

**Evaluating Intercropped Cover Crops and Their Compatibility with Canola and Wheat
Herbicidal Weed Management Strategies on the Canadian Prairies**

by

Janelle Breanne Gawiak

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ABSTRACT

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The use of fall-seeded cover crops on the Canadian Prairies is constrained by the short growing season and limited fall precipitation. Intercropping cover crops with a cash crop can extend the establishment window and increase biomass accumulation; however, herbicide compatibility and intercrop competition remain barriers to adoption. This thesis evaluated the feasibility of intercropping cover crops within canola (*Brassica napus* L.) and spring wheat (*Triticum aestivum* L.) as well as their compatibility with herbicide management strategies. Field experiments were conducted in 2022 and 2023 at two locations (Carman, Manitoba and Kernen, Saskatchewan). In canola, three herbicide frequency treatments (pre-emergence only, pre-emergence and in-season, and a pre-emergence, in-season, and desiccant) were compared for all three herbicide tolerance systems utilized with canola hybrids (Liberty Link®, Roundup Ready®, and Clearfield®). In wheat, three in-season herbicides (bentazon, tralkoxydim, and pyroxsulam) were compared alongside a no-herbicide control. A multispecies cover crop mixture was intercropped simultaneously with both crops, and measurements included cover crop establishment, herbicide injury, weed pressure, fall biomass, and cash crop yield. Cover crop establishment and persistence were highly variable across years, locations, and cash crops, reflecting strong environmental and competitive constraints. In both cropping systems, increased seeding rates and reduced herbicide frequency improved cover crop establishment and persistence. In canola, cover crop biomass was greatest under the pre-emergence only treatment, but the increase in biomass was associated with yield penalties in some environments. Following

in-season herbicide applications, cover crop performance within contrasting canola herbicide tolerance systems varied by site. In wheat, the tralkoxydim herbicide was tolerated by cover crop species and resulted in biomass amounts similar to the no herbicide control, with no effect on wheat yield. Weed suppression benefits from cover crops were limited and inconsistent, especially where cover crop establishment was poor. Overall, this research demonstrates that intercropping cover crops can partially overcome environmental constraints, but success is dependent on herbicide selection, herbicide frequency, and site-specific growing conditions. These findings highlight the need for regionally adapted agronomic strategies and further research to optimize cover crop intercropping strategies for canola and wheat that do not compromise cash crop yield.

FOREWORD

This thesis was written in accordance with the University of Manitoba Faculty of Graduate Studies thesis guidelines and follows the manuscript style format of the Agronomy Journal. The thesis consists of seven chapters, in which the candidate is the first author, including an Introduction (Chapter 1), Literature Review (Chapter 2), two stand-alone research chapters each containing an Abstract, Introduction, Materials and Methods, Results and Discussion, and Summary and Conclusions (Chapters 3 and 4), General Discussion (Chapter 5), Literature Cited (Chapter 6) and Appendices (Chapter 7). At this time, the manuscripts have not been submitted for publication.

CONTRIBUTION OF AUTHORS

J. B. Gawiak: conducted the field-based research experiments in Carman, MB, statistical analysis and presentation of the data, result interpretation, and writing of the thesis. Y E. Lawley: supervision, conceptualization, editing, and reviewing. D. I. Benaragama and J. Thiessen Martens: reviewing and editing. M. Bourgault: data collection from Kernen, SK.

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1.0 INTRODUCTION

The practice of cover cropping in agricultural systems on the Canadian Prairies is within its infancy, while the practice is currently more dominant in Eastern Canada (Statistics Canada, 2023) and the United States Midwest (Myers, 2019), where cover crops have a longer window to be seeded after cash crop harvest. Cover crops are grown primarily to provide ecosystem services within cropping systems, including improved soil health (Blanco-Canqui & Jasa, 2019), reduced soil erosion (Thiessen Martens et al., 2015), and weed suppression (Koudahe et al., 2022). On the Prairies, the practice of using fall shoulder-season cover crops is hindered by poor establishment and restricted biomass production, due to the short growing season and limited moisture availability (Antosh et al., 2022). Despite these challenges, the adoption of cover crops has increased in Manitoba and Alberta by 2% and a further 3% in Saskatchewan between 2017 and 2021 (Statistics Canada, 2023) due to innovative agronomic practices that help overcome climatic constraints.

One such practice is intercropping, where a cover crop is established during cash crop growth to extend the length of the growing season (Lawley, 2013). Intercropping cover crops can increase establishment by allowing cover crops to utilize available light, nutrients, and water earlier in the season, while contributing to weed suppression during the growing season (Thiessen Martens et al., 2015). Recently across the United States, there has been success in increasing establishment and biomass by intercropping cover crops into row crops such as corn (*Zea mays* L.), sunflower (*Helianthus annuus* L.), and soybean (*Glycine max* (L.) Merr.) without negatively impacting cash crop yield (Antosh et al., 2022; Mohammed et al., 2020). Although research on cover crops in Canada is limited, a recent Prairie Cover Crop Survey conducted by Morrison and Lawley (2021) found that 37% of respondents were seeding cover crops at the

same time as a cash crop and 14% were broadcasting a cover crop into a cash crop, indicating interest in the practice of intercropping cover crops.

However, intercropping cover crops comes with its own agronomic complexities. The cover crop species must be able to establish beneath the cash crop canopy, endure the herbicide strategy, and not reduce the yield of the cash crop (Lawley, 2013). Identifying compatible herbicides presents a significant obstacle, as residual herbicides can restrict cover crop growth (Smith & Ruark, 2022). Additionally, a pre-emergence or in-season herbicide application poses a greater risk of injury to a cover crop that is intercropped into the cash crop compared to a cover crop seeded following harvest (Stahl & Ley, 2022). With the application of in-season herbicides, the length between herbicide application and cover crop seeding influences this injury potential.

Research on intercropping cover crops within annual crops on the Canadian Prairies is limited, with research conducted in the United States having limited application due to differences in climate, location, and growing season length. Additionally, research on intercropping cover crops within the two most sown crops on the Canadian Prairies, canola and wheat, is currently negligible. Due to complexities in weed management with intercropping, this research is crucial to provide producers and agronomists across the Canadian Prairies with agronomic information to maximize the benefits of cover crops while minimizing production risks.

This thesis discusses two studies that evaluated intercropped cover crops and their compatibility with canola and wheat weed management strategies, with the following research objectives:

1. To identify compatible herbicide packages and herbicide frequencies for cover crops intercropped in canola (*Brassica napus* L.).

2. To identify compatible in-season herbicides for cover crops intercropped in wheat
(*Triticum aestivum* L.)

2.0 LITERATURE REVIEW

2.1 Cover Crop Utilization

2.1.1 History of Cover Cropping

The agronomic practice of cover cropping has been used within agricultural systems for centuries. The earliest reported use of cover crops as a green manure was in the 12th to 3rd century B.C.E. by the Zhou dynasty of China, where grasses or weeds were used as a manure (Pieters, 1927). Following the Chinese in 116-27 B.C.E., the Roman Empire used lupine or bean cover crops to improve the conditions of “thin land” (Pieters, 1927). More recently, in the 16th century, the use of pea (*Pisum sativum* L.) and buckwheat (*Fagopyrum esculentum* Moench) was suggested to improve fertility from continuous cropping of wheat, barley (*Hordeum vulgare* L), oat (*Avena sativa* L.), and rye (*Secale cereale* L.) (Lal, 2015). Green manuring was later introduced to Germany in the 17th century and to England in the 18th century, prior to being brought over to American colonies along the Eastern seaboard by immigrant farmers later in the 18th century (Pieters, 1927).

2.1.2 History of Cover Cropping in North America

Cover cropping and the use of green manures in America were not common when first introduced to the American colonies. In the 18th century, George Washington was an advocate for cover crop use as he grew a rotation that included “crops to eat and sell” and “crops to replenish the soil” (Groff, 2015). By the 1860’s, cover cropping became a common practice of American agriculture and remained for a century (White, 2014) until its decline following World War II with the introduction of synthetic fertilizers, herbicides, genetics, and machinery (Kladivko, 2020; Shirriff et al., 2022; Dong & Zeng, 2024). The increasing affordability of herbicides enabled the adoption of chemical fallow, which expanded from the 1950’s to its peak

in the 1980's (Carlyle, 1997), further displacing the use of green manures during fallow periods in annual crop rotations (Bodah et al., 2011).

The intensification of chemical and tillage practices in conventional agriculture led to several deleterious effects, including topsoil degradation and soil erosion in the 1960's, prompting renewed interest in conservation agriculture and regenerative practices (Acton & Gregorich, 1995). These approaches have focused on improving soil health through several beneficial management practices, including crop diversity, which can be enhanced by cover cropping (Voisin et al., 2024). While cover cropping is now considered a conventional practice within the United States Midwest and Eastern regions, adoption is increasing in the Northern Great Plains (Wallander et al., 2021). North Dakota and Montana, which share a northern border with the Canadian Prairie provinces of Manitoba, Saskatchewan, and Alberta, have seen an 89 and 18% increase, respectively, in cover crop acres from 2012 to 2017 (Myers, 2019). This increase in adoption across the United States can be attributed to both producer interest in soil health building practices and the establishment of financial incentives from Federal and State conservation programs, in addition to nongovernmental organizations (Wallander et al., 2021).

2.1.3 History of Cover Cropping on the Canadian Prairies

The adoption of cover crops on the Canadian Prairies has historically been limited compared to other regions of the country. The first time that data on cover crop usage in Canada was collected was in the 2015 Canadian Farm Census, which reported that the proportion of farms using cover crops was 14% nationally (Figure 2.1). In Western Canada, the percentage of farms using cover crops was less prominent, with reported usage ranging from less than 1 to 15% (Statistics Canada, 2015). However, it should be noted that during this survey, cover crop usage was overreported due to the misclassification of winter cereals as cover crops.

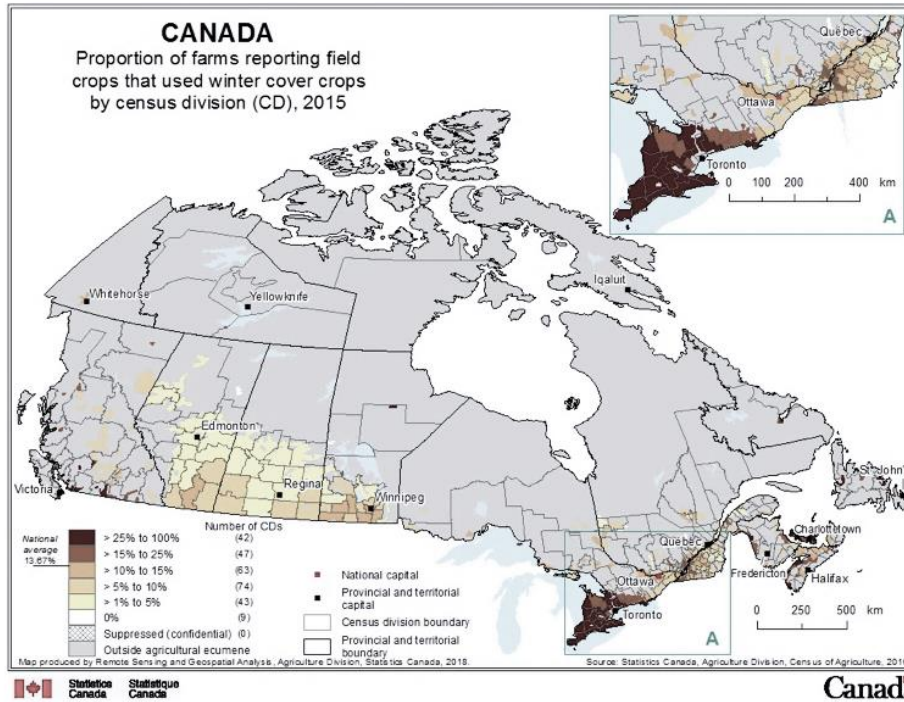


Figure 2.1. Statistics Canada (2015) figure of the proportion of farms that reported field crops with the use of winter cover crops by census division (CD).

More recently, the 2021 Census of Agriculture and the Farm Management Survey indicate that cover crop use remains relatively low in the Prairie provinces but is gradually increasing. Of the 20,330 Canadian farms that reported planting overwintering cover crops after cash crop harvest, 773 were located in Manitoba, 732 in Saskatchewan, and 1130 in Alberta (Statistics Canada, 2023). The Farm Management Survey conducted by Statistics Canada added new questions to the survey in 2017 to better understand cover crop use across Canada. From 2017 to 2021, all five provinces (Alberta, Saskatchewan, Manitoba, Ontario, and Quebec) reported an increase in the percentage of respondents using fall and winter cover crops (Table 2.1). The Prairies remained below the national average, consistent with the Agriculture Census data, and show greater cover crop use in the Eastern Provinces.

Table 2.1. Percent of Canadian field crop farms that reported use of a fall or winter cover crop as a land management practice by province from the Farm Management Survey in 2017 and 2021. Adapted from Statistics Canada (2023).

Province	2017	2021
	%	
Alberta	2	4
Saskatchewan	-	3
Manitoba	4	6
Ontario	33	36
Quebec	19	27
Canada	13	16

To better understand cover crop use on the Canadian Prairies, the University of Manitoba conducted a voluntary producer survey in 2020 across Manitoba, Saskatchewan, and Alberta. In this survey, cover crops were classified as full-season or shoulder-season (Morrison, 2021). Full-season cover crops are grown to replace a cash crop or fallow period during the growing season to provide specific benefits to the agroecosystem (Wagg et al., 2021). From the 281 respondents to the Prairie Cover Crop survey, full-season cover crops were most popular in Alberta, being used on 63% of reported farm acres, whereas in Saskatchewan and Manitoba, they were used on 45 and 36% of reported acres, respectively (Morrison & Lawley, 2021). The greatest use of full-season cover crops occurs in organic production, where green manure crops are integrated into rotations to fix nitrogen and smother weeds due to restrictions on synthetic chemicals (King, 1999). Not only are full-season cover crops used in organic production, but conventional producers also utilize them when a cash crop cannot be planted due to weather or soil constraints or for livestock feed (Lawley, 2013).

