Soybean Yield*

Crop seed yield is the most economically important parameter of agronomic production systems. The impact of soybean cultivar, row spacing, target plant density, and the fall rye cover crop on soybean seed yield varied between the two sites. Under weed-free conditions in 2020, on average, narrow row soybean resulted in 30% greater seed yield than that of the wide row soybean (Table 4.1). A similar trend was observed in 2021, where narrow row soybean had 25% greater seed yield than that of wide row grown soybean. However, the cultivar by cover crop by row spacing interaction for seed yield was significant in 2021, mainly due to the fact that the narrow row bushy-type soybean cultivar with the cover crop or narrow row slender-type soybean cultivar without the cover crop had significantly higher seed yields than those of both cultivars in wide rows (Table 4.1). In 2020, on average, soybean seeded at a target density of 600,000 plants $ha^{-1}$ with the fall rye cover crop, produced the highest seed yield (3,274 kg $ha^{-1}$) in the absence of weed interference, but this was statistically comparable to those of soybean seeded at a target density of 400,00 plants $ha^{-1}$ with the fall rye cover crop or those seeded at a target density of 600,000 plants $ha^{-1}$ without the fall rye cover crop (Table 4.1). In 2021, the highest weed-free soybean yield was observed when either the bushy-type soybean cultivar was seeded into a fall rye cover crop, or the slender-type soybean cultivar was seeded with absent of the cover crop, both in narrow rows (Table 4.1). Lehman and

Lambert (1960) observed greater yield when short-stature soybean were grown in a weed-free environment using a moderate row spacing.

Table 4.1: Effect of soybean row spacing, target plant density, cultivar and the fall rye cover crop on weed-free soybean seed yield near Lethbridge, AB in 2020 and 2021.

| ----------Seed yield (kg ha$^{-1}$) in 2020[a] ---------- | | | | | |
|---|---|---|---|---|---|
| Cover crop | Target plant density (Number of plants ha$^{-1}$) | | | Row spacing (cm) | |
| | 400,000 | 600,000 | **Mean[d]** | | |
| absent | 2,873 a | 3,107 ab | **2,990 A** | 23 | 3,497 b |
| present | 3,096 ab | 3,274 b | **3,186 B** | 69 | 2,687 a |
| **Mean** | **2,085 A** | **3,191 B** | | **Mean** | **3,092** |

| ----------Seed yield (kg ha$^{-1}$) in 2021[a]---------- | | | | | |
|---|---|---|---|---|---|
| Cover crop | Row spacing (cm) | | | | |
| | 23 | | 69 | | **Mean** |
| | slender-type[c] | bushy-type[c] | slender-type | bushy-type | |
| absent | 2,450 c | 2,367 bc | 1,896 a | 1,957 ab | **2,168 A** |
| present | 2,124 abc | 2,446 c | 1,963 b | 1,713 a | **2,062 B** |
| **Mean** | **2,287 A** | **2,407 B** | **1,930 A** | **1,835 B** | |

[a] Within effect groupings, different lower case letters indicate significant differences based on Tukey's HSD ($\alpha$=0.05). [b] Abbreviations: present, with fall rye; absent, without fall rye. [c] Soybean cultivars. [d] Different upper case letters indicate significance deference between main effect means based on Tukey's HSD ($\alpha$=0.05).

The treatment factors that resulted in the greatest soybean yield under weed-free conditions also resulted in the greatest soybean yield under weed interference in 2021 (Table 4.2). In 2020, the presence of the fall rye cover crop reduced soybean yield under weed interference by 28% compared with no cover crop (Table 4.2). In contrast, the higher soybean target density increased soybean yield under weed interference by 19% (Table 4.2). Research conducted in Urbana, Illinois, found that soybean yield increased

and weed biomass decreased as row spacing decreased from 100 to 25 cm (Wax and Pendleton 1968). Greater soybean yield under weed interference as a result of increased soybean seeding density was likely due to greater light interception by the soybean canopy and less weed competition, while reduced yield in the presence of the fall rye cover crop was likely due to higher densities of volunteer canola (described in section 4.4.1). Similarly, Oswaldo et al. (2009) observed lower soybean yields at 240,000 seed $ha^{-1}$ compared with 420,000 seed $ha^{-1}$ at three locations in Iowa; and with 300,000 seed $ha^{-1}$ at two locations. However, in the current study, rainfall was 50% below the 30-year average during pod-fill in August of both years (Table 3.4), which could have limited the benefit of higher soybean target densities in yield maximization.

Table 4.2: Effect of soybean row spacing, target plant density, cultivar and the fall rye cover crop on soybean seed yield under weed interference near Lethbridge, AB in 2020 and 2021.

| ----------Seed yield (kg $ha^{-1}$)[a] in 2020---------- | | | | | |
|---|---|---|---|---|---|
| Target plant density (Number of plants $ha^{-1}$) | | | Cover crop | | |
| 400,000 | 600,000 | **Mean[d]** | absent | present | **Mean** |
| 1,019 a | 1,214 b | **1,117** | 1,300 b | 933 a | **1,117** |

| ----------Seed yield (kg $ha^{-1}$)[a] in 2021---------- | | | | | |
|---|---|---|---|---|---|
| Row spacing (cm) | Cover crop[b] | | | | |
| | absent | | present | | |
| | slender-type[c] | bushy-type[c] | slender-type | bushy-type | **Mean** |
| 23 | 1,808 c | 1,690 bc | 1,462 abc | 1,862 c | **1,696 B** |
| 69 | 1,054 a | 1,193 ab | 1,182 ab | 1,048 a | **1,119 A** |
| **Mean** | **1,431** | **1,442** | **1,322** | **1,455** | |

[a] Within effect groupings, different lower case letters indicate significant differences based on Tukey's HSD (α=0.05). [b] Abbreviations: present, with fall rye; absent, without fall rye. [c] Soybean cultivars. [d] Different upper case letters indicate significance deference between main effect means based on Tukey's HSD (α=0.05).

*4.3.2. Soybean Days to Maturity*

The date of seeding soybean impacts the timing of crop maturity. However, the effect of planting date on yield can be vary among years mainly due to environmental conditions, such as precipitation and temperature (Hu and Wiatrak 2012). Therefore, soybean maturity can be described in various ways, including MG (a rating based mainly on day length, but also influenced by temperature), the number of CHU needed to take the variety to maturity, or the number of frost-free days needed for maturity (Ort et al. 2022).

In the current study, soybean was seeded on May 27$^{th}$ and 28$^{th}$ in 2020 and May 31$^{st}$ in 2021 and on average, it took 16 days for seedling emergence in both years (Table 3.3). In 2020, the soybean planted in narrow rows matured one day earlier than in wide rows (Table 4.3). The slender-type soybean cultivar matured 3-4 days earlier than the bushy-type soybean cultivar in both years of the study (Table 4.3). In 2021, the cover crop delayed soybean maturity by one day compared with the absence of a cover crop. While a one-day difference in soybean maturity was statistically significant for soybean row spacing and the fall rye cover crop each in a single year, it should be noted that this difference is of minimal biological relevance in a field setting.

Table 4.3: Effect of row spacing, cultivar and cover crop on soybean crop maturity in 2020 and 2021 at Lethbridge, Alberta.

| ----------Number of days to crop maturity in 2020[a]---------- | | | | | |
|---|---|---|---|---|---|
| Row spacing (cm) | | | Soybean cultivar[c] | | |
| 23 | 69 | **Mean** | slender-type | bushy-type | **Mean** |
| 116 a | 117 b | **116** | 115 a | 118 b | **117** |
| ----------Number of days to crop maturity in 2021[a]---------- | | | | | |
| Cover crop[b] | | | Soybean cultivar | | |
| absent | present | **Mean** | slender-type | bushy-type | **Mean** |
| 115 a | 116 b | **115** | 114 a | 118 b | **117** |

[a] Within effect groupings, different lower case letters indicate significant differences based on Tukey's HSD ($\alpha$=0.05). [b] Abbreviations: present, with fall rye; absent, without fall rye. [c] Soybean cultivars.

*4.3.3. Soybean Density*

In 2020, there was a significant impact on achieved soybean density by target soybean density (P=0.002, Table A1) while in 2021, soybean target density did not impact on achieved soybean density (P=0.34, Table A2). This is likely due to wide variation in soybean emergence in 2021. Soybean seeded at target densities of 400,000 and 600,000 plants $ha^{-1}$ resulted in 512,188 and 688,718 plants $ha^{-1}$, respectively, on average in 2020 and 570,313 and 770,188 plants $ha^{-1}$, respectively, in 2021. Therefore, the seed mortality assumption of 25% was lower than observed seed mortality (data not shown). This could be due to the use of irrigation in the current study, resulting in more rapid seed imbibition and successful emergence compared with that of rain-fed soybean production in the Canadian prairies.

In both years, soybean row spacing had a significant effect on soybean plant density under weed-free conditions. In 2020, the highest soybean density was recorded in the wide row spacing but in 2021 that result was opposite (Figure 4.2 and Figure 4.3). In 2020, wider row spacing had a 19.1% greater soybean density than that of the narrow row spacing (Figure 4.2). When rows get wider, but the seeding density remains the same, there is greater within-row intraspecific competition (soybean competition with other soybean plants). In wide rows, this can result in plant thinning where some soybean plants do not survive, resulting in lower plant populations per unit area compared with narrow rows. This is likely what happened in 2021. However, perhaps this was not observed in 2020 due to environmental conditions.