In contrast, a shoulder-season cover crop is grown before spring seeding of the cash crop or after the fall harvesting of a cash crop (Janzen and Lawley, 2022). On the Prairies, a shoulder-season cover crop is most often seeded following harvest and was seeded on 37, 41, and 60% of reported farm acres in Alberta, Saskatchewan, and Manitoba, respectively, in the 2020 Prairie

Cover Crop Survey (Morrison & Lawley, 2021). Shoulder-season cover crops are used to protect the soil against water or wind erosion (Morrison, 2021) and to reduce nitrogen leaching and losses (Hashemi et al., 2013). Despite the quick benefit they provide, the Prairies' short growing season and limited moisture availability hinder the establishment and biomass of fall shoulder-season cover crops (Antosh et al., 2022). To mitigate the negative effects of the short growing season, cover crops planted in the fall shoulder-season need to be seeded earlier to accumulate biomass prior to termination (Hashemi et al., 2013).

2.1.4 Barriers to Cover Crop Adoption on the Canadian Prairies

Lower adoption of cover crops on the Canadian Prairies compared to Eastern Canada is largely attributed to the region's climatic constraints. According to the 2020 Prairie Cover Crop Survey, 30% of respondents identified the short growing season as the greatest challenge, followed by 27% citing the lack of moisture available in the fall (Morrison & Lawley, 2021). These environmental limitations both restrict the range of cover crop species that can establish and limit their performance, resulting in producers developing innovative regimes to successfully adopt cover crops (Morrison, 2021).

The Canadian Prairie ecozone is characterized by a semi-arid climate (Sauchyn et al., 2002), where agricultural production is affected by aridity and variability in temperature and precipitation (Canadian Environmental Assessment Agency, n.d.; Mapfumo et al., 2023). Unlike the humid and temperate regions of Eastern Canada, the Prairies experience extremes in temperatures with long, cold winters spanning from November to March and short, warm summers (Garnett & Khandekar, 2017). Average annual precipitation ranges from 300 to 550 mm, with most rainfall events coinciding with the growing season in May to August (McGinn, 2010; Garnett & Khandekar, 2017). During the growing season, the Prairies can experience both extreme precipitation and severe droughts (Basu et al., 2020). The amount of precipitation

received on the Prairies is below the Canadian average (McGinn, 2010), and with the warm summer temperatures, evaporation and transpiration rates are elevated, increasing the risk of droughts due to lower soil moisture (Basu et al., 2020). Periods of recurrent drought, which are typical of the Prairies, can make cover crop establishment following the main crop a challenge (Idowu & Grove, 2014).

Beyond climatic limitations, one of the most significant barriers to adoption is the lack of published agronomic research from the Canadian Prairies and the Northern Great Plains (Liebig et al., 2015). Nearly 40% of respondents to the 2020 Prairie Cover Crop Survey indicated that more information specific to the Prairies is required to enable adoption (Morrison & Lawley, 2021). The lack of regional information limits the development of optimized agronomic strategies suited to the Prairie conditions (Food and Water Wellness Foundation, 2024), as current recommendations are based on data from humid or temperate climates (Blanco-Canqui et al., 2015; Chahal et al., 2020; Yang et al., 2023). Furthermore, information on cover crops specific to the Canadian Prairies is crucial for understanding what cover crop species can reliably establish and the benefits or risks they present, but also for supporting decisions by producers, agronomists, and policy makers (Morrison & Lawley, 2021).

2.2 Cover Crop Species Selection

Cover crops vary in plant-specific functional traits, including root system architecture and rooting depth, canopy development, and leaf area (Wagg et al., 2021). Cover crop species selection also depends on other characteristics, including ease of establishment and termination, weed suppressive abilities, and low competitiveness (Scavo et al., 2022). Selection is also influenced by local climate, soil, and management factors that influence cover crop performance (Scavo et al., 2022; Koudahe et al., 2022). On the Canadian Prairies and across North America, cover crop species fall into three main families: grasses (*Poaceae*), brassicas (*Brassicaceae*) and

non-leguminous broadleaves, or legumes (*Fabacea*), each offering unique benefits and having specific management considerations (Belfry & Van Eerd, 2016). The 2020 Prairie Cover Crop Survey found that of the 15 most commonly grown cover crop species, five species were grasses, four were legumes, and two were brassicas (Morrison & Lawley, 2021).

2.2.1 Grass Cover Crops

Cover crop species from the *Poaceae* family are utilized for their rapid growth and persistent residues that provide substantial ground cover (Koudahe et al., 2022). Blanco (2023) conducted a quantitative synthesis of published field experiments and found that in semi-arid regions, grass cover crops produced greater biomass ($3370 \pm 3220 \text{ kg ha}^{-1}$) than brassicas (1890 ± 1220) and legumes (2190 ± 1940) (Blanco, 2023). Additionally, a two-year field experiment in Nebraska conducted by Thapa et al. (2025) observed that grass monocultures of oat, triticale (*X Triticosecale* Wittmack), and barley ($470\text{-}1130 \text{ kg ha}^{-1}$) produced greater biomass 60-81 days after seeding when compared to brassica monocultures of collard (*Brassica oleracea* L. var. *viridis*) and rapeseed ($50\text{-}120 \text{ kg ha}^{-1}$) or legume monocultures of faba bean (*Vicia faba* L.) and pea ($160\text{-}530 \text{ kg ha}^{-1}$).

The high carbon content of grass cover crop biomass often results in a biomass C:N ratio above 25:1, causing nitrogen immobilization and denitrification inhibition (Natural Resources Conservation Service, 2022; Guardia et al., 2016). However, experiments from the Canadian Prairies report C:N ratios of cover crop biomass below 25:1 due to limited plant growth in the fall shoulder-season (Janzen, 2023; Penner, 2024; Otchere et al., 2023). On-farm field experiments at four locations in Manitoba found fall rye and oat cover crops had a C:N ratio in the range of 9 to 14 (Penner, 2024), whereas small-plot experiments in Manitoba with fall rye cover crops had C:N ratios below 18 for biomass (Janzen, 2023). As a result of their slower

decomposition, grass cover crops are more effective at increasing soil carbon and organic matter compared to legumes (Blanco-Canqui, 2013). A 12-year Nebraska study found that grass cover crops (cereal rye and grain sorghum (*Sorghum bicolor* (L.) Moench)) increased soil organic matter by 11% while legume cover crops (Austrian winter pea (*P. sativum* L. subsp. *arvense*) and soybean) had no effect, which was similar to the no cover crop control (Blanco-Canqui & Jasa, 2019). Their high biomass production can also suppress weed seedlings as they compete for light and nutrients (Koudahe et al., 2022). Over a three-year field experiment in Pennsylvania, grass cover crops provided the greatest suppression with a mean weed biomass of 41 kg ha⁻¹ followed by brassicas (136 kg ha⁻¹) and legumes (328 kg ha⁻¹) when a cover crop followed winter wheat harvest (Baribar et al., 2017).

Although grass cover crops do not fix nitrogen, their expansive rooting system captures residual nitrate, reducing leaching and denitrification (Ruffo & Bollero, 2003). However, these effects are dependent on cover crop rooting depth and nitrogen availability within the soil (Justes et al., 2017). A two-year field study in Illinois integrated cereal rye in a corn–soybean system and found cereal rye reduced total N losses to 13 kg N ha⁻¹ when compared to 26 kg N ha⁻¹ without the cereal rye cover crop (Johnson II et al., 2024). In addition to nitrogen, grass species can relocate phosphorus, potassium, and calcium to the surface from deep within the soil profile (Chatterjee & Clay, 2016). In a continuous no-till corn–soybean–winter wheat rotation in Nebraska, cereal rye and sorghum cover crops increased phosphorus by 3 mg kg⁻¹, potassium by 90 mg kg⁻¹, and calcium by 250 mg kg⁻¹ following winter wheat when compared to a no cover crop control at a depth of 0 to 7.5 cm (Blanco-Canqui & Jasa, 2019).

Grass cover crops provide greater wind and water erosion control than broadleaf or legume cover crops due to taller residues and slower decomposition (Blanco-Canqui et al.,

2015). The fine and fibrous rooting system of grass species aids in the reduction of erosion while improving soil structure through increasing the mean soil aggregate size. A field experiment in Nebraska found that mean soil aggregate size increased from 1.8 mm in the absence of cover crops to 2.4 mm with grass cover crop species after 12 years of cover crop management (Blanco-Canqui & Jasa, 2019). Compared to fallow, winter and spring triticale cover crops (*X Triticosecale* Wittmack) increased the mean dry aggregate size by 0.6 and 0.8 mm, respectively, and reduced the wind erodible fraction by 0.2 in Kansas field experiments (Blanco-Canqui et al., 2013).

2.2.2 Brassica and Non-Legume Broadleaf Cover Crops

Brassica species are commonly grown for their rapid fall growth, moderate biomass production, and nitrogen scavenging abilities (Clark, 2007). The 2020 Prairie Cover Crop Survey found that radish (*Raphanus sativus* L.) and turnip (*Brassica rapa* L. subsp. *rapa*) were among the top 10 cover crop species used by producers on the prairies and were being grown by 36 and 30% of respondents, respectively (Morrison & Lawley, 2021). Non-leguminous broadleaf species of cover crops can capture nitrogen amounts similar to grass species. A North Dakota field experiment found radish with a biomass of 1600 kg ha⁻¹ accumulated 54 kg N ha⁻¹, whereas rye with a biomass of 1300 kg ha⁻¹ accumulated a lesser 39 kg N ha⁻¹ (Leiva, 2025). However, brassica and non-leguminous broadleaf cover crops release their nitrogen more rapidly due to their quick decaying residues (Koudahe et al., 2022) and low C:N ratio (Opoku et al., 2024) that immobilize less nitrogen (Clark, 2007) compared to grass cover crops.

In addition to their scavenging ability, brassica cover crops are recognized for their use as biofumigants, which release biotoxins upon decomposition that can reduce disease and weed pressure (Clark, 2007). When incorporated, a bioassay of spring-seeded brassica species of

rapeseed and mustard (*Sinapis alba* L.) delayed weed emergence by 2 days and reduced weed emergence by 23 to 34% compared to a no cover crop fallow (Haramoto & Gallandt, 2005).

The deep tap-rooting system specific to some broadleaved cover crop species can alleviate soil compaction more effectively than grass species due to their ability to penetrate compacted layers (Clark, 2007; Chen & Weil, 2010). Forage radish (*R. sativus* L. var. *longipinnatus*) and rapeseed were shown to reduce compaction by exhibiting 2.7 and 2.0-times greater root density, respectively, and a greater root penetration than rye at a soil depth of 15 to 50 cm in compacted Maryland soils (Chen & Weil, 2010). Upon decomposition, the macropores left behind by cover crop taproots can further improve soil aeration and water infiltration if left undisturbed by tillage (Koudahe et al., 2022).

2.2.3 Legume Cover Crops

Legume cover crop species can fix 60 to 80 kg ha⁻¹ of atmospheric nitrogen through biological nitrogen fixation with rhizobium symbiosis, depending on conditions (Moller et al., 2008) and can further reduce nitrate leaching by 40%, reducing dependence on synthetic agricultural inputs (Abdalla et al., 2019; Wong et al., 2023). Due to their ability to fix nitrogen, the C:N ratio of legume cover crops is often lower compared to grass cover crops, enabling nitrogen mineralization and availability to the subsequent crop (Drost et al., 2020; Kaye et al., 2019). Legume biomass with a high nitrogen percentage (3 to 4% N in dry matter) can provide 11 to 18 kilograms of plant-available nitrogen per tonne of dry matter, which is released as early as four weeks after termination (Sullivan et al., 2020). The nitrogen contribution of legume cover crops to subsequent crops has been estimated using the fertilizer replacement value as a measure of the nitrogen content of above-ground biomass (Thiessen Martens et al., 2005). In Winnipeg, Manitoba, relay-cropped alfalfa (*Medicago sativa* L.) contributed approximately twice the amount of nitrogen as red clover (*Trifolium pratense* L.), with fertilizer replacement values

ranging from 51-62 kg N ha⁻¹ and 24-26 kg N ha⁻¹, respectively, for a following oat crop (Thiessen Martens et al., 2005). By supplying nitrogen to the system, legume cover crops can indirectly reduce NO₂ fluxes through reduced inorganic fertilizer use (Blanco-Canqui et al., 2015).

Despite their ability to fix atmospheric nitrogen, legume cover crops from the *Fabaceae* family produce less biomass than grass and non-legume broadleaf cover crops (Wong et al., 2023), primarily attributed to slower establishment (Quinn et al., 2019). Across the Great Plains, spring-seeded oat cover crops consistently produced more biomass than pea. A study in Colorado found that oat cover crop biomass ranged from 3460 to 3540 kg ha⁻¹ compared to 2400 to 3300 kg ha⁻¹ for pea, while a study in Nebraska reported oat cover crop biomass ranged from 2560 to 5160 kg ha⁻¹ and pea biomass ranged from 2510 to 4990 kg ha⁻¹ (Nielsen et al., 2015). Similarly, a study in North Dakota found the biomass of fall-seeded spring triticale cover crops to range from 349 to 1944 kg ha⁻¹, whereas pea produced a lesser 190 to 1308 kg ha⁻¹ (Liebig et al., 2015).