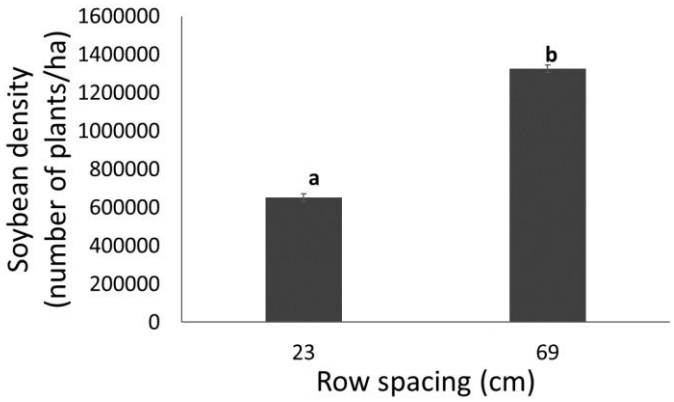



Figure 4.2: Effect of row spacing on soybean density under weed-free condition near Lethbridge, AB in 2020. Different letters indicate significant differences based on Tukey's HSD ($\alpha = 0.05$). Error bars indicate ± one standard error of the means.

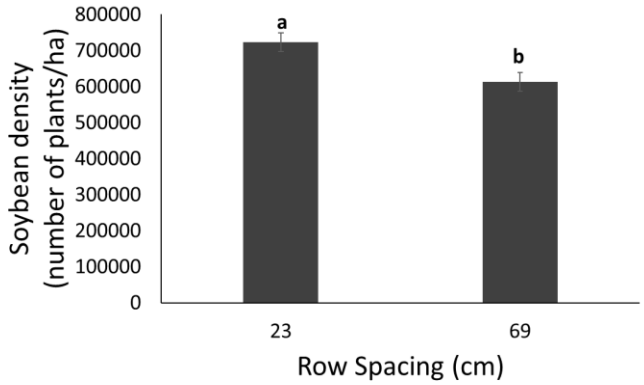



Figure 4.3: Effect of row spacing on soybean density under weed-free condition near Lethbridge, AB in 2021. Different letters indicate significant differences based on Tukey's HSD ($\alpha = 0.05$). Error bars indicate ± one standard error of the means.

*4.3.4. Aboveground Biomass*

Under weed-free conditions in 2020, decreasing soybean row spacing from 69 cm to 23 cm caused an increase in aboveground biomass production in slender-type soybean by 1,870 kg $ha^{-1}$ (Table 4.4). Under weed-free conditions, on average, soybean grown at narrow-row spacing without a fall rye cover crop produced significantly higher aboveground biomass than that of wide-row soybean with a fall rye cover crop (Table 4.4). In contrast, the cover crop had no significant effect on soybean aboveground biomass in soybean in 2021 (Table A2) likely due to minimal fall rye biomass at soybean planting (Figure 4.1). Under weed-free conditions in 2021, on average, the bushy-type soybean cultivar produced 15% greater aboveground biomass than the slender-type cultivar, while the wide row soybean produced 25% greater aboveground biomass than the narrow row soybean (Figure 4.4). Under weed-free conditions in 2020, the higher soybean target density resulted in 12% greater aboveground biomass compared with the

current recommended density (Table 4.4). However, in 2021, soybean target plant density did not affect aboveground biomass (Table A2).

Table 4.4: Effect of soybean row spacing, target plant density and the fall rye cover crop on weed-free soybean biomass near Lethbridge, AB in 2020.

| ----Soybean aboveground biomass (kg ha$^{-1}$)---- | | | |
|---|---|---|---|
| Row spacing (cm) | Soybean cultivar[c] | | **Mean[d]** |
| | slender-type | bushy-type | |
| 23 | 6,306 a | 5,465 b | **5,886 A** |
| 69 | 4,436 c | 4,690 ab | **4,568 B** |
| **Mean** | **5,371** | **5,083** | |
| Row spacing (cm) | Cover crop[b] | | |
| | absent | present | **Mean** |
| 23 | 6,819 c | 4,952 b | **5,886 A** |
| 69 | 5,117 b | 4,018 a | **4,568 B** |
| **Mean** | **5,968** | **4,485** | |
| Target plant density (Number of plants ha$^{-1}$) | | | |
| 400,000 | | 4,929 a | |
| 600,000 | | 5,525 b | |
| **Mean** | | **5,227** | |

[a] Within effect groupings, different lower case letters indicate significant differences based on Tukey's HSD ($\alpha$=0.05). [b] Abbreviations: present, with fall rye; absent, without fall rye. [c] Soybean cultivars. [d] Different upper case letters indicate significance deference between main effect means based on Tukey's HSD ($\alpha$=0.05).

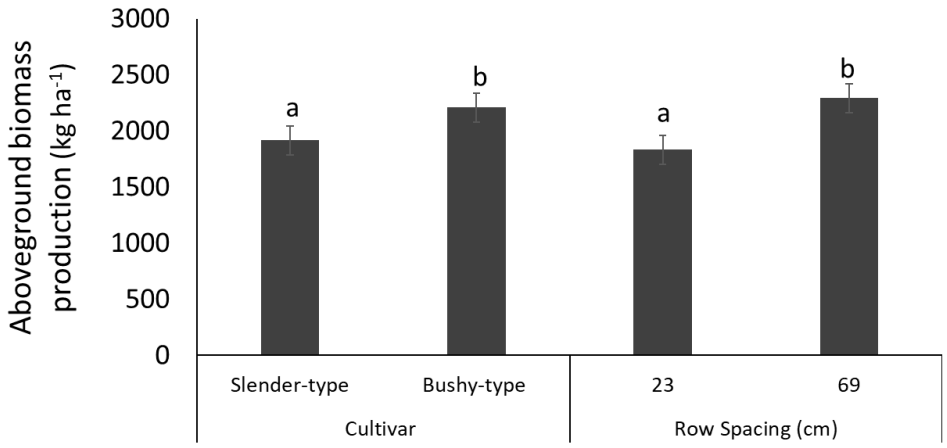



Figure 4.4: Effect of cultivar and row spacing on soybean biomass production under weed-free condition near Lethbridge, AB in 2021. Different letters indicate significant differences based on Tukey's HSD ($\alpha = 0.05$). Error bars indicate ± one standard error of the means.

Under weed interference in 2020, soybean aboveground biomass was 63% lower on average compared to without the fall rye cover crop (Table 4.5). This was likely due to the higher volunteer canola densities present in the cover crop treatments (see section 4.4.1). On average, soybean seeded at a target of 600,000 plants $ha^{-1}$ produced 56% greater biomass than 400,000 plants $ha^{-1}$. However, a row spacing by cultivar interaction was present, where the slender-type or bushy-type cultivar with the narrow row spacing resulted in greater aboveground biomass in the high target density than all low target density treatments (Table 4.5). Under weedy conditions in 2021, soybean with high target plant density resulted in 55% greater aboveground biomass than that of the current recommended target plant density (Figure 4.5). Moreover, the bushy-type soybean cultivar produced 13% greater aboveground biomass than that of the slender-type cultivar (Figure 4.5). This probably was due to the canopy architecture of the bushy-type cultivar,

which can promote quicker canopy closure by increasing LAI, thereby helping to supress weeds and late-season weed emergence (Jha et al. 2017).

Table 4.5: Effect of soybean cultivar, row spacing, target plant density and the fall rye cover crop on soybean biomass under weed interference near Lethbridge, AB in 2020.

| Target plant density (Number of plants ha$^{-1}$) | Soybean aboveground biomass (kg ha$^{-1}$) in 2020[a] | | | | | |
|---|---|---|---|---|---|---|
| | Row spacing (cm) | | | | | |
| | 23 | | | 69 | | |
| | Soybean cultivar [c] | | | Soybean cultivar [c] | | |
| | slender-type | bushy-type | **Mean[d]** | slender-type | bushy-type | **Mean** |
| 400,000 | 2,738 abc | 3,020 bc | **3379 A** | 2,045 ab | 1,487 a | **1766 A** |
| 600,000 | 3,366 c | 2,424 abc | **2895 B** | 1,749 a | 2,277 abc | **2013 B** |
| **Mean** | **3,052 A** | **2,722 B** | | **1,897 A** | **1,882 B** | |
| | Cover crop[b] | | | | | |
| | absent | present | | | **Mean** | |
| | 3,039 b | 1,787 a | | | **2,413** | |

[a] Within effect groupings, different lower case letters indicate significant differences based on Tukey's HSD (α=0.05). [b] Abbreviations: present, with fall rye; absent, without fall rye. [c] Soybean cultivars. [d] Different upper case letters indicate significance deference between main effect means based on Tukey's HSD (α=0.05).

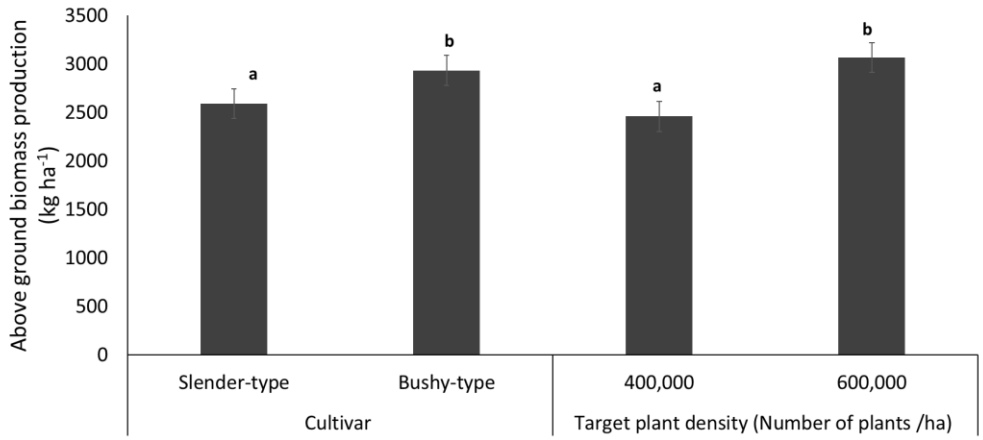



Figure 4.5: Effect of soybean cultivar and target plant density on soybean biomass under weedy interference near Lethbridge, AB in 2021. Different letters indicate significant differences based on Tukey's HSD ($\alpha = 0.05$). Error bars indicate ± one standard error of the means.

*4.3.5. Soybean Yield Loss*

Soybean yield loss due to weed interference is a direct measure of the ability for soybean to withstand weed interference. Potential yield losses in soybean due to weed interference were estimated to be 27% in the United States and 10% in Canada (Soltani et al. 2017). In 2020, the fall rye cover crop was the only factor that affected soybean yield loss due to weed interference. The presence of the cover crop increased soybean yield loss by 11% compared with that of no cover crop (Figure 4.6). Greater density of volunteer canola in the fall rye cover crop treatments (section 4.4.1) likely contributed to greater yield loss caused by the cover crop in 2020. In general, fall rye has the ability to suppress weeds physically through high biomass accumulation and chemically through allelopathy (De Bruin and Pedersen 2008). However, the fall rye cover crop failed to suppress weeds and resulted in soybean yield reduction in the current study.

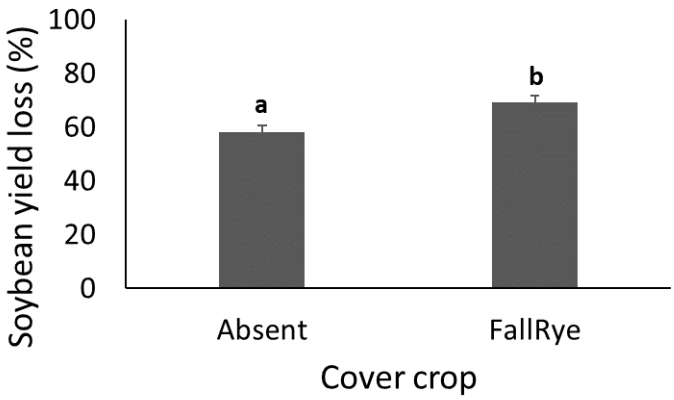



Figure 4.6: The impact of presence vs. absence of a fall rye cover crop on soybean yield loss due to weed interference near Lethbridge, AB in 2020. Different letters indicate significant differences based on Tukey's HSD ($\alpha = 0.05$). Error bars indicate ± one standard error of the means.

In 2021, wide row soybean resulted in a 45% greater yield loss than narrow rows (Figure 4.7). The wide row soybean did not reach complete canopy closure (Jayasekara, personal observation), and consequently open canopy conditions facilitated weed seedling establishment resulting in increased weed interference. On average, 23% greater soybean yield loss was observed in 2020 than in 2021 (data not shown). This was mainly due to the greater density of weeds present in 2020 (section 4.4.1). Nevertheless, soybean yield loss data in the current study indicate that growing soybean in 23 cm rows can improve the ability for soybean to withstand weed interference as compared with 69 cm rows.

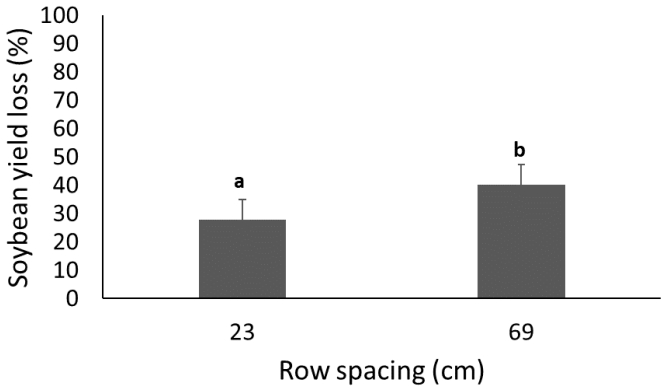



Figure 4.7: Effect of soybean row spacing on yield loss due to weed interference near Lethbridge, AB in 2021. Different letters indicate significant differences based on Tukey's HSD ($\alpha = 0.05$). Error bars indicate ± one standard error of the means.

*4.3.6. Light Penetration Through the Crop Canopy*

Photosynthesis is an important process in which plants convert light into chemical energy through cellular respiration (Chen and Blankenship 2021). For this process, plants require PAR, which includes wavelengths between 400 and 690 nm (Kim et al. 1994). High capture of PAR by the crop canopy can benefit soybean crop yield (Fan et al. 2018). There are three major factors contributing to the amount of light captured by the crop canopy, including LAI, light intercepting efficiency, and leaf photosynthesis (Nagasuga 2019).

The current study evaluated two different soybean cultivars characterized as slender-type (described as lanceolate leaf shape with medium plant height) and bushy-type (described as aggressive growth with substantial branching). In 2020, the crop canopy established by each cultivar intercepted a similar amount of PAR at the V3, R3, and R5 growth stages (Figure 4.8). However, there was a difference based on the F-test, ($p<0.0205$; Table A3) but these differences were minor overall.

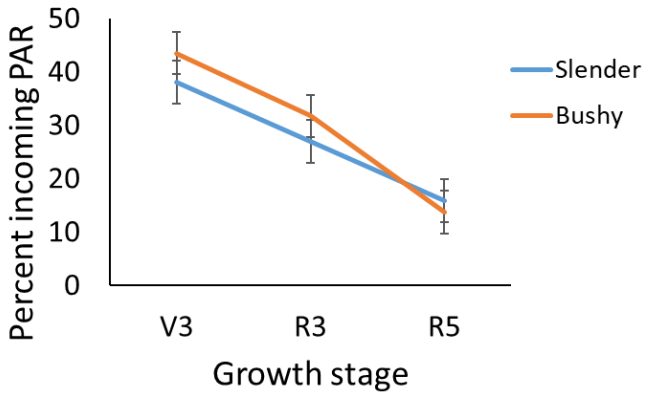



Figure 4.8: Effect of soybean cultivar on the percentage of total incoming photosynthetically active radiation (PAR) beneath the crop canopy at three growth stages of soybean in 2020.

Soybean row spacing can influence ground cover, LAI, light interception by the crop canopy, and canopy photosynthesis (Hiebsch et al. 1990). In the current study, wide row soybean resulted in about double the percentage of total incoming PAR that penetrated through the crop canopy compared with narrow rows at all growth stages evaluated (V3, R3, and R5) (Figure 4.9). These results suggest that canopy closure and concomitant ground cover are high and more rapid in narrow compared with wide row soybean. Weber et al. (1966) suggested that plants seeded in narrow rows (13 cm) generally accumulate LAI faster than plants grown in wider rows (25 cm). At the same soybean plant density, the LAI required to intercept 95% of the solar radiation and days from emergence to 95% interception were higher in wide rows (76 cm) than narrow rows (25 cm) (Hicks et al. 1969).

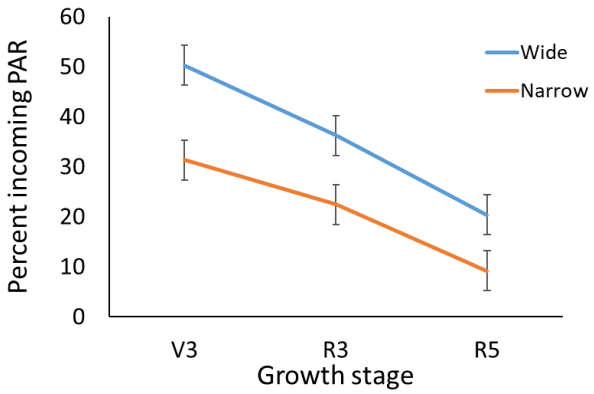



Figure 4.9: Effect of soybean row spacing on the percentage of total incoming photosynthetically active radiation (PAR) beneath the crop canopy at three growth stages of soybean in 2020. Error bars indicate ± one standard error of the means.

Fall rye has been used extensively to produce a weed-suppressive mulch on the soil surface due to its high biomass production and high allelopathic potential (Verma and Kohnke 1951). In the 2020, soybean seeded into a fall rye cover crop resulted in a lower percentage of total incoming PAR that reached the soil surface during vegetative growth (V3 growth stage) compared with soybean absent of a cover crop (Figure 4.10). Lower PAR reaching the soil surface was due to the cover crop providing a physical barrier that shaded the soil. Cover crop mulches can also reduce or delay the germination and early growth of many weed species (Bhowmik and Bekech 1993; Geddes et al. 2015).