2.2.4 Cover Crop Mixtures

When used as a monoculture, cover crops may not provide all desired benefits, and thus mixtures of grass, broadleaf, and legume species are often used. The most extensively used cover crop mixture is one that combines a grass and legume species, as grasses establish quickly to suppress weed seedlings, while supporting the slower-establishing legumes (Clark, 2007). By planting cover crops in mixtures, functional stability and resiliency are often improved, resulting in greater and more consistent cover crop productivity (Wortman et al., 2012).

Cover crop mixtures can overyield relative to the monoculture cover crops (Smith et al., 2014; Wortman et al., 2012). Overyielding occurs when the mixture biomass exceeds its monoculture components (Schmid et al., 2008). Often, land equivalent ratios (LER) are utilized

to determine the productivity of crop mixtures relative to their monocultures, where values greater than 1 indicateoveryielding (Smith et al., 2014). For cover crops, LERs can be utilized to determine if there areoveryielding benefits for the intercropped cash crop. Over two years, Smith et al. (2014) found that a five-species cover crop mixture had an LER greater than 1. This was consistent with the findings of Wortman et al. (2012), who reported that cover crop mixtures of four, six, and eight species had average LERs exceeding 1. Consistent with findings based on LERs, measurements of cover crop biomass also supportoveryielding. In a Nevada field experiment by Opoku et al. (2024), the average two-year biomass of annual ryegrass (*Lolium multiflorum* Lam.) (6799 kg ha⁻¹), faba bean (*Vicia faba* L.) (3391 kg ha⁻¹), and yellow sweet clover (*Melilotus officinalis* (L.) Lam.) (6069 kg ha⁻¹) was less than that of their mixture (6893 kg ha⁻¹). Similar results were observed in the study for a second mixture, where biomass of the mixture (9714 kg ha⁻¹) was greater than its monoculture components of oat (7970 kg ha⁻¹), winter pea (3377 kg ha⁻¹), and faba bean (3391 kg ha⁻¹) (Opoku et al., 2024).

However, other studies have not observedoveryielding in cover crop mixtures. In these cases, one high-yielding species, often a grass, dominates the mixture (McKenzie-Gopsill et al., 2022). A two-year field experiment in Colorado and Nebraska found that a 10-species mixture produced the greatest biomass in only one out of four site-years, and the oat monoculture otherwise outyielded the mixture (Nielsen et al., 2015). Similarly, a three-year field experiment in North Dakota found that an equal mixture of red clover, forage radish, proso millet (*Panicum miliaceum* L.), and triticale yielded 2654 kg ha⁻¹, which was less than the triticale monoculture, which yielded 3165 kg ha⁻¹ (Sanderson et al., 2018).

Including cover crop species from different functional groups can provide greater agronomic benefits. Cover crop mixtures can suppress weeds as effectively as the most

productive monocultures (Baribar et al., 2018; McKenzie-Gopsill et al., 2022), decrease the C:N ratio compared to grass monocultures (Opoku et al., 2024), and can increase legume nitrogen fixation relative to a legume monoculture (Thapa et al., 2018; Bressler & Blesh, 2023).

2.3 Intercropping of Cover Crops

Intercropping cover crops is the practice of establishing a cover crop during the cash crop growing season (Lawley, 2013). It can enable successful cover crop establishment and benefit acquisition in a short growing season (Thiessen Martens et al., 2015). Intercropped cover crops can suppress weeds during the growing season, post-harvest, and into the following spring if the cover crop species overwinters (Rees et al., 2021). Recent studies in the Northern Great Plains on intercropping cover crop mixtures into row crops, such as corn and soybean, have shown increased establishment and biomass production without reducing cash crop yield (Antosh et al., 2022; Mohammed et al., 2020). Studies in the Northern Great Plains have also demonstrated success when intercropping legume cover crops, such as alfalfa or clovers, in winter cereal crops (Blackshaw et al., 2010; Anderson, 2017; Thiessen-Martens et al., 2001).

Despite these potential benefits, intercropping cover crops comes with its own challenges. The cover crop must be able to establish beneath the cash crop canopy, endure the herbicide strategy, and avoid reducing cash crop yield (Lawley, 2013). Cover crop establishment can be hindered by canopy closure, especially if the cover crop emerges after the cash crop. Furthermore, the shady and humid conditions beneath a crop canopy can reduce the cover crop plant stand (Lawley, 2013), limiting the number of plants that will survive until harvest.

2.3.1 Intercrop Management

While intercropping can improve establishment and system productivity, the practice introduces greater agronomic management complexities. Successful implementation requires

careful consideration during key stages of the growing season, particularly during seeding, in-season weed management, and harvest.

2.3.1.1 Seeding Practices for Intercrops

Various spatial arrangements can be utilized when establishing intercrops and are dependent on management goals and available equipment. The primary types of intercrops include row, strip, and mixed systems, which vary in management complexity, machinery requirements, and the level of interaction between intercropped species.

Row intercropping involves seeding the intercropped species in distinct rows. Row intercropping can occur as alternate-row intercropping, where each distinct species is sown in its own row, or as within-row, where multiple species are seeded within the same row (Lithourgidis et al., 2011). Within-row intercropping can be accomplished using a singular seed box or air cart tank, whereas alternate-row intercropping requires modified drills with multiple seed boxes or air cart tanks to support seeding species in independent rows. Row intercropping promotes interspecific interactions between intercropped plant species, including shading, structural support, root intermingling, and resource competition (Glaze-Corcoran et al., 2020).

Strip intercropping, in contrast, involves growing the intercrop species in adjacent strips that remain completely distinct from one another (Bybee-Finley & Ryan, 2018). Strip intercropping can be accomplished using existing machinery coupled with the use of GPS guidance (Feike et al., 2012; Campanelli et al., 2023; Glaze-Corcoran et al., 2020). The width of intercrop strips is often based on the width of available seeding equipment (Van Oort et al., 2020) or with sectional control within large seeders. The strips must be wide enough to permit independent field operations and management for seeding, crop protection, and harvest, but are in proximity for interspecific interactions between border rows of the strips (Li et al., 2001; Ma et al., 2024; Cruse & Gilley, 2008). Strip intercropping is most prominent on sloped terrains,

where it is often used to prevent erosion, but also can be used on fields with limited slope (Lithourgidis et al., 2011).

Mixed intercropping occurs when two or more species are seeded with no distinct rows or divisions (Petrie & Bates, 2017; Bybee-Finley & Ryan, 2018; Brooker et al., 2014). With no spatial arrangement, mixed intercrops are established by broadcasting (Bybee-Finley & Ryan, 2018). However, their seeding ratio is difficult to develop and is inconsistent throughout the field due to nonuniform seed mixing that can be accentuated by contrasting seed size of the intercrop species (Glaze-Corcoran et al., 2020). Within this arrangement, there is the greatest potential for interspecific competition and beneficial interactions (Glaze-Corcoran et al., 2020). Mixed intercropping is often used when equipment options are limited, and can be used in fields with variable conditions for establishment, in pastures where there is a greater risk of species failure (Lithourgidis et al., 2011), or in fields used for extended livestock grazing (Glaze-Corcoran et al., 2020).

When intercropping cover crops, seeding rates and species selection must account for seed size and shape, seeding depth, relative time to maturity, and spatial arrangement (Glaze-Corcoran et al., 2020). In row intercropping systems, using seeding rates optimized for the monoculture grain crop can lead to increased interspecific competition. Therefore, a typical seeding rate used for intercrops on the Canadian Prairies is to seed a legume at two-thirds of its monoculture rate and cereals or oilseeds at half their monoculture rate (Liu et al., 2025; Guenther, 2018; Government of Saskatchewan, n.d.; Khakbazan et al., 2025). Alternatively, the replacement strategy can be used, where the target plant population of the primary species is replaced with the secondary species to maintain the overall density of the intercrop (Glaze-Corcoran et al., 2020). However, in strip intercropping, this strategy is not used. Instead, the

seeding rates resemble those used for the monocultures (Glaze-Corcoran et al., 2020).

Additionally, row and strip configurations require consideration of strip width or the number of rows and row spacing. These factors are often constrained by the dimensions and features of available machinery. In mixed intercrop arrangements, the emphasis shifts to the ratio of each species in the intercrop mixtures as it influences crop composition and competitiveness (Glaze-Corcoran et al., 2020). Target plant density rather than seed weight or volume should be used to determine the intercrop seeding ratio (Glaze-Corcoran et al., 2020).

2.3.1.2 Weed Management

The spatial arrangement of intercrops can influence both crop interactions and weed suppression. Intercropping is a cultural strategy used to reduce weed pressure by increasing ground cover and resource competition (Maitra et al., 2021). A meta-analysis by Gu et al. (2021) found that intercrops had 58% lower weed biomass than the monocultures of the less competitive species in the intercrop mixture, across 330 observations from 39 publications. It should be emphasized that in 8% of the records, weed biomass was greater in the intercrop than in the monoculture of the less competitive species (Gu et al., 2021). Thus, when weed suppression from the intercrop is insufficient, in-season herbicide management may be required to maintain crop competitiveness and yield.

Identifying compatible herbicides remains a significant obstacle to intercrop management. A cover crop that is intercropped into the cash crop has a greater risk of herbicide injury compared to a cover crop seeded following harvest (Stahl & Ley, 2022). The relative timing between herbicide application and cover crop emergence influences herbicide injury potential for both pre-emergence and in-season herbicide applications. Furthermore, residual herbicides can restrict intercrop germination and injure emerging seedlings (Smith & Ruark, 2022). Herbicide selectivity between grass and broadleaf species can complicate the selection of

in-season herbicides when grasses and broadleaves are grown together (Maitra et al., 2021; Nurk et al., 2017; Mbanyele et al., 2024). In Western Canada, herbicide-tolerant canola hybrids (Roundup Ready®, Liberty Link®, and Clearfield ®) have improved the effectiveness of herbicidal weed management in canola intercrop systems (Hummel et al., 2009; Nelson et al., 2012). In wheat, there are currently selective herbicides registered for use on broadleaf weeds (MCPA, MCPB, and 2,4-D-B) and grass weeds (tralkoxydim and difenzoquat) when establishing a grass and broadleaf intercrop (Government of Manitoba, n.d. a; Manitoba Agriculture, 2025).

Where chemical control options are limited, integrated weed management practices become essential. The seeding density, spatial configuration, row spacing, and species diversity are all critical factors of intercropping systems that influence weed suppression (Liebman & Dyck, 1993; Bainard et al., 2020; Maitra et al., 2021). In Carman, Manitoba, a higher oat density of 160 plants m⁻² had a greater suppressive ability and reduced weed biomass to 1322 kg ha⁻¹ compared to oat seeded at a lower density of 48 plants m⁻², where weed biomass was 1753 kg ha⁻¹ (Bailey-Elkin et al., 2021). While the seeding rate influences crop competitiveness, intercrop arrangement can alter their suppressive ability against weeds. A Saskatchewan field experiment found that a barley-radish intercrop seeded within-row on 30 cm spacing had greater weed density of 6 plants m⁻² and a greater weed biomass of 732 kg ha⁻¹ than when seeded in alternating rows on 15 cm spacing (Bainard et al., 2020). However, an intercrop of pea-oat showed the opposite trend, with weed density decreasing by 1 plant m⁻² and weed biomass increasing by 59.4 kg ha⁻¹ when comparing 30 cm within-row intercropping to a 15 cm alternate-row arrangement (Bainard et al., 2020). In conventional cropping systems, successful weed management for intercrops depends on using chemical, mechanical, and cultural approaches that

are adapted for the specific intercrop and weed species, intercropping arrangement, and machinery.

2.3.1.3 Harvest of Intercrops

The complexity of harvest increases when utilizing intercrops, as each species may not mature in the same number of days or reach an appropriate moisture level at the same time for mechanical harvest. When intercropping cover crops, differences in species maturity are often a selection criterion when selecting the species to intercrop. In a 2017 Ontario survey, 30% of respondents who intercropped red clover into winter wheat identified the disadvantage of harvesting difficulties due to excessive growth and green plant material (Ogilvie et al., 2020). These challenges are minimized in strip intercrops, as the strip width allows for the harvest of each species individually (Raza et al., 2023). In row or mixed intercrops, selecting species with similar maturity is critical for grain intercrops as differences in growth patterns and crop dry-down can delay harvest and reduce efficiency (Mbanyele et al., 2024). When asynchronous maturity occurs, swathing or the application of a pre-harvest desiccant can promote uniform dry-down and facilitate harvest (Hummel et al., 2009). For intercropped cover crops, swathing addresses non-uniform maturity and allows for crop dry down that is more even and rapid (Canola Council of Canada, 2019; Alberta Grains et al., 2025) while minimizing chemical damage to the cover crops. In contrast, pre-harvest herbicides, such as glyphosate, for weed control and grain drying (Malalgoda et al., 2020), or a desiccant, such as Diquat ion, can achieve similar results as swathing (Canola Council of Canada, 2019) but can injure or suppress cover crop performance after harvest. Currently, limited information is available in the published literature on the use of pre-harvest herbicides and desiccants on intercropped cover crops.

2.3.2 Current Uses of Intercropped Cover Crops

Despite several management challenges, intercropping cover crops presents as a promising strategy that has gained producer interest in the Canadian Prairies due to its potential to achieve greater fall establishment and biomass accumulation. However, most research on cover crops has focused on the seeding of cover crops after harvest, leaving the potential of intercropped cover crops largely unknown (Belfry & Van Eerd, 2016). In North America most research on intercropping cover crops has been conducted in the United States Midwest, Northern Corn Belt, and in Ontario in long season row crops like corn (Klopp, 2024; Brooker et al., 2020; Rusch et al., 2020; Clark, 2018), and more recently soybean (Klopp, 2024; Oliveira, et al., 2019; Clark, 2018). Cover crops that are intercropped have a narrow time frame to establish when the competition between the cash and cover crops is minimized (McConnell et al., 2023). Thus, the success of intercropping cover crops within row crops is affected by several factors, including crop stage and row spacing, seeding method, and tillage practice (Klopp, 2024).