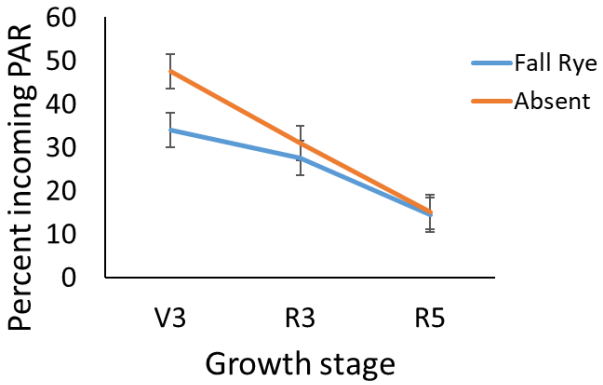



Figure 4.10: Effect of cover crop on the percentage of total incoming photosynthetically active radiation (PAR) beneath the crop canopy at three growth stages of soybean in 2020. Error bars indicate ± one standard error of the means.

In 2021, wide row soybean with the fall rye cover crop resulted in the greatest percentage of total incoming PAR reaching the soil surface compared with the other treatments (Figure 4.11). However, in 2021, percent incoming PAR increased at the R5 stage compared with the R3 stage and this was likely due to the wind on the particular day that these data were collected. As an example, there might have been more light making through the crop canopy when wind speed was high due to movement of the soybean leaves and canopy (Figure 4.11).

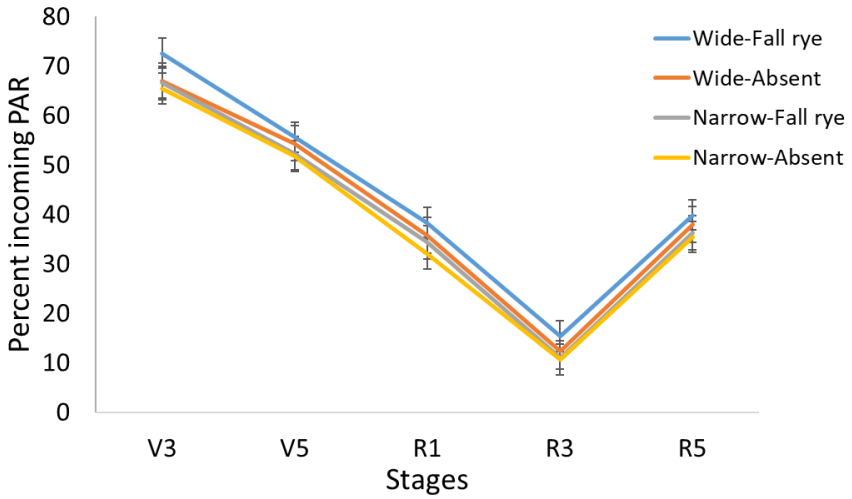



Figure 4.11: Impact of soybean row spacing and fall rye cover crop on the percentage of total incoming photosynthetically active radiation (PAR) beneath the crop canopy at different soybean growth stages in 2021. Error bars indicate ± one standard error of the means.

## 4.4. Impact of Soybean Cultivar, Row Spacing, Target Plant Density, and Fall Rye Cover Crop on Weed Density, Biomass and Seed Dockage

### *4.4.1. Weed Density*

Weeds can be a major production issue in profitable soybean cultivation. Among the two sites near Lethbridge, AB, the greatest mid-season density was observed in 2020, (55 plants $m^{-2}$) and this contributed to the higher soybean yield losses due to weed interference compared with 2021 (Figures 4.6 and 4.7). In 2020, 17 different weed species were present in the experiment, and among them, the predominant weeds were volunteer canola, dandelion (*Taraxacum officinale* F. H. Wigg.) and kochia (present at 55, 10, and 7 plants $m^{-2}$, respectively). Overall, 13 different weed species were observed in 2021, with dandelion, green foxtail, and prickly lettuce (*Lactuca serriola* L.) being the most abundant (present at 4, 2, and 3 plants $m^{-2}$, respectively). In 2020, soybean target

plant density and cover crop influenced weed density (Figure 4.12). Increasing soybean target plant density from 400,000 to 600,000 plant $ha^{-1}$ resulted in a 21% reduction in weed population density (Figure 4.12). Similarly, Liebert and Ryan (2017) observed that increasing soybean seeding density from 195,000 to 914,999 seeds $ha^{-1}$ caused a significant reduction in weed density. Furthermore, high soybean densities have been shown to hasten canopy closure and cause improved weed suppression and soybean yield (Zhang et al. 2011). However, managing weeds with higher seeding rates is not always economically favorable due to cost of patented seed technology (Place et al. 2009). Economic optimum seeding rates are always less than seeding rates that result in maximum yield (De Bruin and Pedersen 2008) and tend to vary among weedy and weed-free conditions (Mierau et al. 2020). In 2020, soybean seeded into the fall rye cover crop had 68% greater weed density on average, than that produced absent of a cover crop (Figure 4.12). In 2020, visual observation and weed density counts showed that the cover crop facilitated germination of the volunteer canola seed that was broadcast in the weedy plots. This was because the fall rye mulch created a more favorable environment by maintaining surface soil moisture for germination and establishment of the volunteer canola (Jayasekara, personal observation), resulting in greater weed density in soybean with the fall rye cover crop than without.

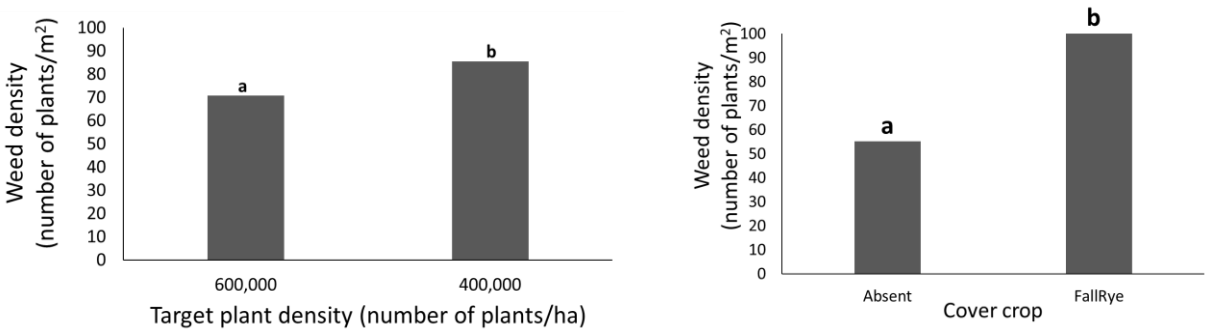



Figure 4.12: The impact of soybean target plant density and the fall rye cover crop on weed density near Lethbridge, AB in 2020. Different letters indicate significant differences based on Tukey's HSD ($\alpha = 0.05$). Values are back-transformed natural logarithm means.

Soybean row spacing was the only factor that influenced weed density in 2021 (Figure 4.13). On average, the wide row soybean resulted in 19% greater weed density than that of narrow row soybean (Figure 4.13). However, it is well understood that narrow row soybean at high seeding rates can hasten soybean canopy closure (De Bruin and Pedersen 2008). More rapid canopy closure can help to minimize the germination of later emerging weed cohorts. Place et al. (2009) observed that the best possible way to obtain soybean yield in both vegetative and reproductive growth is to use a row spacing of 19 cm at seeding rates of 420,000 seeds $ha^{-1}$. Together, weed density data suggest that both narrow row spacing and higher target plant densities of soybean can facilitate weed suppression.

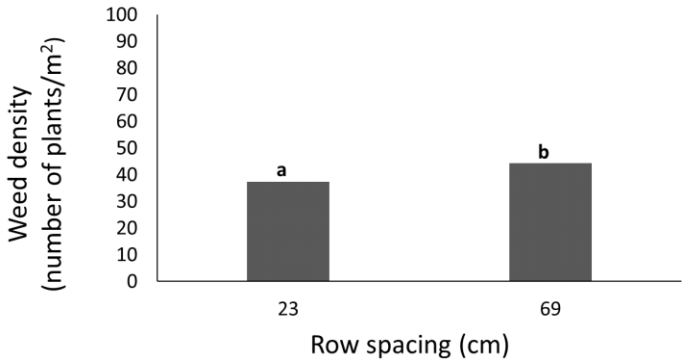



Figure 4.13: The impact of soybean row spacing on weed density near Lethbridge, AB in 2021. Different letters indicate significant differences based on Tukey's HSD ($\alpha = 0.05$). Values are back-transformed natural logarithm means.