2.3.2.1 Intercropping Cover Crops in Corn

In corn, the cover crop intercropping window typically occurs between the V5 to V7 stages, which is after the in-season herbicide application and is just as the crop is entering a period of rapid growth (Rees et al., 2019). During these stages, cover crops can be intercropped using broadcasting equipment or with a seed drill, depending upon available machinery, labour constraints, and operational costs (Koehler-Cole & Elmore, 2020). The broadcasting of cover crops into corn was practiced in the United States in the 1900s to allow for earlier growth than drill seeding after harvest (Frye et al., 1988). Broadcasting using drones, helicopters, airplanes, and high-clearance machinery allows for cover crops to be established during the reproductive stages of corn (Koehler-Cole & Elmore, 2020). Broadcasting seed often results in lower stands than when drilling due to poor seed-to-soil contact and dependence on rainfall for seed

germination (Fisher et al., 2011). Furthermore, biomass accumulation of broadcasted cover crops is often less than that of drilled cover crops due to decreased seed to soil contact and lower plant establishment (Noland et al., 2018). Consequently, higher seeding rates are required when broadcast seeding, resulting in greater operational costs (Koehler-Cole & Elmore, 2020).

In the Northern Great Plains of the United States, cover crops have been intercropped at or near the V7 stage in field corn to extend the post-harvest growing season (Noland et al., 2018). In Minnesota, winter rye and red clover biomass when intercropped with corn were 85 and 110 kg ha⁻¹, respectively, when drilled compared to 15 and 50 kg ha⁻¹ when broadcast (Noland et al. 2018). Similarly, a two-year field experiment in North Dakota found that a drilled mixture of rye, camelina (*Camelina sativa* (L.) Crantz), and radish produced 383 kg ha⁻¹ more biomass than when broadcast at the V7 stage of corn (Schmitt et al., 2021). An experiment in South Dakota confirmed that the biomass of drilled intercropped cover crop treatments was greater than the biomass of broadcast treatments. In the experiment, a mixture of crimson clover (*Trifolium incarnatum* L.), winter wheat, and lentil (*Lens culinaris* Medikus) produced 58 kg ha⁻¹ of cover crop biomass when drilled compared to 1 kg ha⁻¹ when broadcast into corn at V5 (Bich et al., 2014).

Cover crop intercropping experiments with corn have also been conducted in Ontario (Belfry & Van Eerd, 2016; Clark, 2018). Belfry and Van Eerd (2016) found that early (V4 to V6) cover crop seeding in seed corn produced 371 kg ha⁻¹ more biomass than the later (V10 to V12) seeding time, while sweet corn intercropped cover crops showed minimal growth at either timing due to reduced light infiltration into the canopy. Additionally, in 12 on-farm experiments across Ontario, alfalfa was intercropped into seed corn over 3 years. In these experiments, fall biomass of alfalfa at corn harvest ranged from 101 to 306 kg ha⁻¹ and had no effect on corn yield (Belfry

& Van Eerd, 2016). An additional experiment within the study compared the biomass production of a range of cover crop species including cereal rye (725 kg ha⁻¹), crimson clover (507 kg ha⁻¹), double cut red clover (345 kg ha⁻¹), and once again alfalfa (666 kg ha⁻¹), which produced the most biomass with no corn yield penalty (Belfry & Van Eerd, 2016). A third study on grain corn in Ontario also found that corn yield was not negatively impacted by intercropped cover crops over two years, cover crop biomass in this study was lower and more variable (Clark, 2018). Red clover biomass was 200 kg ha⁻¹ at the end of fall in 2015, however, in 2016, cover crop biomass was only 20 kg ha⁻¹. In the same study, annual ryegrass biomass increased from 130 kg ha⁻¹ in 2015 to 420 kg ha⁻¹ in 2016 (Clark, 2018). Overall, corn intercropping research has demonstrated that cover crops can be successfully established during corn vegetative growth stages with minimal yield penalty to the corn.

2.3.2.2 Intercropping Cover Crops in Soybean

The available published research on intercropping cover crops with soybeans is more limited than that on corn (Brhel et al., 2019). Some key challenges have been identified when intercropping cover crops with soybean, including earlier canopy closure and lower light penetration into the soybean canopy (Klopp, 2024). Yield losses have also been observed as early intercropping coincides with the critical weed-free period of soybean (Klopp, 2024). For example, when seeding cover crops at soybean planting to the V4 stage, Klopp (2024) reported yield losses up to 20%. Later establishment of intercropped cover crops during the reproductive stages following leaf drop has been recommended to minimize yield reduction. Establishment of the cover crops into soybean can be accomplished with broadcast seeding with a drone, helicopter, or airplane (Klopp, 2024).

Fewer cover crop species reliably establish and produce sufficient biomass when intercropped with soybean compared to corn (Caswell et al., 2019). Most research on the

intercropping of cover crops in soybean has evaluated winter cereals such as rye (Moore et al., 2014), where establishment timing is a key management decision. In North Dakota, rye has been shown to produce greater cover crop biomass when intercropped at R4 (970 to 1610 kg ha⁻¹) compared to R6 (440 to 1020 kg ha⁻¹) (Peterson et al., 2019). Despite differences in biomass, Peterson et al. (2019) found that both seeding timings did not negatively impact soybean yield. However, fall rye biomass production is highly variable depending on cover crop seeding methods and establishment timing. Across five environments in North Dakota, winter rye broadcast into soybean at the R6 growth stage produced only 242 kg ha⁻¹ of biomass (Kandel et al., 2021). Similar amounts of biomass accumulation were observed in a three-year Minnesota field experiment where annual ryegrass seeded into soybean at the R7 to R8 stage accumulated 0 to 200 kg ha⁻¹ of biomass (Rabin et al., 2023).

Several cover crop species have been evaluated for their potential to be intercropped into soybean. A two-year field experiment in North Dakota by Peterson et al. (2019) evaluated winter pea, winter camelina, and forage radish drilled into soybean at the R4 to R6 stage which produced an average biomass of 1610, 1150, and 1250 kg ha⁻¹, respectively. When broadcast, biomass was once again lower as a two-year experiment in Iowa, Minnesota, and North Dakota found that the biomass of camelina was 107 kg ha⁻¹, and pennycress was 146 kg ha⁻¹ (*Thlaspi arvense* L.) when averaged across the R6 to R8 seeding stages (Mohammed et al., 2020). While intercropping in soybean is possible, biomass production remains constrained and requires further evaluation to optimize intercropping strategies.

2.3.3 Intercropping for Small Grain and Forage Production

Research on intercropping cover crops with wheat and canola remains limited; however, intercropping for grain production has been widely evaluated on the Canadian Prairies. Management practices derived from grain intercropping can be used as a foundation for

designing effective cover crop intercropping strategies. For grain and forage production, the most common intercrop combination consists of a legume and a non-legume species (Fletcher et al., 2016; Mbanyele et al., 2024). Legumes are integrated into intercropping systems to biologically fix nitrogen, thereby reducing nitrogen fertilizer use and interspecific competition for nitrogen (Ehrmann & Ritz, 2014). Resource partitioning can also occur when intercropped species have complementary canopy structures and rooting systems (Vandermeer, 1984).

2.3.3.1 Intercropping in Wheat

Up until the 1970's, growing cereal–cereal intercrops of wheat, barley, and oat was a common practice to produce livestock feed on the Canadian Prairies (Clark, 2024). In a two-year study in Carman, Manitoba, Pridham and Entz (2008) observed weed biomass suppression when intercropping wheat with oat (320-770 kg ha⁻¹), barley (430-620 kg ha⁻¹), or rye (320-1270 kg ha⁻¹) compared to a half-seeding-rate wheat monoculture (1070-2810 kg ha⁻¹). This reduction in weed biomass could be attributed to the additional competition of the intercropped species when compared to the lower seeding rate monoculture treatment. Competition between these similar cereal species later in the season decreased wheat biomass when intercropped with oat (2510-2590 kg ha⁻¹), barley (1850-2450 kg ha⁻¹), and spring rye (3910-4250 kg ha⁻¹) when compared to a half seeding rate of wheat (6310- 6580 kg ha⁻¹) (Pridham & Entz, 2008). This competition persisted to harvest and resulted in wheat yields which decreased to 800 to 1126 kg ha⁻¹ when intercropped with oat, 661 to 1078 kg ha⁻¹ with barley, and 904 to 1519 kg ha⁻¹ with spring rye compared to a half seeding rate of wheat (1745-2312 kg ha⁻¹) (Pridham & Entz, 2008). However, the same experiment found variable weed suppressive benefits of the intercrops when compared to the full seeding-rate wheat monoculture. In the first year, intercrop of wheat–oat (770 kg ha⁻¹) and wheat-barley (620 kg ha⁻¹) had less weed biomass than the full-rate wheat monoculture (1410 kg ha⁻¹), whereas in the second year, the full-rate wheat monoculture resulted in the least

weed biomass (Pridham & Entz, 2008). Similar results were observed in Edmonton, Alberta, where wheat intercropped with barley decreased wheat yield to 968 kg ha⁻¹ when compared to 2172 kg ha⁻¹ as a half-seeding-rate monoculture due to competition (Nelson et al., 2012).

Wheat-pea intercropping systems have increased in popularity in both conventional and organic systems. Under conventional management in Manitoba, a three-year unpublished experiment achieved land equivalent ratios greater than one, indicating overyielding of wheat-pea intercrops (Westman Agricultural Diversification Organization, 2021). In contrast, earlier studies in Carman, Manitoba, found no yield advantage with intercropping as LERs of 0.94 and 0.91 were reported (Szumigalski & Van Acker, 2005). Under organic management however, stronger complementary effects were observed with an LER of 1.64, which was greater than its conventional counterpart of 1.09 (Nelson et al., 2012). Weed suppression has also been observed within wheat-pea intercrops. For example, weed biomass was reduced to 1900 kg ha⁻¹ with a wheat-pea intercrop compared to the pea monoculture, where weed biomass was 2250 kg ha⁻¹ (Szumigalski & Van Acker, 2005). However, this intercrop had greater weed biomass than the wheat monoculture treatment (1600 kg ha⁻¹).

The intercropping of lentils with wheat has also been studied as a promising strategy to support both lentil harvest (Carr et al., 1995) and weed suppression (Liebman, 1988). Lentil is a poor competitor against early-season weeds due to its slow growth pattern and limited in-season herbicide options (Carr et al., 1995; Alberta Pulse Growers, n.d.). In North Dakota, a wheat-lentil intercrop decreased weed biomass by 54% when seeded in mixed rows and by a greater 57% when seeded in alternating rows when compared to a lentil monocrop (Carr et al., 1995). Despite this weed suppression, the intercrop treatment did not yield greater than the monoculture treatments with LERs ranging from 0.97 to 1.12 (Carr et al., 1995). This was a result of lentils

being outcompeted by the wheat in a 1:1 seeding ratio, as wheat yield of the alternate row (1435 kg ha⁻¹) or mixed row (1755 kg ha⁻¹) intercrop was statistically similar to the wheat monoculture (1696 kg ha⁻¹) (Carr et al., 1995). More recent studies in Saskatchewan have also confirmed that lentil-wheat intercrops do not show tendencies for overyielding, as LERs of 0.88 and 1.00 were reported for the intercrop (McAuley, 2023).

Given their importance on the Prairies, wheat and canola intercrops have been examined for their potential for yield complementarity and weed suppression due to contrasting crop architecture (Hummel et al., 2009; Szumigalski & Van Acker, 2005). In Edmonton, Alberta, an intercrop of wheat and canola resulted in an LER of 1.17, indicating overyielding (Nelson et al., 2012), whereas broader testing at three locations in Alberta found no yield advantage with LERs (Hummel et al., 2009). Contrasting results occurred in Manitoba, where the wheat–canola intercrop overyielded significantly in only one out of five site-years (Szumigalski & Van Acker, 2005). Weed suppression has been more consistent in the absence of herbicides, as the intercrop of wheat and canola was shown to suppress weed biomass to 1450 kg ha⁻¹ compared to 1600 kg ha⁻¹ in a wheat monoculture and 1810 kg ha⁻¹ in the canola monoculture (Szumigalski & Van Acker, 2005). Nelson et al. (2012) also observed a relative weed biomass of 2.44, indicating weed suppression.

2.3.3.2 Intercropping in Canola

Beyond wheat, canola has also been intercropped with pulse crops on the Prairies. Peaola, the intercrop of pea and canola, is one of the most common intercrops grown on the Canadian Prairies and has been most widely adopted in Saskatchewan (Manitoba Pulse and Soybean Growers, 2018; Vankoughnet, 2015; Kalil et al., 2023). Pea is susceptible to lodging when grown as a monoculture, thus canola is intercropped with pea to improve structural support (Lakeland Agricultural Research Association, 2013). Additionally, weed suppression can be

enhanced as a result of differing crop competitiveness, growth habits, and nutrient use efficiency (Lakeland Agricultural Research Association, 2013). Field experiments in Manitoba conducted by Szumigalski and Van Acker (2005) found that an intercrop of pea and canola was able to reduce weed biomass to 1990 kg ha⁻¹ when compared to the pea monoculture (2250 kg ha⁻¹), although weed biomass in the intercrop treatment remained greater than the canola monoculture (1810 kg ha⁻¹). The intercrop of canola and pea (1570 kg ha⁻¹) was able to produce a higher grain yield than canola (960 kg ha⁻¹) but not pea (1890 kg ha⁻¹) monocultures, and overyielded with an LER of 1.19 (Szumigalski & Van Acker, 2005). Similarly, on-farm field experiments in Carman, Manitoba, observed that the peaola intercrop resulted in overyielding with an LER of 1.16 (Manitoba Pulse and Soybean Growers, 2018).

With increasing demand for edible oils, researchers within the Midwest United States have looked at intercropping canola and soybean in strips to increase yield, protein, and oil content (Ayisi et al., 1997). A two-year Minnesota field experiment reported LERs that ranged from 1.03 to 1.62 (Ayisi et al., 1997) and increases in the protein and oil contents of both crops up to 79 and 73%, respectively, when compared to the average of the monocultures (Ayisi et al., 1997). Early adopters of intercropping have also seen success when intercropping canola and soybean, as they observe decreased flea beetle pressure to canola (Bennett, 2021). Furthermore, in Ontario, producers have begun experimenting with winter canola and soybean row intercrops to improve sustainability and profitability (King, 2023).

Yield and weed suppression benefits of grain intercrops for wheat and canola point to the potential benefits that could be gained from adopting intercropping for the establishment of fall cover crops for the Canadian Prairies. In grain intercrops, complementary resource partitioning between species can improve system productivity while increasing crop competitiveness with

weeds. Similar mechanisms may benefit intercropped cover crops, as earlier establishment can increase biomass accumulation when compared to cover crops seeded after harvest in the fall shoulder-season. However, unlike grain intercrops where both species are harvested, intercropped cover crops are grown primarily to provide ecosystem services and must do so without negatively impacting the cash crop (Klopp, 2024).

2.4 Benefits and Risks Associated with Cover Crops

The inclusion of cover crops into agroecosystems can provide numerous benefits, including weed suppression (Koudahe et al., 2022), improvements in soil physical and chemical properties (Blanco-Canqui & Jasa, 2019), and positive effects on cash crop yield (Bourgeois et al., 2022). However, the successful integration of cover crops is dependent on climatic conditions and farm-specific management strategies. Trade-offs such as increased competition (Thomas et al., 2017) and moisture use (Nielsen et al., 2016), which can decrease cash crop yields as well as increase management costs (Morrison & Lawley, 2021), have been reported. On the Canadian Prairies, where the short growing season and variable moisture create additional challenges, evaluating both the potential benefits and risks of cover crops is important, as limited regional research is currently available.

2.4.1 Weed Suppression

Given the increasing weed management challenges on the Prairies, the potential of cover crops to assist in weed management is of interest. Living cover crops primarily suppress weeds through direct competition, which reduces weed biomass and seed production (Fernando & Shrestha, 2023) and can interfere with weeds at more phases during their life cycles (Teasdale et al., 2007). When intercropped, cover crops compete for above- and belowground resources, and alter the microclimates of the canopy and soil to create less favourable environments for weed growth (Fernando & Shrestha, 2023). Cover crops that establish a leaf canopy rapidly and

produce high biomass provide greater weed suppression (Teasdale, 2017). Therefore, grass cover crops are more competitive than legumes (Baraibar et al., 2018). A meta-analysis across the United States Midwest found that grass cover crops reduced weed biomass by 68% compared to a reduction of 33% from mixtures and other species (Nichols et al., 2020). Upon termination, cover crops continue to suppress weeds as a mulch by reducing weed seedling germination and emergence by impeding light penetration (Fernando & Shrestha, 2023). Across three soybean experiments in Manitoba, mid-season terminated rye and wheat reduced volunteer canola biomass to approximately 2250 kg ha⁻¹ and 2500 kg ha⁻¹, respectively, when compared to a no cover crop control (2800 kg ha⁻¹) (Geddes & Gulden, 2021). However, this reduction was not sufficient to eliminate the need for additional weed management practices, including herbicide applications or tillage.

Allelochemicals produced by cover crops can suppress weeds through non-competitive interference (Fernando & Shrestha, 2023). These compounds are actively released into the soil through volatilization, leaching, or root exudates while cover crops are living and upon decomposition (Scavo et al., 2018), inhibiting weed germination and growth (Bonanomi et al., 2005). Species such as cereal rye and winter wheat produce benzoxazinones (Vanhie et al., 2020; Li et al., 2013), whereas brassicas, including rapeseed and mustard, produce glucosinolates and brassinosteroids (Haramoto & Gallandt, 2004; Kelton et al., 2012; Shahzad et al., 2019). An experiment across multiple sites in Manitoba found that extracts from field-grown rye inhibited the germination of redroot pigweed (*Amaranthus retroflexus* L.) by 31-45% and green foxtail (*Setaria viridis* (L.) Beauv.) by 25 to 35% when grown on petri dishes (Flood & Entz, 2009). A field experiment in Maine observed that incorporated spring-seeded brassica species of rapeseed and mustard delayed weed emergence by two days and reduced weed emergence by 23 to 34%

compared to fallow (Haramoto & Gallandt, 2005). Additionally, legumes such as hairy vetch (*Vicia villosa* Roth) (Teasdale & Daughtry, 1993; Kamo et al., 2006; Kelton et al., 2012), subterranean clover (*Trifolium subterraneum* L.) (Enache & Ilnicki, 1990), and crimson clover (Sheldon et al., 2021), also have allelopathic effects as a living mulch and upon residue decomposition.

2.4.2 Soil Health

Beyond weed suppression, the implementation of cover crops into crop rotations is considered a crucial management practice to enhance agroecosystem resilience by improving soil health (Blanco-Canqui et al., 2023). Soil health has been defined by Doran (2002) as “the capacity of a living soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health”. From the 2020 Prairie Cover Crop Survey, 68% of respondents reported improved soil health as the primary benefit of cover crop use (Morrison & Lawley, 2021). However, a Prairie experiment found that over 3 years, soil health indicators remained unchanged following cover cropping (Wu et al., 2023). While cover crops have been found to improve soil physical and chemical properties, the magnitude of these benefits is determined by biomass production and composition (Bourgeois et al., 2022), which is frequently constrained on the Prairies.

The use of cover crops can enhance soil structure by increasing soil porosity and reducing bulk density, thereby improving water infiltration and soil water content (Blanco-Canqui & Ruis, 2020). A review by Haruna et al. (2020) found that residue inputs and biopores from cover crop roots increased soil porosity by 33% and reduced bulk density by 4%. An additional meta-analysis by Blanco-Canqui and Ruis (2020) found that in 31% of cases, cover crops reduced bulk density by 3 to 24%. Villamil et al. (2006) found that fall rye sown in a corn-soybean rotation in

Illinois reduced bulk density by 6% and increased micropores and mesopores by 29 and 6%, respectively. In a Maryland field experiment, Chen and Weil (2010) found that tap-rooted species, such as forage radish and rapeseed, have a greater ability to reduce soil compaction through biodrilling, producing nearly two times greater root density than fall rye under high compaction at a depth of 35 to 50 cm. Furthermore, tap-rooted species, including oilseed radish, have also been found to increase macroporosity by 3.7% compared to annual ryegrass in a Michigan field experiment (Lucas et al., 2022).

Cover crops are also deployed to prevent soil erosion as they can reduce soil loss by 96% through the improvement of bulk density and porosity (Hurana et al., 2020). Cover crops contribute an abundance of surface residue and extensive root networks that hold the topsoil in place, reducing losses from wind and water erosion (Sumiahadi et al., 2019). Rye intercropped into corn in Michigan reduced runoff by 50% and erosion by a greater 96% when compared to a corn monoculture (Wendt & Burwell, 1985), whereas spring-seeded legumes in winter wheat reduced water runoff by 73% and soil erosion by 68% in Kansas (Blanco-Canqui et al., 2015). In the Prairie region, 41% of respondents to the 2020 Prairie Cover Crop Survey observed the benefit of a reduction in soil erosion following cover crop adoption (Morrison & Lawley, 2021).

In addition to soil physical properties, cover crops have been shown to alter chemical properties of the soil by increasing organic matter (Šimansky et al., 2021) and soil organic carbon stores through carbon sequestration, which has the potential to aid in mitigating climate change (Kaye & Quemada, 2017; Chahal et al., 2020). The amount of carbon that cover crops can store within the soil depends on cover crop biomass and species composition, soil type and carbon level, as well as the location and climate (Blanco-Canqui et al., 2015). A Kansas field study by Blanco-Canqui et al. (2013) found that a cover crop of spring-sown lentil increased soil

organic carbon when measured the following summer by 2.4 Mg ha⁻¹ in a winter wheat rotation, whereas a triticale cover crop had a greater increase of 3.1 Mg ha⁻¹ due to greater residue input when compared to fallow. This increase in SOC can be attributed to the initial residue input of the cover crop species. In the following spring, the increase in SOC from spring-sown lentil and triticale was reduced to 2.1 Mg ha⁻¹ and 1.6 Mg ha⁻¹, respectively (Blanco-Canqui et al., 2013). The reduction in SOC in the spring can be attributed to microbial decomposition of the cover crop residue, where a portion is mineralized and released as carbon dioxide (Six et al., 2002). This process is more pronounced in grass species due to their greater residue input.

Despite differences in cover crop species, the belowground biomass inputs from rooting systems are vital for increasing soil organic carbon concentrations (Blanco-Canqui et al., 2015; Saadat et al., 2025). For example, a Massachusetts experiment by Saadat et al. (2025) found that upon termination of buckwheat, oat, and pea, the carbon and nitrogen content was greater in the roots of buckwheat and oat than in pea. This greater nutrient content resulted in a C:N ratio ranging from 40:1 to 50:1, resulting in a greater potential for carbon storage (Saadat et al., 2025). While greater residue inputs from grasses can increase SOC due to carbon additions, residues with low C:N ratios can also enhance SOC stores through promoting rapid microbial processing and the formation of microbial necromass which contributes to stable soil organic matter (Cotrufo et al., 2013).

2.4.3 Effects on Cash Crops

While cover crops can reduce erosion and improve soil health through increased ground cover and biomass production, they can also increase the risk of soil water depletion due to greater water use (Obour et al., 2021). The risk of depleted soil moisture increases when cover crops are intercropped with cash crops as species are subjected to a combination of intra- and inter-species competition (MacLaren et al., 2023). A field experiment in Carman, Manitoba, by

Kahimba et al. (2008) found that a berseem clover (*Trifolium alexandrinum* L.)-oat intercrop reduced the root zone (0.05 m to 0.7 m) soil water content by 35% when compared to the oat monoculture. This reduction in soil water content resulted in significantly lower biomass yields for the oat and berseem clover intercrop (6146 kg ha⁻¹) when compared to the oat monoculture (7327 kg ha⁻¹) (Kahimba et al., 2008). These soil moisture reductions persisted to the following spring, where root zone (0.1 m to 0.9 m) soil water content in April was 5% lower following the intercrop treatment when compared to the oat monoculture treatment (Kahimba et al., 2008).

Subsequent cash crop yields have also been found to decrease following cover crop use due to intercrop competition. If one species is more dominant, it will capture more resources, thereby reducing the growth and yield of the other species. Consequently, intercropped species are selected for complementary traits to minimize these effects (Wang et al., 2020). In the Northern Great Plains, a two-year field experiment examining spring shoulder-season cover crops including four single species cover crops (flax (*Linum usitatissimum* L.), oat, pea, canola) and a 10-species mixture, found wheat yields decreased by an average of 10% following spring cover crop use compared to a no cover crop fallow, regardless of the number of cover crop species sown (Nielsen et al., 2016). Similarly, a field experiment in Manitoba found that an overwintering fall rye cover crop reduced a subsequent spring wheat crop yield by 19-36% relative to the no cover crop control, whereas a mixture of non-overwintering species, including oat, field pea, faba bean, and fall rye, reduced wheat yield by 6-24% (Janzen, 2023). Further studies conducted in the Northern Great Plains of Montana quantified spring wheat yield reductions up to 35% following 15 cover crop mixtures (Bourgault et al., 2021). A causal forest analysis conducted by Deines et al. (2022) in the United States corn belt found soybean yields

decreased by 4% and corn yields decreased by 6% compared to fields that did not implement cover cropping.

In years when water is not a limiting factor on cash crop productivity, cover crops can have neutral or positive effects on subsequent crop yield. In a three-year North Dakota field experiment, monocultures and mixtures of 18 fall cover crop species did not affect the subsequent cash crop yield of corn, soybean, spring wheat, and field pea when compared to the no cover crop control (Hendrickson et al., 2021). In Lethbridge, Alberta, Blackshaw (2008) observed dry bean (*Phaseolus vulgaris* L.) yield increases of 5 to 13% in 2 out of 3 years when fall- or spring-seeded cover crops were coupled with an in-season herbicide application. In the absence of an in-season herbicide, dry bean yield increases ranged from 20 to 90% following fall-seeded winter rye, barley, and oat cover crops (Blackshaw, 2008).

2.4.4 Management Complexities

Beyond yield impacts, cover crops also introduce additional economic and logistical challenges. Seed cost is the primary expense, with 70% of respondents to the 2020 Prairie Cover Crop Survey identifying that they pay between 5 to \$30 CAD per acre for cover crop seed (Morrison & Lawley, 2021). Seed costs are dependent on several factors, including cover crop species, seed size, and seeding rate. A recent economic analysis conducted by Penner (2024) reported the mean seed costs for fall-seeded cover crops were \$41 CAD ha⁻¹ with a range of \$13 to \$83 CAD ha⁻¹ for on-farm experiments in Manitoba.