*4.4.2. Weed Biomass*

The differences observed in weed density corresponded with similar differences in weed biomass. In 2020, seeding soybean at the recommended density (400,000 target plants $ha^{-1}$) resulted in 17% greater weed biomass than at 600,000 plants $ha^{-1}$ (Table 4.6). This corresponds with lower weed density observed at the higher soybean target density (Figure 4.12). However, the differences in weed biomass in 2021 were driven by the soybean row spacing, cultivar and the fall rye cover crop and not soybean target density (Table A4). A previous study showed soybean planted at 19 cm row spacing at 432,000 target plants $ha^{-1}$ were more competitive and reduced weed dry weight by one third compared with 76 cm row spacing at a density of 185,000 target plants $ha^{-1}$ (Rich and Renner 2007). These results demonstrate that increased seeding rates may not be an effective stand-alone weed control method, but are best when used in conjunction with narrow row spacing. In the current study, weed biomass in 2021 was lower when the fall rye cover crop was present (Table 4.6) even at very low fall rye biomass (Figure 4.1) indicating that weed suppression by the fall rye cover crop was like due to allelopathy or

nutrient immobilization, rather than physical suppression. Several studies have documented the relationship between cover crops and weed suppression. Jewett and Thelen (2007) studied how winter wheat and fall rye cover crop burndown or harvest strategies affected spring soil nitrate concentrations in Michigan. They observed that the fall rye and winter wheat cover crops decreased $NO_3^-$ in the soil profile by up to 60% following corn or soybean crops (Jewett and Thelen 2007). Barnes and Putnam (1983) observed a 90% reduction in weed biomass with cereal rye cover crop compared with no cover crop in a no-herbicide applied field pea (*Pisum sativum* L.) system. Other research showed that fall rye reduced broadleaf weed biomass at all selected sites in Manitoba (Heather et al. 2019).

In 2021, the bushy-type soybean cultivar seeded at narrow rows resulted in 30% lower weed biomass than that of the slender-type cultivar at wide row spacing (Table 4.6). The use of narrow row spacing combined with the use of a bushy-type cultivar could accelerate canopy closure by increasing LAI (Lee et al. 2005). This can reduce the light available to weeds beneath the crop canopy, and suppress their growth and impact on crop yield. However, this was not observed based on PAR reaching the soil surface in the current study (Section 4.3.6). Together, similar to the weed density data, the weed biomass data suggest that higher soybean target densities and narrow row spacing can improve the ability for soybean to compete with weeds. In addition, growing a bushy-type soybean cultivar can augment the weed suppression observed in narrow rows.

Table 4.6: Effect of soybean cultivar, row spacing, target plant density, and the fall rye cover crop on weed biomass near Lethbridge, AB in 2020 and 2021.

| Target plant density (Number of plants $ha^{-1}$) | Weed biomass ($g\ m^{-2}$) in 2020 | Cover crop[b] | Weed biomass ($g\ m^{-2}$) in 2021 |
|---|---|---|---|
| 400,000 | 291 b | absent | 268 b |
| 600,000 | 248 a | present | 251 a |
| **Mean[d]** | **269** | | **260** |

| | Weed biomass ($g\ m^{-2}$) in 2021 Soybean cultivar[c] | | |
|---|---|---|---|
| Row spacing (cm) | slender-type | bushy-type | **Mean** |
| 23 | 251 b | 230 a | **241 A** |
| 68 | 300 b | 288 b | **294 B** |
| **Mean** | **276** | **259** | |

[a] Within effect groupings, different lower case letters indicate significant differences based on Tukey's HSD ($\alpha$=0.05). [b] Abbreviations: present; with fall rye, absent; without fall rye. [c] Soybean cultivars. [d] Different upper case letters indicate significance deference between main effect means based on Tukey's HSD ($\alpha$=0.05).

### *4.4.3. Weed Seed Dockage*

Weed seeds present in the harvested grain result in 'dockage' and lower profit when the grain is sold. The Canadian Grain Commission defined 'dockage' as materials inter-mixed with a bundle of grain that can be detached using normal cleaning procedures (Dexter and D'Egidio 2012). Grain handlers face difficulties when dockage cleaning due to heavy dust, and samples with more dockage require more extensive cleaning (Canadian Grain Commission 2019). In addition, weed seed dockage in grain shipments can create difficulties when the primary use of the seed is for export markets. While weed seed dockage is undesirable for farmers, measuring the amount of weed seeds collected along

with the grain can provide insight into how many weeds are going to seed in the soybean crop (i.e., another measure of weed infestation and a significant contributor to the selection pressure for herbicide resistance).

In 2020, the fall rye cover crop resulted in 14% greater weed seed dockage compared with the absence of a cover crop (Table 4.7). The majority of previous research suggests that fall rye cover crops compete strongly with weeds for space, light, nutrients and moisture and can reduce weed growth by 80-100% for the duration of cover crop life cycle (Sarrantonio and Gallandt 2003). However, the opposite trend was observed in the current study due to high density of volunteer canola in 2020 resulting in a greater weed seed dockage (Table 4.7). In 2021, an interaction of cover crop by soybean target plant density was observed for weed seed dockage. The highest weed seed dockage was observed when soybean were seeded at 400,000 target plants $ha^{-1}$ into the fall rye cover crop, and lowest weed seed dockage was observed when soybean were seeded at the higher target plant density (600,000 target plants $ha^{-1}$) absent of the cover crop (Table 4.7). Together, these data suggest that the presence of a fall rye cover crop contributed to greater weed seed dockage, and therefore is not recommended as a tool for weed suppression in irrigated soybean production in Alberta based on the current study.

Table 4.7: Effect of soybean target plant density and the fall rye cover crop on weed dockage near Lethbridge, AB in 2020 and 2021.

| ----------Weed seed dockage (g $m^{-2}$) in 2020[a]---------- | | |
|---|---|---|
| | Cover crop | |
| absent | present | **Mean** |
| 1,524 a | 1,742 b | **1,633** |

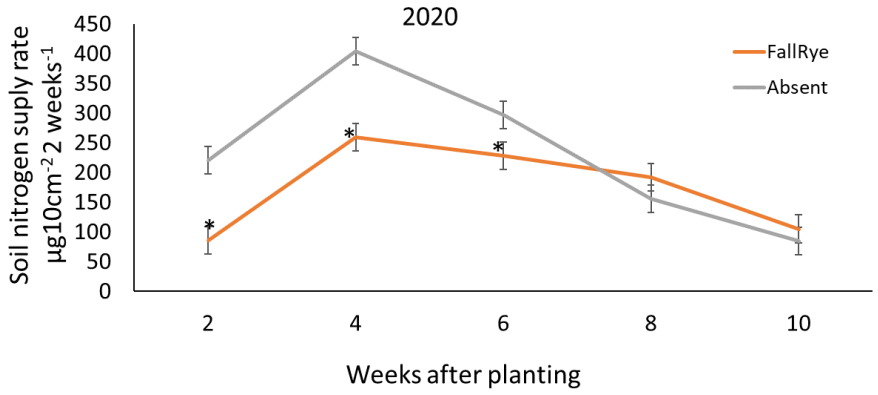
| ----------Weed seed dockage (g $m^{-2}$) in 2021[a]---------- | | |
|---|---|---|
| Target plant density (Number of plants $ha^{-1}$) | Cover crop absent | present |
| 400,000 | 1,326 ab | 1,740 a |
| 600,000 | 1,190 b | 1,321 ab |
| **Mean** | **1,258** | **1,531** |

[a] Within effect groupings, different lower case letters indicate significant differences based on Tukey's HSD ($\alpha$=0.05). [b] Abbreviations: present; with fall rye, absent; without fall rye.

## 4.5. Environmental Data

### *4.5.1. Surface Soil $NO_3^-$ Supply (PRS® Probe Data)*

Soybean seeded into the fall rye cover crop had a lower $NO_3^-$ nitrogen supply rate the absence of a cover crop during early soybean growth and development (Figure 4.14). This suggests that the fall rye helped to mobilize plant available nitrogen from the soil, meaning that less would be available to weeds growing within the soybean crop. This could be one potential mechanism for how the cover crop could impact weeds, however minimal weed suppression overall, and occasionally weed stimulation was observed due to the presence of the fall rye cover crop (Figure 4.14).



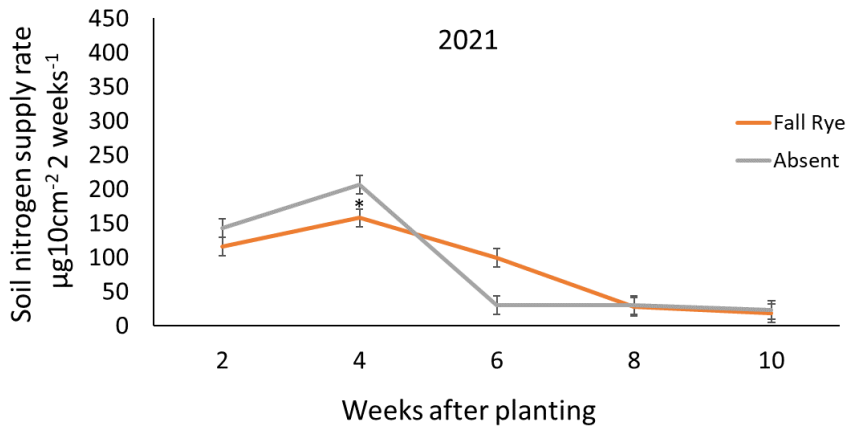



Figure 4.14: Effect of the fall rye cover crop on soil $NO_3^-$ nitrogen supply rate during the first 10 weeks of soybean growth and development in 2020 and 2021. Asterisks indicate significant differences based on Tukey's HSD ($\alpha = 0.05$). Error bars indicate ± one standard error of the means.