Further costs are associated with the seeding cover crops and can range from \$12 to \$44 USD ha⁻¹ (Myers et al., 2019). Producers who modify their seeding equipment or combine seeding with another field operation, such as fertilization, can reduce their seeding costs per acre compared to those who hire specialized or aerial seeding companies (Myers et al., 2019). This was observed in the economic analysis conducted by Penner (2024), where producers who used

their own machinery spent on average \$19 CAD ha⁻¹ on seeding costs (fuel and labour) compared to \$49 CAD ha⁻¹ when an external source was hired for seeding.

The seeding of cover crops also adds management complexities, particularly on the Canadian Prairies, which experience a short growing season. The establishment of cover crops often coincides with cash crop seeding or harvest operations. If a cover crop is established during the cash crop growing season, specialized machinery with multiple seed boxes or tanks for simultaneous seeding, or additional field passes with high clearance broadcast spreaders or aerial seeding equipment is required to avoid interfering with the cash crop (Kientzy et al., 2023). Conversely, post-harvest seeding of cover crops can generally be accomplished with existing seeding equipment (Kientzy et al., 2023) but requires additional labour and equipment use that can increase equipment maintenance costs. While intercropping, the simultaneous seeding of cash crops and cover crops can improve cover crop establishment but can increase the risk of yield loss due to competition (Feng et al., 2024). Broadcast or aerial seeding of cover crops later in the growing season reduces competition but can result in poor establishment due to limited seed to soil contact (Kientzy et al., 2023).

If cover crops do not winterkill, additional costs are incurred with mechanical or chemical termination. In Iowa, terminating a cover crop with tillage costs on average \$74 USD ha⁻¹ compared to \$133 USD ha⁻¹ when herbicides are used (Plastina et al., 2018). Those termination costs are greater than those reported by Penner (2024), where chemical termination costs in Manitoba ranged from \$20 to \$37 CAD ha⁻¹ for herbicide costs and an additional \$2 to \$8 CAD ha⁻¹ for fuel and labour. Penner (2024) also noted that termination costs can be reduced if cover crop termination can be combined with a preexisting weed management strategy.

Although cover crops present financial considerations and management complexities, these constraints can be addressed through strategic planning and adapted management strategies.

2.5 Research Gaps and Need for Future Research

Despite the growing interest in cover cropping on the Canadian Prairies, research remains limited on how to integrate cover crops successfully into Prairie grain systems. Most published research focuses on row crops, such as corn and soybean, in Eastern Canada and the United States Midwest, where longer growing seasons may decrease the risk associated with cover crop establishment and productivity. As a result, there is considerable uncertainty regarding how cover crop species choice, seeding method and timing, and spatial arrangement influence cover crop establishment and biomass production, along with the subsequent cash crop yield under Prairie conditions. Preliminary research has mostly focused on fall shoulder-season cover crops planted after cash crop harvest rather than cover crop intercropping, an approach established to extend the length of the cover crop growing season.

Prairie-specific research is required on cover crop intercropping to determine what species or mixtures can reliably establish, survive a herbicide strategy, and produce measurable biomass without negatively impacting the subsequent cash crops. Furthermore, the potential agronomic benefits that cover crops can provide remain unsubstantiated under the Prairie climate, soils, and cropping systems. Addressing these knowledge gaps is crucial for supporting the development of region-specific cover cropping strategies that support producers, agronomists, and policy makers to enable widespread adoption across the Canadian Prairies.

3.0 ARE INTERCROPPED COVER CROPS COMPATIBLE WITH CANOLA WEED MANAGEMENT ON THE CANADIAN PRAIRIES?

3.1 Abstract

The short growing season and limited fall precipitation in the semi-arid climate of western Canada hinder widespread adoption of fall cover crops. Intercropping is a potential solution by increasing the window for cover crop establishment and growth. However, intercropping also creates challenges when using herbicides to control weeds in cash crops like canola (*Brassica Napus* L.). Field experiments in 2022 and 2023 were conducted at two sites (Carman, Manitoba and Kernen, Saskatchewan) to compare three herbicide frequency treatments (pre-emergence only, pre-emergence and in-season, and a pre-emergence, in-season, and desiccant) for the three herbicide tolerance systems utilized with canola hybrids (Liberty Link®, Roundup Ready®, and Clearfield®). A cover crop mixture of red clover (*Trifolium pratense* L.), white Dutch clover (*Trifolium repens* L.), subterranean clover (*Trifolium subterraneum* L.), Persian clover (*Trifolium resupinatum* L.), alfalfa (*Medicago sativa* L.), and Italian ryegrass (*Lolium multiflorum* L.) was drilled at the same time as canola in alternating rows. Experiment measurements included cover crop establishment, herbicide damage ratings, aboveground fall cover crop biomass, weed density and biomass, and canola yield and quality. Cover crops established at both sites; however, cover crop biomass varied across years, locations, herbicide frequency, and herbicide tolerance systems. After low cover crop establishment and biomass accumulation in 2022, seeding rates were increased in 2023 at both locations. In 2023, with increased establishment, the greatest fall cover crop biomass was observed in the pre-emergence only treatments and decreased with subsequent herbicide applications at both locations. Following in-season herbicide applications, cover crop performance within contrasting herbicide tolerance systems varied by site. The Clearfield system achieved greater biomass in Carman 2023, whereas the

Liberty and Roundup systems were more successful in Kernen 2023. Where greater cover crop biomass occurred in 2023, canola yield penalties were observed. This project demonstrates the potential of intercropping as a strategy to overcome environmental constraints currently limiting fall cover crops in Western Canada. Further agronomic research in a wider range of locations will be needed to adapt and refine agronomic management strategies to optimize canola and cover crop performance for cropping systems across Western Canada.

3.2 Introduction

The introduction of cover crops into an agroecosystem brings both short- and long-term benefits. Cover crops can improve soil health and are measured by physical (Blanco-Canqui & Ruis, 2020; Hurana et al., 2020), chemical (Šimansky et al., 2021; Blanco-Canqui et al., 2015), and biological properties (Adetunji et al., 2020; Muhammad et al., 2021). Cover crops also can suppress weeds through direct competition (Fernando & Shrestha, 2023; Teasdale et al., 2007; Blanco-Canqui et al., 2015) and non-competitive interference with the secretion of allelochemicals (Fernando & Shrestha, 2023). However, the benefits from cover crops often come with increased management complexities during seeding and harvest, increased labour and seed costs (Myers et al., 2019), and increased agronomic risks, including soil moisture depletion (Obour et al., 2021) and potential yield reductions (Bourgault et al., 2021). The timeline and trade-offs between the potential benefits and risks of cover crops influence decision-making by Prairie farmers about the adoption.

The incorporation of cover crops into their rotations in the Canadian Prairies has been increasing in recent years. According to the 2021 Farm Management Survey, 773 farms in Manitoba, 732 farms in Saskatchewan, and 1130 farms in Alberta reported planting cover crops, representing 6, 3, and 4%, respectively, of farms in each province (Statistics Canada, 2023). A Prairie Cover Crop Survey conducted by Morrison and Lawley (2021) identified that shoulder-

season cover crops were grown on 12,242 ha in Manitoba (63 respondents), 6995 ha in Saskatchewan (37 respondents), and 3491 ha in AB (32 respondents). The short growing season and semi-arid Prairie climate have hindered wider adoption of cover crops in the fall shoulder-season (Wu et al. 2024)

Establishing cover crops with cash crops as an intercrop is a management practice that could enable cover crop adoption on a greater number of hectares across the Canadian Prairies. In their survey, Morrison and Lawley (2021) identified that 37% of early adopter Prairie farm respondents had established cover crops as an intercrop in 2020. When compared to seeding cover crops in the fall after cash crop harvest, cover crop intercropping could increase the window for cover crop establishment and biomass production (Youngerman et al., 2018) as earlier establishment would increase the length of the growing season, the number of growing degree days, and moisture availability for the cover crop.

While growing season length is the primary constraint for fall cover crops, herbicidal weed management strategies in the cash crop are limited when cover crops are intercropped. Of the 281 respondents to the 2020 Prairie Cover Crop Survey, 21% identified that cover crops impacted their herbicide choice (Morrison & Lawley, 2021). The use of cover crops limits the use of residual herbicides, as their use could inhibit germination and emergence. When intercropping cover crops, in-season herbicide options are restricted as there are limited herbicides registered for use on cover crop species when intercropped with cash crops. In canola, where herbicide-tolerant traits dominate production, research has focused on grain intercrops of pea and canola, leaving the intercropping of cover crops in canola largely unexplored.

Canada is one of the leading producers and is the leading exporter of canola, producing 20 million tonnes of canola annually, with production being greatest in the Prairie Provinces

(Canola Council of Canada, n.d.). Following its introduction in 1995, herbicide-tolerant canola usage became widespread and accounted for 99% of sown seed in 2010 (Canola Council of Canada, 2016). Roundup Ready® and Liberty Link® are most often sown and account for 47 and 46% of tolerant varieties utilized, whereas Clearfield® accounts for a lesser 6% (Canola Council of Canada, n.d.). Each herbicide-tolerant canola system enables a specific in-season herbicide application for post-emergence weed control (Table 3.1).

Table 3.1. Canola herbicide-tolerance systems and their associated traits and characteristics. Adapted from Manitoba Agriculture (2025).

Herbicide tolerant canola	Trait introduction method	Herbicide group	Mode of action	Active ingredient	Translocation type	Herbicide selectivity
Roundup Ready®	Transgenic	9	EPSPS ^a inhibitor	Glyphosate	Systemic	Non-selective
Liberty Link®	Transgenic	10	Glutamine inhibitor	Glufosinate	Contact	Non-selective
Clearfield®	Mutagenesis	2	ALS ^b inhibitor	Imazamox+ imazethapyr	Systemic	Selective

^a 5-enolpyruvylshikimate-3-phosphate synthase

^b acetolactate synthase

As canola is a major crop grown widely in western Canada. Intercropping cover crops with canola may be an important strategy to increase living soil cover to advance soil health across a large number of acres in the Canadian Prairies (Thiessen Martens et al., 2015). However, increasing interspecific competition for light, nutrients, and water between cover crops and the canola cash crop may have negative trade-offs. The magnitude of potential yield impacts depends on management practices within the intercrop system. Despite the importance of canola as a major cash crop in Western Canadian agriculture, no studies could be identified in the literature that examined intercropping cover crops with canola. The main objective of this study was, therefore, to identify compatible herbicide packages and frequencies of applications for

cover crops intercropped with canola while also evaluating the impact of cover crops on canola yield. It was hypothesized that 1) herbicide type is expected to influence cover crop injury and biomass, with greater injury occurring following an application of systemic herbicides, through evaluating herbicide damage and fall cover crop biomass, and 2) cover crop biomass will decrease with increasing herbicide frequency. For evaluating yield impacts from cover crops, it was hypothesized that canola yield is expected to decrease when intercropped with a cover crop mixture.

3.3 Materials and Methods

3.3.1 Site Descriptions

Small-plot field experiments were conducted at the University of Manitoba Ian N. Morrison Research Station in Carman, MB (49°49' N, 98°03' W) and the University of Saskatchewan Kernen Crop Research Farm near Saskatoon, SK (52°09' N, 106°32' W) in 2022 and 2023. A new experimental area was used each year at each location, hereafter referred to as site-year. Site-year is denoted by location and the year when the cover crop was established: Carman22, Carman23, Kernen22, and Kernen23. Prior to seeding the cash and cover crops in the first year of the study, the experimental area was seeded to oat for Carman22 and spring wheat for Carman23. In Kernen, experiments followed a canola-chemical fallow sequence.

The two sites had contrasting soil types. The soil in Carman was an imperfectly drained Gleyed Black Chernozem in the Rignold Series with a sandy clay loam texture (Manitoba Agriculture, 2010). In Kernen, the soil was a Dark Brown Chernozem classified as the Sutherland Series, which is moderately well drained with a silty clay texture (Saskatchewan Soil Survey, 1993). In addition to contrasting soil types, the sites also differed in the 30-year normal (1981 to 2010) length of the frost-free period and annual precipitation. Carman is characterized by a longer normal frost-free period, averaging 135 days, with average annual precipitation of

545 mm. Kernen has a shorter normal frost-free period of 117 days and receives less average annual precipitation than Carman, with 340 mm (Environment and Climate Change Canada, n.d.)

3.3.2 Experimental Design and Treatments

The experiment was organized as a randomized complete block design with four replicates. Treatments were arranged in a split-plot design with herbicide tolerance system as the main plot factor and herbicide frequency as the subplot factor. Main plots were randomly assigned to a canola herbicide tolerance system. The three tolerance systems were determined by selecting the three most common herbicide tolerance systems available on the Canadian Prairies: Liberty Link[®], Roundup Ready[®], and Clearfield[®] (Table 3.1). The subplot treatment consisted of three sequential herbicide frequency combinations: pre-emergence only, pre-emergence and in-season, and a pre-emergence, in-season, and desiccant (Table 3.2). A no cover crop control treatment was included within each herbicide tolerance system to evaluate the effects of cover crops, and received the pre-emergence, in-season, and desiccant applications.

Individual plot sizes varied between locations based on available equipment. At Carman, individual plots were 1.9 m wide by 8 m long (15.2 m²) for both site-years. At Kernen, plots were 1.5 m wide by 8 m long (12.2 m²) in Kernen22 and 1.5 m wide by 10 m (15.2 m²) in Kernen23. Between subplots, an unseeded buffer area of 1 m was used at Carman, and a 1.5 m buffer was used at Kernen. At Carman, an additional unseeded buffer of 2 m was added between the herbicide tolerance system main plots.

Table 3.2. List of treatments included in a split-plot experiment with a main plot of herbicide tolerance system (Liberty Link®, Roundup Ready®, and Clearfield®) and a sub-plot of the herbicide frequency: pre-emergence only (PRE), pre-emergence and in-season (PRE, IS), and pre-emergence, in-season with a pre-harvest desiccant (PRE, IS, D).

Main plot	Subplot	
Herbicide tolerance system	Cover crop presence	Herbicide frequency
Liberty Link®	Yes	PRE ^a
	Yes	PRE, IS ^b
	Yes	PRE, IS, D ^c
	No cover crop control	PRE, IS, D
Roundup Ready®	Yes	PRE
	Yes	PRE, IS
	Yes	PRE, IS, D
	No cover crop control	PRE, IS, D
Clearfield®	Yes	PRE
	Yes	PRE, IS
	Yes	PRE, IS, D
	No cover crop control	PRE, IS, D

^a Pre-emergence (PRE) herbicide applied was glyphosate.

^b In-season (IS) herbicides dictated by herbicide tolerance system: Liberty Link® glufosinate, Roundup Ready® glyphosate, Clearfield® imazamox+ imazethapyr.

^c Desiccant (D) applied was diquat.

All treatments at Carman and Kernen23 received a pre-emergence glyphosate application (Roundup Transorb® HC, Bayer Crop Science Inc.) using a tractor-mounted sprayer at a rate of 2.7 L ha⁻¹ (1334 g a.e. ha⁻¹) at Carman, and a rate of 1.3 L ha⁻¹ (702 g a.e. ha⁻¹) at Kernen. At Kernen23, the herbicide carfentrazone-ethyl (AIM® EC, FMC) at 0.01 L ha⁻¹ (2.4 g a.i. ha⁻¹) was added to treat glyphosate-resistant weeds. In Kernen22, the pre-emergence application did not occur due to dry conditions that limited weed emergence before seeding.

In-season herbicide applications were dependent on the canola herbicide tolerance system used in the main plot treatment and were applied in all treatments prior to canola bolting with a hand boom at 100 L ha⁻¹ water volume. Treatments consisted of glufosinate (Liberty Link®), glyphosate (Roundup Ready®), and imazamox + imazethapyr (Clearfield®). For Liberty Link®, glufosinate, a group 10 non-selective herbicide, was applied at a rate of 2.5 L ha⁻¹ and contained

375 g a.i. ha⁻¹ glufosinate ammonium (Liberty® 150 SN, BASF Canada Inc.). For Roundup Ready®, glyphosate, a group 9 non-selective herbicide was applied to the Roundup Ready canola variety at a rate of 1.7 L ha⁻¹ and contained 918 g a.e. ha⁻¹ glyphosate (Roundup WeatherMAX® With Transorb 2 Technology, Bayer Crop Science Inc.) at Carman, and a rate of 3.3 L ha⁻¹ containing 1782 g a.e. ha⁻¹ glyphosate (Roundup Transorb HC, Bayer Crop Science Inc.) at Kernen. For Clearfield®, imazamox + imazapyr, a group 2 selective herbicide, was applied to Clearfield canola at a rate of 0.6 L ha⁻¹ and contained 20 g a.i. ha⁻¹ of imazamox and 9 g a.i. ha⁻¹ of imazapyr (Ares™ SN, Corteva Agriscience).

A pre-harvest desiccant application of diquat ion (Reglone® Ion, Syngenta Canada) was applied with a hand boom to selected treatments when canola reached 60% color change. In Carman, diquat was applied at a rate of 2.0 L ha⁻¹ (400 g a.i. ha⁻¹) and in Kernen at a rate of 3.5 L ha⁻¹ (692 g a.i. ha⁻¹). If the crop senesced prior to desiccating, the application still occurred, so cover crops were exposed to the treatment.

A cover crop species mixture was established as an intercrop at the same time as canola in alternating rows in all treatments except the no cover crop control treatments. The cover crop species mixture included two overwintering clovers (red clover and white Dutch clover), two non-overwintering clovers (Persian clover and subterranean clover), as well as alfalfa and Italian ryegrass. A detailed description of the cover crop treatment and management is provided in section 3.3.4.

3.3.3 Crop Management

Crop management decisions were guided by environmental conditions in each year and the recommended practices for each province where the experiment was conducted. Spring soil tests to guide fertilizer application were conducted annually at each location prior to experiment establishment in May. Soil was sampled from 0 to 15 cm and 15 to 60 cm at 10 randomly

selected locations within the experimental area using a Dutch auger at Carman for both years. In Kernen, soil was sampled at the same depths from 5 selected locations at the NW, NE, SW, SE, and center of the experimental area using a hydraulic soil probe. At both locations, 1 composite soil sample for each depth was sent to Agvise Laboratories (Northwood, ND, USA) for Carman²², Carman²³, and Kernen²³ and to A&L Canada Laboratories Inc. (London, ON, CAN) for Kernen²². Soil samples were analyzed for nitrate using the KCl method (Gelderman & Beegle, 2011) and Olsen phosphorus using sodium bicarbonate (Frank et al., 2011). Fertilizer rates for nitrogen, phosphorus, potassium, and sulphur were determined based on soil test recommendations for a target canola yield of 2520 kg ha⁻¹ (Table 3.3). In Carman, fertilizer was deep banded prior to planting at a depth of 8 cm on 19 cm spacing perpendicular to the direction of seeding. In Kernen, fertilizer was banded at planting 1 cm away from the canola seed at a depth of 3 cm.

Three canola hybrid cultivars of different herbicide tolerance systems were planted to the target population of 110 plants m⁻² (1,100,000 plants ha⁻¹). Cultivars selected for each herbicide-tolerant canola system were as follows: DKC 82 SCLL (Liberty Link®), rated as an early maturity hybrid by Bayer Inc.; DK902TF TruFlex (Roundup Ready®), an ultra-early maturity hybrid from Bayer Inc.; and P508MCL (Clearfield®), a mid-maturity Pioneer canola hybrid with Corteva herbicide tolerance traits. Canola was seeded using a JT-10D R-Tech disc opener plot seeder (R-Tech Industries Ltd., Homewood, Manitoba) with a row spacing of 38 cm for a total of 5 canola rows per plot. In Kernen, canola was seeded with a JT-8DMS R-Tech disc opener plot seeder (R-Tech Industries Ltd., Homewood, Manitoba) on a row spacing of 41 cm for a total of 5 canola rows per plot. Depending on soil moisture, canola was seeded at a depth of 1 cm to 3 cm.

Table 3.3. Date of spring soil sampling and soil test results for soil nitrate (N), Olsen phosphorus (P), potassium (K), sulphur (S), zinc (Z), pH, and soil organic matter (SOM), as well as fertilizer application dates and rates for Carman22, Carman23, Kernen22, and Kernen23.

Site-year	Depth	Sampling Date	Spring soil test results							Fertilizer application rate				
			N	S	P	K	Z	pH	SOM	Application Date	N	P	K	S
	cm		—kg ha ⁻¹ —		——ppm——				g kg ⁻¹		——kg ha ⁻¹ ——			
Carman22	0-15	May 6	16.8	51.6	25.0	321.0	3.3	5.2	42.0	May 17	78.5	11.2	0.0	0.0
	15-60		80.7	>403.5				6.7						
Carman23	0-15	May 3	13.5	15.7	9.0	257.0	2.0	5.7	54.0	May 11	133.4	40.4	0.0	19.1
	15-60		30.3	47.1				7.1						
Kernen22	0-15	May 12	34.7	16.8	19.0	519.0	2.2	7.6	46.0	May 26	89.7	22.4	0.0	11.2
	15-60		23.5	29.2				7.9						
Kernen23	0-15	May 4	43.7	27.4	11.6	476.2	0.5	7.8	50.0	May 11	89.7	22.4	0.0	11.2
	15-60		28.8	77.8				8.3						

Diseases and insect pests were monitored at each location. Scouting for flea beetles was conducted after canola emergence in May and June using a threshold of 25% cotyledon loss. In Kernan23, the cotyledon loss threshold was met, and 5 g a.i. ha⁻¹ deltamethrin (Decis® 5EC insecticide, Bayer Crop Science Inc.) was applied at a rate of 0.1 L ha⁻¹. A second application of 100 g a.i. ha⁻¹ lambda-cyhalothrin (Matador 120EC, Syngenta Canada) was applied at 0.83 L ha⁻¹ for further control. The threshold for flea beetle damage was not exceeded in the other site-years, and no insecticide applications were warranted. In June and July, patches of blister beetles (*Lytta nuttalli*, Nuttall) were present in Kernan22 and Carman23. Although there is no established economic or damage threshold for blister beetle control, an application of 5 g a.i. ha⁻¹ deltamethrin (Decis® 5EC insecticide, Bayer Crop Science Inc.) at a rate of 0.1 L ha⁻¹ was applied. Environmental conditions were monitored during the growing season for sclerotinia infection, but no symptoms were observed, nor were conditions favourable for a disease outbreak. Thus, no fungicides were applied in any of the site-years for the experiment.

At the Carman site, additional management was required to mechanically harvest canola. In Carman22, lamb's quarters (*Chenopodium album* L.) and redroot pigweed in some of the treatments were large enough to interfere with the direct harvesting of canola. A desiccant application of Diquat Ion was applied to all plots, regardless of their pre-planned desiccant treatment, to facilitate harvest, as cover crop persistence was low. In Carman23, where cover crop persistence was greater, a swather was used rather than a desiccant to protect the cover crops while facilitating harvest. Individual plots were swathed with a R-Tech Plot Master F42 swather (R-Tech Industries Ltd., Homewood, Manitoba) and dried for 3-weeks before harvest with a pickup header on a Kincaid 8-XP small plot combine (Kincaid Equipment Manufacturing,

Table 3.4. Dates of field operations, herbicide applications, and measurements for Carman22, Carman23, Kernen22, and Kernen23.

Field Operation	Site-year			
	Carman22	Carman23	Kernen22	Kernen23
Canola and cover crop seeding	May 22	May 13	May 26	May 11
Harvest	Sept. 8	Sept. 4	Sept. 6	Aug. 28
Herbicide applications				
Pre-emergence	May 27	May 14	-	May 9
In-season	June 17	June 12	June 28	June 12
Desiccant	Aug. 24	Aug. 14	Applied but date unknown	Aug. 15 (RR ^a) Aug. 25 (LL ^b , CF ^c)
Data collection				
Cash crop emergence counts	June 9	May 30	June 15	June 6
Cover crop emergence counts	June 9	June 9	June 15	June 6
Herbicide damage ratings:				
Rating 1 (3 DAA)	-	June 16	-	June 15
Rating 2 (7 DAA)	-	June 20	-	June 19
Rating 3 (14 DAA)	-	June 27	-	June 26
Weed counts	July 12	July 10	July 11	June 12
Weed biomass	July 29	Aug. 2	Aug. 23	Aug. 15
Cover crop biomass	Oct. 5	Oct. 7	Oct. 13	Oct. 23

^a Roundup Ready®

^b Liberty Link®

^c Clearfield®

Haven, Kansas). In both years at Kernen, canola was direct harvested using a Zürn 130-SE small plot combine (Zürn Harvesting GmbH & Co. KG, Baden-Württemberg, Germany). Within each site-year, all three canola varieties were harvested on the same day.

3.3.4 Cover Crop Management

The cover crop mixture used in this experiment consisted of red clover, white Dutch clover, Persian clover, subterranean clover, alfalfa, and Italian ryegrass. The cover crop mixture was seeded for a target stand of 40 plants m⁻² in 2022 (Table 3.5). Due to low establishment of cover crops in 2022, the target stand was increased to 100 plants m⁻² in 2023. Seeding rates for each species were adjusted for seed lot germination and thousand kernel weight.

Table 3.5. Cover crop species, target stand, and seeding rates for the cover crop mixture for experiments in 2022 and 2023.

Cover crop species	Target stand		Seeding rate	
	2022	2023	2022	2023
	plants m ⁻²		kg ha ⁻¹	
Red clover	5	15	0.252	0.756
White Dutch clover	5	15	0.112	0.336
Subterranean clover	5	15	0.785	2.355
Persian clover	5	15	1.401	4.203
Alfalfa	10	30	0.308	0.924
Italian ryegrass	10	10	0.448	0.448
Mix total	40	100	3.306	9.022

Cover crops were drilled with disc plot seeders (Section 3.3.3) at the same time as canola at 38 cm row spacing in Carman and 41 cm in Kernen, resulting in 5 cover crop rows per plot. The cover crops were drilled in alternating rows with canola on a row spacing of 19 cm between canola and cover crop rows in Carman and 20 cm between rows in Kernen. The cover crop mixture was seeded at the same depth as the canola at 1 to 3 cm based on soil moisture.

3.3.5 Data Collections

3.3.5.1 Cover Crop

Cover crop performance was assessed by measuring plant emergence, herbicide damage ratings, and aboveground biomass. To avoid edge effects, plant counts were taken at least 1 m from the plot edge, and no counts were taken from the outer rows of the plot. Cover crop plant counts were measured from two adjacent one-meter rows at both the front and back of the treatment plot. Plant counts were conducted in the spring, one to three weeks after seeding, to assess cover crop emergence. At Carman, individual plant counts were taken for clovers, alfalfa, and Italian ryegrass, whereas at Kernen, the total number of cover crops were counted irrespective of species.

Herbicide damage ratings for cover crops were recorded following the in-season herbicide application. Ratings were conducted 3, 7, and 14 days after application (DAA) to assess the injury to cover crops. The observation period was based on the timing of expected herbicide injury symptoms for the three herbicides included in the study: glufosinate 2 to 4 DAA (BASF Canada Inc., n.d. b), glyphosate 2 to 10 DAA (Bayer Cropscience Inc., 2020), and Imazamox + Imazapyr 7 to 14 DAA (Corteva Agriscience, n.d. a).