Soybean grown in narrow rows resulted in lower soil $NO_3^-$ nitrogen supply by eight and ten weeks after seeding compared with wide rows in 2020 (Figure 4.15). The symbiotic relationship between soybean and *Bradyrhyzobium japonicum*, and therefore nitrogen fixation, does not establish until the V2 stage (Keyser and Li 1992). Therefore, soybean seedlings use nitrogen from the soil during early growth and development. Since the PRS® probes were buried in the inter-row, they were closer to the soybean rows when grown using narrow spacing compared with wide spacing. Therefore, less nitrogen was available to weeds growing in soybean produced in narrow rows compared with wide rows. This could be one reason for greater weed suppression observed in narrow row soybean (Figure 4.13; Table 4.6).

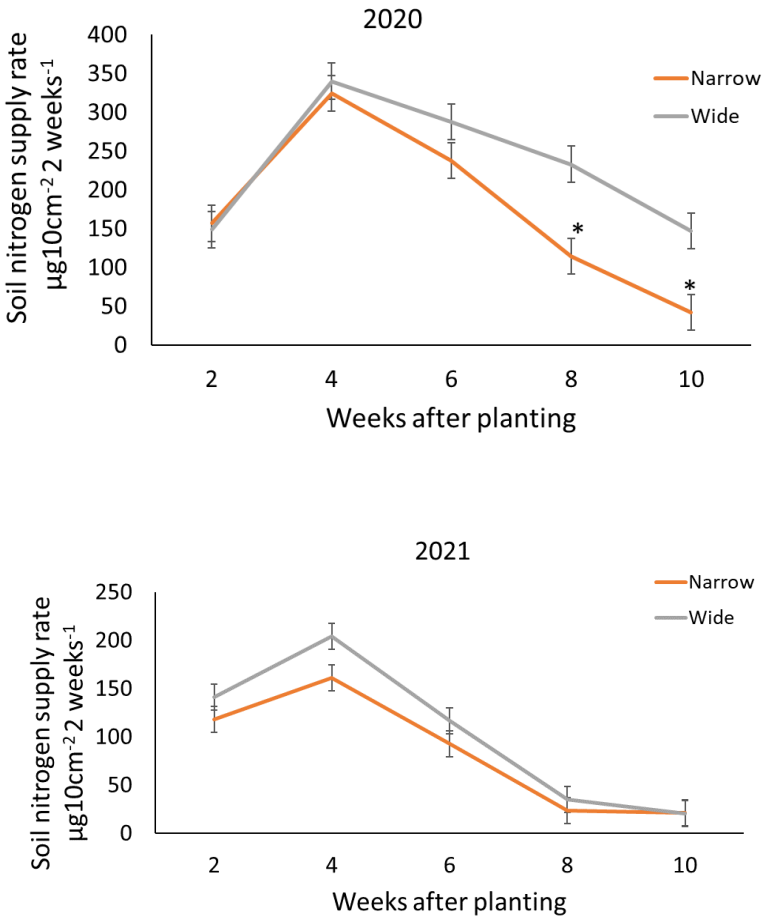



Figure 4.15: Effect of soybean row spacing on soil $NO_3^-$ nitrogen supply rate during the first 10 weeks of soybean growth and development in 2020 and 2021. Asterisks indicate significant differences based on Tukey's HSD ($\alpha = 0.05$). Error bars indicate ± one standard error of the means.

*4.5.2. Soil Volumetric Water Content*

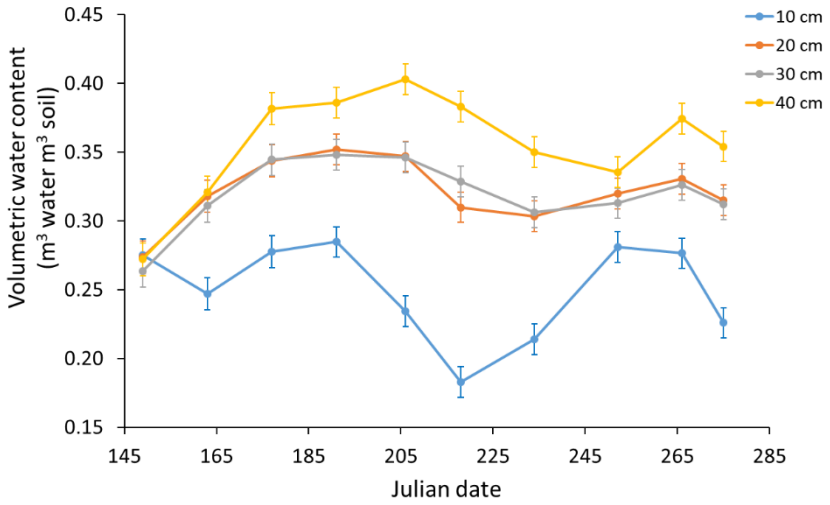



Figure 4.16: Soil volumetric water content at 10, 20, 30 and 40 cm depths every two weeks from soybean planting to harvest in 2020. Error bars indicate ± one standard error of the means.

Soil moisture content and evapotranspiration are key components of water balance and are directly linked to ecosystem productivity. Monthly precipitation during the early growing season was comparatively high in 2020 than 2021 (Table 3.4). Both field studies were irrigated as required to maintain adequate moisture to alleviate water stress between soybean R2 and R6 stages, which can affect seed yield in soybean (Table 3.4). In 2020, the upper (10 cm) soil layer contained less soil moisture compared with lower (20–40 cm) soil layers (Figure 4.16) likely due to grater evaporation from upper soil layers. However, differences in volumetric water content were not observed among the soybean cultivar, row spacing, target plant density, and fall rye cover crop treatments in 2020 (Table A5).

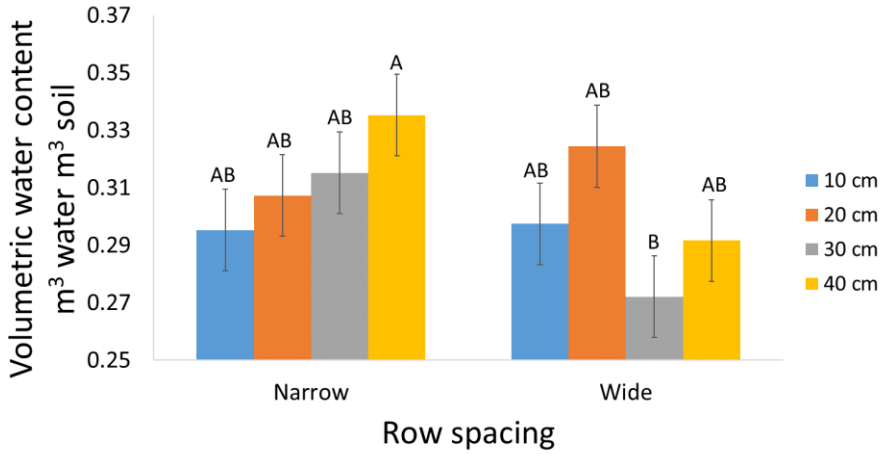



Figure 4.17: Soil volumetric water content at 10, 20, 30 and 40 cm depths in narrow (23 cm) and wide row (69 cm) soybean treatments in 2021. Different letters indicate significant differences based on Tukey's HSD (α=0.05). Error bars indicate ± one standard error of the means.

During the soybean growing period, evapotranspiration could affect the soil moisture content at different soil depths. While volumetric water content was similar in the upper (10–20 cm) soil layers of narrow (23 cm) and wide row (69 cm) soybean in 2021, soybean grown in narrow rows had numerically greater soil moisture at depth (30–40 cm) than wide rows; albeit these differences were not statistically significant based on Tukey's HSD (α = 0.05) (Figure 4.17). This could be due to rapid canopy closure in narrow row soybean, which could reduce evaporative losses compared to wide rows. It should be noted that the fall rye cover crop did not reduce soil volumetric water content in either year of the current study as is often cited in other research (Wagner-Riddle et al. 1994), likely due to the use of supplementary irrigation.

*4.5.2. Cumulative Growing Degree Days*

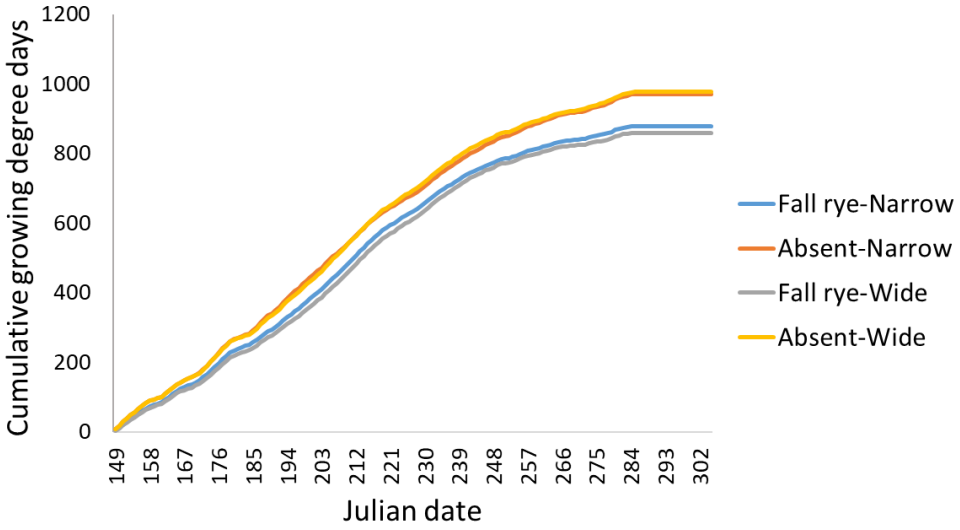



Figure 4.18: Cumulative growing degree days (Tbase = 10°C) from soybean seeding to harvest near Lethbridge, AB in 2020.

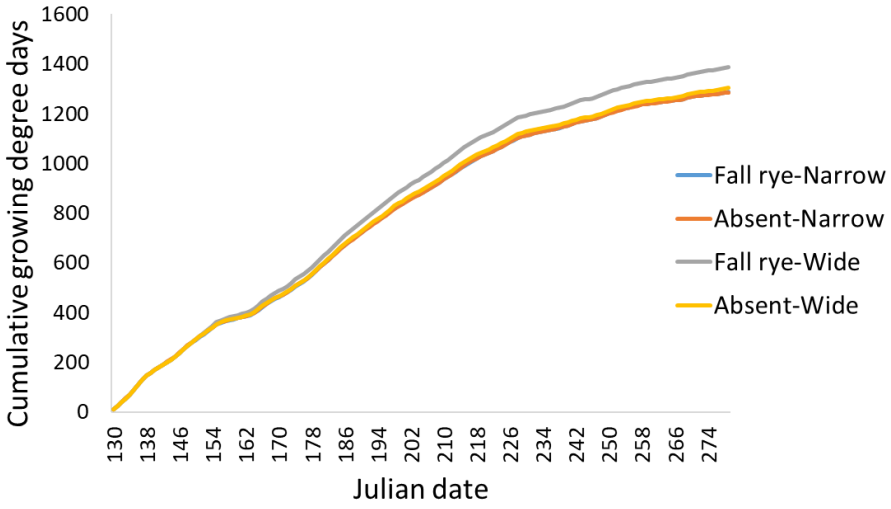



Figure 4.19: Cumulative growing degree days (Tbase = 10°C) from soybean seeding to harvest near Lethbridge, AB in 2021.

Soil temperature is vital in agriculture systems because it can affect microbial activities, seed germination, plant growth and development. A soil temperature of 10°C has been recommended for seeding soybean because cool soil temperatures could cause chilling injury to the imbibed soybean seed (Leibovitch et al. 2001), and result in a longer period for seedling emergence, which could increase risk of mortality due to insects, weeds and pathogens (Staniak et al. 2021). Soybean plants are well adapted to growing in warm environments, but poorly adapted to cool conditions experienced during the spring and fall in western Canada. In addition, the duration from soybean seeding to maturity is dependent on cumulative thermal time during the growing season, where more rapid accumulation of GDD results in hastened maturity prior to fall frosts which can limit soybean yield (Edwards et al. 2005). In the current study, soil temperature was monitored continuously at 5 cm soil depth in the four treatments comparing wide vs. narrow soybean row spacing and with vs. without the fall rye cover crop because these treatment factors were expected to influence soil temperature more than soybean target plant density and cultivar. In 2020, the presence of a fall rye cover crop terminated before soybean seeding resulted in less cumulative GDD throughout the growing season compared with the treatments absent of a rye cover crop (Figure 4.18). The influence of the cover crop was far greater than that of narrow vs. wide soybean row spacing. Far greater fall rye biomass was observed in 2020 compared with 2021 (Figure 4.1). Therefore, the influence of the fall rye cover crop on soil temperature was not apparent to the same degree in 2021, and perhaps was even opposite (Figure 4.19). The purpose of growing a shoulder season fall rye cover crop in the current study was to produce residue that covers the soil surface helping to improve soil health, mitigate soil erosion, scavenge for soil nutrients and facilitate weed suppression. However, an indirect effect of the cover crop in 2020 was

cooler soil temperatures, resulting in lower cumulative thermal time. Cooler soil temperatures may have reduced the rate of growth and development of the soybean seeded into the fall rye cover crop.

# 5.0. CONCLUSIONS

The introduction of short-season soybean cultivars to irrigated cropping systems in southern Alberta has created a new agronomic and economic opportunity for crop producers in the region. Over the last decade soybean have become a successful field crop grown in western Canada. In response, however, the use and reliance on glyphosate as an herbicide has increased, since almost all of the soybean grown are GR (either alone or in combination with another herbicide mode of action). GR soybean could add greater selection pressure for GR weeds, and therefore it is critical to develop integrated production systems that help soybean suppress weeds. The current study furthered knowledge on the implementation of cultural weed management techniques to mitigate the occurrence of herbicide-resistant weeds in soybean cultivation in southern Alberta. The research filled knowledge gaps on how soybean cultivar, row spacing, target plant density, and a fall rye cover crop can be used to suppress weeds in irrigated soybean, helping to maximize soybean yield while also mitigating further selection for herbicide-resistant weeds.

Results from the current study showed that higher soybean target densities (600,000 target plants $ha^{-1}$) can increase the ability for soybean to withstand weed interference (i.e., lower yield loss in the presence of weeds). However, increasing seeding rates may also increase production expenses due to the high cost of patented seed technology. Partial budgeting analysis (Appendix B) using data from the current study suggests that there was minor differences in profit, when using the higher target plant density because the additional seed costs were ameliorated by higher yields. Therefore, farmers could use the higher target density successfully as a weed management tool at a cost ranging from $20–

24 $ha^{-1}$. This cost is roughly similar to an additional glyphosate application (Ontario of Agriculture 2019). Future research should assess whether similar results may be achieved by forgoing the second in-crop glyphosate application, thereby paying for the minor reduction in immediate profit as a result of higher seed costs.

Narrow row spacing (23 cm) with recommended plant density (400,000 plants $ha^{-1}$) could be used to increase soybean yield while decreasing weed competition. Narrow row soybean resulted in 30% and 25% greater yield compared with wide rows under weed-free conditions in 2020 and 2021, respectively. Conclusions made from the current research show that these benefits were observed also for short-season soybean grown in northern production regions, similar to those observed elsewhere. The use of narrow rows (23 cm) helped to mitigate weed establishment and growth in the soybean crop, directly resulting in soybean yield improvements. Growing a bushy-type soybean cultivar augmented weed suppression when grown in narrow rows compared with the slender-type soybean cultivar. The impact of the fall rye cover crop on weed growth and development varied among years, suggesting that this tools warrants further investigation over a larger number of environments. When the fall rye produced large biomass in 2020, it also resulted in a reduction in soybean yield.

Together, my M.Sc. research showed that growing bushy-type soybean cultivars in narrow rows at higher target densities would result in the greatest ability for soybean to compete with and withstand competition from weeds. However, the benefits of each of these factors were not always consistent between years. Often weed management benefits are additive or synergistic when different tools are used in combination, which is the premise of "integrated" weed management. Therefore implementing these tools together

in an integrated weed management system could increase the chance of greater yield and improved weed control under variable environmental conditions from year to year.

# 6.0. REFERENCE MATTER

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## 6.2. Appendices

### 6.2.1. Appendix A

Table A1: ANOVA summary (P-values) for the main and interaction effects of row spacing, cultivar, target plant density and cover crop on plant density, above ground biomass production, days to maturity and seed yield of soybeans in 2020 at Lethbridge, Alberta.

| Effect | Variables (2020)[a,b] | | | | | |
|---|---|---|---|---|---|---|
| | Seed yield (kg ha$^{-1}$) | | Above ground biomass (kg ha$^{-1}$) | | Plant density (Plants ha$^{-1}$) | Days to maturity |
| | Weedy | Weed-free | Weedy | Weed-free | Weedy | Weed-free |
| Cultivar (Cu) | ns[a] | ns | ns | ns | ns | ns |
| Row Spacing (RS) | ns | **0.002**[b] | ns | ns | ns | **< 0.001** |
| Target Density (TD) | **0.002** | ns | ns | **<0.001** | **0.002** | ns |
| Cover Crop (CC) | **< 0.001** | ns | **< 0.001** | ns | **< 0.001** | ns |
| Cu× RS | ns | ns | ns | **0.006** | ns | ns |
| Cu×TD | ns | ns | ns | ns | ns | ns |
| RS×TD | ns | ns | ns | ns | ns | ns |
| Cu×CC | ns | ns | ns | ns | ns | ns |
| RS×CC | ns | ns | ns | **< 0.001** | ns | ns |
| D×CC | ns | **0.007** | ns | ns | ns | **0.007** |
| Cu×RS×TD | ns | ns | **< 0.001** | ns | ns | ns |
| Cu×RS×CC | ns | ns | ns | ns | ns | ns |
| Cu×TD×CC | ns | ns | ns | ns | ns | ns |
| RS×TD×CC | ns | ns | ns | ns | ns | ns |
| Cu×RS×TD×CC | ns | ns | ns | ns | ns | ns |

[a] ns denotes treatment effects are not significant ($P > 0.05$)
[b] Bold values indicate significant treatment effects at $P \leq 0.05$

Table A2: ANOVA summary (P-values) for the main and interaction effects of row spacing, cultivar, target plant density and cover crop on plant density, above ground biomass production, days to maturity and seed yield of soybeans in 2021 at Lethbridge, Alberta.

| Effect | Variables (2021)[a,b] | | | | | |
|---|---|---|---|---|---|---|
| | Seed yield (kg ha$^{-1}$) | | Above ground biomass (kg ha$^{-1}$) | | Plant density (Plants ha$^{-1}$) | Days to maturity |
| | Weedy | Weed-free | Weedy | Weed-free | Weedy | Weed-free |
| Cultivar (Cu) | ns[a] | ns | **0.034**[b] | **0.013** | ns | **< 0.001** |
| Row Spacing (RS) | **< 0.001** | ns | ns | **< 0.001** | **0.026** | ns |
| Target Density (TD) | ns | ns | **< 0.001** | ns | ns | ns |
| Cover Crop (CC) | ns | ns | ns | ns | ns | **0.007** |
| Cu× RS | ns | ns | ns | ns | ns | ns |
| Cu×TD | ns | ns | ns | ns | ns | ns |
| RS×TD | ns | ns | ns | ns | ns | ns |
| Cu×CC | ns | ns | ns | ns | ns | ns |
| RS×CC | ns | ns | ns | ns | ns | ns |
| TD×CC | ns | ns | ns | ns | ns | ns |
| Cu×RS×TD | ns | ns | ns | ns | ns | ns |
| Cu×RS×CC | **< 0.001** | **0.010** | ns | ns | ns | ns |
| Cu×TD×CC | ns | ns | ns | ns | ns | ns |
| RS×TD×CC | ns | ns | ns | ns | ns | ns |
| Cu×RS×TD×CC | ns | ns | ns | ns | ns | ns |

[a] ns denotes treatment effects are not significant ($P > 0.05$)
[b] Bold values indicate significant treatment effects at $P \leq 0.05$

Table A3: ANOVA summary (P-values) for effects of row spacing, cultivar, target plant density, growth stage of soybean and cover crop on light interception by the crop canopy in 2020 and 2021 at Lethbridge, Alberta.

| Percent incoming PAR[a,b] | | |
|---|---|---|
| Treatment | 2020 | 2021 |
| Cultivar(Cu) | ns[a] | ns |
| Row space (RS) | **<.0001[b]** | ns |
| Cover crop (CC) | ns | ns |
| Population density(D) | **0.0013** | ns |
| Stage(S) | **0.0005** | **<.0001** |
| Cu× RS | **0.0188** | ns |
| Cu× TD | ns | ns |
| RS× TD | ns | ns |
| Cu× RS× TD | ns | ns |
| Cu× CC | ns | ns |
| RS× CC | ns | ns |
| Cu× RS× CC | ns | ns |
| TD× CC | ns | ns |
| Cu× TD× CC | ns | ns |
| RS× TD× CC | ns | ns |
| Cu× RS× TD× CC | ns | ns |
| S× Cu | **0.0205** | ns |
| S× RS | **0.0133** | ns |
| S× CC | **<.0001** | ns |
| S× RS× CC | 0.2211 | **0.0267** |

[a] ns denotes treatment effects are not significant ($P > 0.05$)
[b] Bold values indicate significant treatment effects at $P \leq 0.05$

Table A4: ANOVA summary (P-values) for the main and interaction effects of soybean row spacing, cultivar, target density and cover crop on each weed response variable in 2020 and 2021 at Lethbridge, Alberta.

| | Weed variables[a,b] | | | | | |
|---|---|---|---|---|---|---|
| | Weed density (plants $ha^{-1}$) | | Above ground biomass (kg $ha^{-1}$) | | Weed seed dockage (g $m^{-2}$) | |
| | 2020 | 2021 | 2020 | 2021 | 2020 | 2021 |
| Cultivar (Cu) | ns[a] | ns | ns | ns | ns | ns |
| Row Spacing (RS) | ns | **0.001**[b] | ns | ns | ns | ns |
| Target Density (TD) | **0.001** | ns | **0.003** | ns | ns | ns |
| Cover Crop (CC) | **0.034** | ns | ns | **0.024** | **< 0.001** | ns |
| Cu× RS | ns | ns | ns | **0.007** | ns | ns |
| Cu×TD | ns | ns | ns | ns | ns | ns |
| RS×TD | ns | ns | ns | ns | ns | ns |
| Cu×CC | ns | ns | ns | ns | ns | ns |
| RS×CC | ns | ns | ns | ns | ns | ns |
| TD×CC | ns | ns | ns | ns | ns | **< 0.001** |
| Cu×RS×TD | ns | ns | ns | ns | ns | ns |
| Cu×RS×CC | ns | ns | ns | ns | ns | ns |
| Cu×TD×CC | ns | ns | ns | ns | ns | ns |
| RS×TD×CC | ns | ns | ns | ns | ns | ns |
| Cu×RS×TD×CC | ns | ns | ns | ns | ns | ns |

[a] ns denotes treatment effects are not significant ($P > 0.05$)
[b] Bold values indicate significant treatment effects at $P \leq 0.05$

Table A5: ANOVA summary (P-values) for the main and interaction effects of soybean row spacing, cultivar, target plant density, cover crop, burial number and soil depth on each environmental (PRS and PR2) variable in 2020, 2021 experiments at Lethbridge, Alberta.

| Environmental variables[a,b] | | | | |
|---|---|---|---|---|
| | PRS[c] | | PR2[d] | |
| | 2020 | 2021 | 2020 | 2021 |
| Cultivar (Cu) | ns[a] | ns | ns | ns |
| Row Spacing (RS) | **0.009[b]** | **0.0207** | ns | ns |
| Target Density (TD) | ns | ns | ns | ns |
| Cover Crop (CC) | **0.0069** | **0.0307** | ns | ns |
| Burial Number (BN) | **<.0001** | **<.0001** | ns | ns |
| Depth (D) | ns | ns | **<.0001** | ns |
| Date (Da) | ns | ns | **<.0001** | **<.0001** |
| Cu× RS | ns | ns | ns | ns |
| Cu×TD | ns | ns | ns | ns |
| RS×TD | ns | ns | ns | ns |
| Cu×CC | ns | ns | ns | ns |
| RS×CC | ns | ns | ns | ns |
| TD×CC | ns | ns | ns | ns |
| BN×CC | **0.0021** | | ns | ns |
| D×RS | ns | ns | ns | **0.0436** |
| Da×RS | ns | ns | **0.0424** | ns |
| Da×CC | ns | ns | **<.0001** | ns |
| D×Da | ns | ns | **<.0001** | ns |
| Cu×RS×TD | ns | ns | ns | ns |
| Cu×RS×CC | ns | ns | ns | ns |
| Cu×TD×CC | ns | ns | ns | ns |
| RS×TD×CC | ns | ns | ns | ns |
| Cu×RS×TD×CC | ns | ns | ns | ns |

[a] ns denotes treatment effects are not significant ($P > 0.05$)
[b] Bold values indicate significant treatment effects at $P \leq 0.05$
[c] Plant root simulator probe data
[d] Soil volumetric water content data

### 6.2.2. Appendix B

Partial budget analysis for each target plant density

Seed cost for 400,000 plants $ha^{-1}$ = [CAD \$3.67 10,000 $seeds^{-1}$ (Thai et al. 2022)] × 400,000 plants $ha^{-1}$ × 1.33 (inverse of 75% seed survival) = CAD \$195 $ha^{-1}$

Seed cost for 600,000 plants $ha^{-1}$ = (CAD \$3.67 10,000 $seeds^{-1}$) × 600,000 plants $ha^{-1}$ × 1.33 (inverse of 75% seed survival) = CAD \$293 $ha^{-1}$

Weed management cost = \$CAD 17.34 $ha^{-1}$ × 2 applications per year = \$34.68 $ha^{-1}$ (Ontario of Agriculture 2019)

Soybean market price = \$0.378 $kg^{-1}$ (MAFRD 2016)

Ex: Partial budget at 400,000 target plants $ha^{-1}$ in weed-free conditions in 2020 experiment site, Lethbridge, AB

Soybean yield = 2985 kg $ha^{-1}$

Gross revenue = (2985 kg $ha^{-1}$ × \$0.378 $kg^{-1}$) = CAD \$1128

Gross revenue - Seed cost = CAD \$1128 - CAD \$195 $ha^{-1}$ = CAD \$933

Partial budget at 600,000 target plants $ha^{-1}$ in weed-free conditions in 2020 experiment site, Lethbridge, AB

Soybean yield = 3190 kg $ha^{-1}$

Gross revenue = (3190 kg $ha^{-1}$ × \$0.378 $kg^{-1}$) = CAD \$1206

Gross revenue - Seed cost = CAD \$ 1206 - CAD \$293 $ha^{-1}$ = CAD \$913

Partial budget at 400,000 target plants $ha^{-1}$ in weedy condition in 2020 experiment site, Lethbridge, AB

Soybean yield = 1019 kg $ha^{-1}$

Gross revenue = (1019 kg $ha^{-1}$× \$0.378 $kg^{-1}$) = CAD \$385

Gross revenue - Seed cost = CAD \$385 - 195 $ha^{-1}$ = CAD \$190

Partial budget 600,000 target plants $ha^{-1}$ in weedy condition in 2020 experiment site, Lethbridge, AB

Soybean yield = 1214 kg $ha^{-1}$

Gross revenue = (1214 kg $ha^{-1}$× \$0.378 $kg^{-1}$) = CAD \$459

Gross revenue - Seed cost = CAD \$ 459- CAD \$293 $ha^{-1}$= CAD \$166