Cover crops in each treatment were visually evaluated and compared to the pre-emergence only treatment for each herbicide tolerance system. Individual plots were rated using a 0 to 100 rating scale for crop phytotoxicity adapted from the Canadian Weed Science Society (2018). On the scale, 0% indicated no damage or plant phytotoxicity, where 100% was complete plant death (Table 3.6). Based on this scale, plots rated with an initial damage rating of up to 10% were expected to have cover crops that would outgrow the herbicide injury and be able to recover (Canadian Weed Science Society, 2018). Damage ratings were taken at the front and back of the plot, with ratings performed separately for alfalfa and Italian ryegrass, while clover

species were grouped together. Specific symptoms, including chlorosis, necrosis, stunting, and wilting, were described for each species.

Table 3.6. Canadian Weed Science Society (CWSS-SCM) description of a 0-100 rating scale for crop phytotoxicity adjusted for cover crop species (Canadian Weed Science Society, 2018).

Phytotoxicity range	Assessment of cover crop injury
0-9%	Slight discoloration and/or stunting
10%	Just acceptable
11-30%	Not acceptable
> 30%	Severe

Fall cover crop biomass samples were taken in early to mid-October, prior to the first predicted killing frost. Biomass was sampled from two adjacent one-meter rows at the front of the plot at Carman22, Carman23, and Kernen22. In Kernen23, biomass samples were taken from two adjacent 0.5-meter rows. For all site-years, cover crop biomass was cut at the soil surface and oven dried at 60°C for 48 hours until constant dry weights were obtained.

3.3.5.2 Weeds

Weed counts were taken after the in-crop herbicide application had taken effect, during the vegetative stage of the canola crop. A 0.25 m² quadrat was placed at the front and back of each plot, positioned so the cover crop row was centred. The number of new and surviving weeds within the quadrat were counted. Common species within the experimental area were recorded.

Weed biomass was collected during canola pod-fill (Table 3.4). An area of 0.381 m² was sampled using a quadrat at the front of individual plots, positioned so that the cover crop row was centred, and the edges of the plot were avoided. Weed biomass within the quadrat was cut at the soil surface and oven dried at 60°C for 48 hours, or until constant dry weights were obtained.

3.3.5.3 Canola

Canola was harvested in early to mid-September using a plot combine (Section 3.3.3). Grain samples were dried with ambient air prior to being cleaned. In Carman, samples were initially cleaned using a grain cleaner (Clipper M2BC, Bluffton, IN). Clean weights were recorded, and grain moisture was analyzed using a GAC 2500-INTL Grain Analysis Computer (Dickey-John, Auburn, IL, USA). A representative 1 kg subsample from each plot was further processed to calculate percent dockage using a spiral separator to remove weed seeds prior to grain quality analysis for Carman. In Kernen, grain samples were cleaned using a dockage tester (AG60-2023, Carter Day International, Minneapolis, MN, USA). Grain samples from both locations were analyzed for moisture, protein, and oil content using near infrared (NIR) spectroscopy (Foss Infratec™ 6008 9470/ Rev. 1, Hilleroed, Denmark) at a wavelength range of 570 to 1100 nm.

3.3.6 Statistical Analyses

Statistical analyses were performed using SAS 9.4 (SAS Institute Inc., Cary, NC). The PROC GLIMMIX procedure was utilized to conduct an analysis of variance (ANOVA) to evaluate the treatment effects on dependent variables. The models accounted for year, location, herbicide tolerance system, and herbicide frequency, and their interactions as fixed effects. Random effects in the model included replication nested within location (to account for variation between replication within the location level) as well as the replication by herbicide interaction (to account for variation at the replication and main plot levels). Assumptions for ANOVA were evaluated using PROC UNIVARIATE to test the normality of residuals with the Shapiro-Wilk W test and by visually inspecting histograms of each response variable. Homogeneity of variances was tested by visual inspection of a plot of residuals, where residuals should not form a pattern. Data distributions were either Gaussian, lognormal, Poisson, beta, or negative binomial

as detailed below. Link functions were selected according to the specified error distribution: an identity link for Gaussian distributions; a log link for lognormal, Poisson, and negative binomial distributions; and a logit link for beta distributions. Models with Gaussian and log normal error distributions were estimated using the restricted maximum likelihood (REML), while models with Poisson, negative binomial, and beta distributions were estimated using the default pseudo-likelihood (ML- based) method. Default options for the GLIMMIX procedure were included in the model using the link statement, the Satterthwaite method to determine denominator degrees of freedom, and the compound symmetry covariance structure. To further investigate differences among treatment means, the LSmeans statement was used for pairwise comparisons between means of the treatment groups with Tukey's Honest Significant Difference (HSD) adjustment at a probability of 5% ($p < 0.05$). Means comparisons were conducted within each site-year.

Statistical models for cover crop biomass and canola yield included all four fixed effects (year, location, herbicide tolerance system, and herbicide frequency) as well as their interactions. Yield followed a Gaussian distribution, but to account for non-normality, a lognormal distribution was used for cover crop biomass. Results were back-transformed prior to reporting.

crop emergence was analyzed with a reduced model statement using ANOVA and the PROC GLIMMIX procedure. The model accounted for three fixed effects (year, location, and herbicide tolerance system), as no in-season herbicides (herbicide frequency) were applied at the time of cover crop emergence counts. As the count data did not follow a normal distribution, a negative binomial transformation was applied prior to statistical analysis and back-transformed for presentation. To account for the use of the negative binomial statement, the nloptions statement was included to control the number of iterations to 500 when estimating the parameters of the negative binomial model.

A reduced data set with desiccant treatments removed was used for the analysis of weed density and weed biomass, as desiccation treatments had yet to be applied at the time of sampling. The model statement included all four fixed effects (year, location, herbicide tolerance system, and herbicide frequency) and their interactions. Neither variable followed a normal distribution, therefore a negative binomial distribution with the `nloptions` statement was applied for weed density, and a lognormal distribution was applied for weed biomass prior to statistical analysis and back transformed for presentation.

Herbicide damage ratings were subjected to a repeated measures ANOVA conducted by each of the species rated: clovers, alfalfa, or Italian ryegrass. The PROC GLIMMIX procedure was utilized with location, herbicide tolerance system, day after application, and their interactions were included as fixed effects in the model. The denominator degrees of freedom were calculated using the Kenward-Roger method (1997) to account for repeated measures of a split-plot design with non-normal data (Padilla et al., 2008). As ratings were a percentage value, data points were converted to a proportion (between 0 and 1) by dividing the rating by 100 to meet the assumptions of the beta distribution, which was used with the logit link function. Prior to presentation, the data was back-transformed for presentation. Random statements were used to specify the repeated measures structure. The Day after application was a random effect within the model to determine if ratings taken on different days were independent from one another. Day was grouped within the combination of location and herbicide, which was nested within replication to account for variation among days within each experimental condition. The spatial power covariance structure was utilized to account for unequal spacing between ratings (Gbur et al., 2012). Days after application was used to define the distance between the repeated measures.

3.4 Results and Discussion

3.4.1 Meteorological Conditions

Mean air temperature during the growing season was similar to the climate normals in 2022, with the exception of the months of August to October, which were above normal for both sites as a result of a subtropical Hawaiian high-pressure ridge (Phillips, 2023). The high-pressure ridge placed Manitoba and Saskatchewan under a heat dome, resulting in Carman's temperatures being 1°C warmer than the normal in both September and October, whereas Kernen experienced greater temperature deviations with temperatures being 3°C and 2.7°C warmer than normal in September and October, respectively. The first killing frost in 2022 occurred on September 28th in Carman and earlier on September 21st in Kernen.

The beginning of the 2023 growing season in Manitoba and Saskatchewan was met with the warmest May and June since 1988, with average temperatures greater than the normal because of El Niño (Phillips, 2024). In Carman and Kernen, May was 4.5°C and 3.7°C warmer than normal, followed by June, which was 3.8°C and 3.1°C warmer, respectively (Table 3.7). These early-season extreme temperatures were followed by a cooler-than-normal July, whereas August temperatures returned to near normal. September and October again exceeded the long-term normal, mirroring the trends observed in 2022. The first killing frost in 2023 occurred later at both locations, with the date being October 10th in Carman and October 16th in Kernen.

Plant growth is strongly influenced by temperature, and growing degree days (GDD) can be used to compare between years and locations in this study (Agriculture and Agrifood Canada, 2021). Throughout the growing season, more GDD (base 5) were accumulated in 2023 compared to 2022 at both locations. In 2022, Carman accumulated 1798 GDD, which was similar to Kernen, where 1799 GDD was accumulated. Due to the higher temperatures in 2023, GDD increased to 2088 and 1923 in Carman and Kernen, respectively.

Table 3.7. Monthly mean air temperature and cumulative precipitation during the growing season (April to October) and deviation from the Environment Canada 30-year long-term normal (1981 to 2010) for Carman22, Carman23, Kernen22, and Kernen23.

Month	Site-year			
	Carman22	Carman23	Kernen22	Kernen23
Mean air temperature				
°C				
Apr.	-1.0 (-5.5)	0.1 (-4.4)	1.8 (-3.4)	1.4 (-3.8)
May	10.8 (-0.8)	16.1 (+4.5)	11.0 (-0.8)	15.5 (+3.7)
June	17.8 (+0.6)	21.0 (+3.8)	15.7 (-0.4)	19.2 (+3.1)
July	19.2 (-0.2)	18.4 (-1.0)	19.3 (+0.3)	17.7 (-1.3)
Aug.	19.3 (+0.8)	18.9 (+0.4)	19.6 (+1.4)	18.1 (-0.1)
Sept.	14.4 (+1.0)	15.9 (+2.5)	15.0 (+3.0)	14.9 (+2.9)
Oct.	6.4 (+1.0)	6.2 (+0.8)	7.1 (+2.7)	4.2 (-0.2)
Cumulative precipitation				
mm				
Apr.	127.6 (+98.1)	31.2 (+1.7)	3.0 (-18.8)	8.2 (-13.6)
May	98.9 (+29.0)	17.4 (-52.5)	25.8 (-10.7)	51.9 (+15.4)
June	39.4 (-57.0)	25.1 (-71.3)	38.0 (-25.6)	43.8 (-19.8)
July	82.8 (+4.2)	23.9 (-54.7)	46.5 (-7.3)	19.9 (-33.9)
Aug.	48.7 (-26.1)	59.1 (-15.7)	25.6 (-18.8)	50.4 (+6.0)
Sept.	26.7 (-22.3)	48.2 (-0.8)	6.8 (-31.3)	16.5 (-21.6)
Oct.	27.5 (-15.9)	64.7 (+21.3)	5.1 (-13.7)	20.3 (+1.5)
Season total (Apr.-Oct.)	451.6 (+10.0)	269.6 (-172.0)	150.8 (-126.2)	211.0 (-66.0)

In 2022, precipitation was lower than the normal in Carman, with the exceptions of July, which was similar to the normal, and April and May, which were greater than normal. This was a result of three heavy precipitation days where rainfall greater than 20 mm occurred. In these three months, Carman received 68% of the total precipitation. For all other months, precipitation was less than the normal. Overall, Carman received 102% of the normal precipitation in 2022. Opposite conditions occurred in Kernen during the 2022 growing season, with a moderate drought that saw 58% of normal precipitation, and every month received less than the normal precipitation. With the heat dome that occurred in the later months of the 2022 growing season, both locations had drought conditions during September and October, which coincides with the fall shoulder-season when the majority of cover crop growth was expected to occur. In

September and October in Carman, the drought was moderate with precipitation being 54 and 63% of the normal, respectively, whereas in Kernn the drought was extreme with precipitation being 18 and 28% of the normal, respectively.

In 2023, drought conditions occurred at Carman, where only 58% of the normal growing season precipitation was received. Unlike May 2022, when there were heavy precipitation days, only 25% of the normal precipitation occurred in 2023. Overall, the early summer months received less than 30% of the normal precipitation, and according to Asrari et al. (2011), would be classified as an extreme drought. Precipitation events in the fall resulted in September being similar to the normal, whereas October received more than the normal precipitation. In 2023, the drought conditions continued but improved at Kernn, where 79% of the normal precipitation was accumulated. At the time of cover crop establishment in May and June, precipitation was comparable to the normal. In the fall months of September and October, moderate drought conditions occurred with 65% of the normal precipitation received (Table 3.7).

Adequate soil moisture is also required for successful crop and cover crop establishment. In the Prairies, soil moisture is often recharged during the winter months. During the winter prior to each experiment (November to March), all site-years accumulated less than the normal precipitation. Prior to the year of establishment in 2022, Carman22 (November 2021-April 2022) received 94.7 mm, which was 9.1 mm less than the normal. Conditions prior to Carman23 (November 2022-April 2023) were worse, where only 44.2 mm of precipitation was accumulated, which was 59.6 mm less than normal. In both years of the study, Kernn received similarly low winter precipitation amounts. Kernn22 received 27.6 mm of precipitation, which was 35.8 mm less than normal. Kernn23 received more precipitation with 32.0 mm accumulated, but still experienced a deficit of 31.4 mm when compared to the normal.

The weather on the day that in-season herbicides were applied in 2023 varied by location. The average daytime temperature (5 am to 5 pm) in Carman was 24.6°C with a maximum temperature of 29.4°C. Average relative humidity was 32.2% with a dewpoint of 8.2°C on the day of application. Minimal precipitation of 0.2 mm was received the day before application, and no precipitation occurred 24 hours after application. In Kern, the average temperature was lower than in Carman at 23.2°C but reached a maximum of 29.9°C. The relative humidity and dew point were greater in Kern with 42.8% relative humidity and a dew point of 11.8°C, with no precipitation occurring 24 hours before or after the herbicide application.

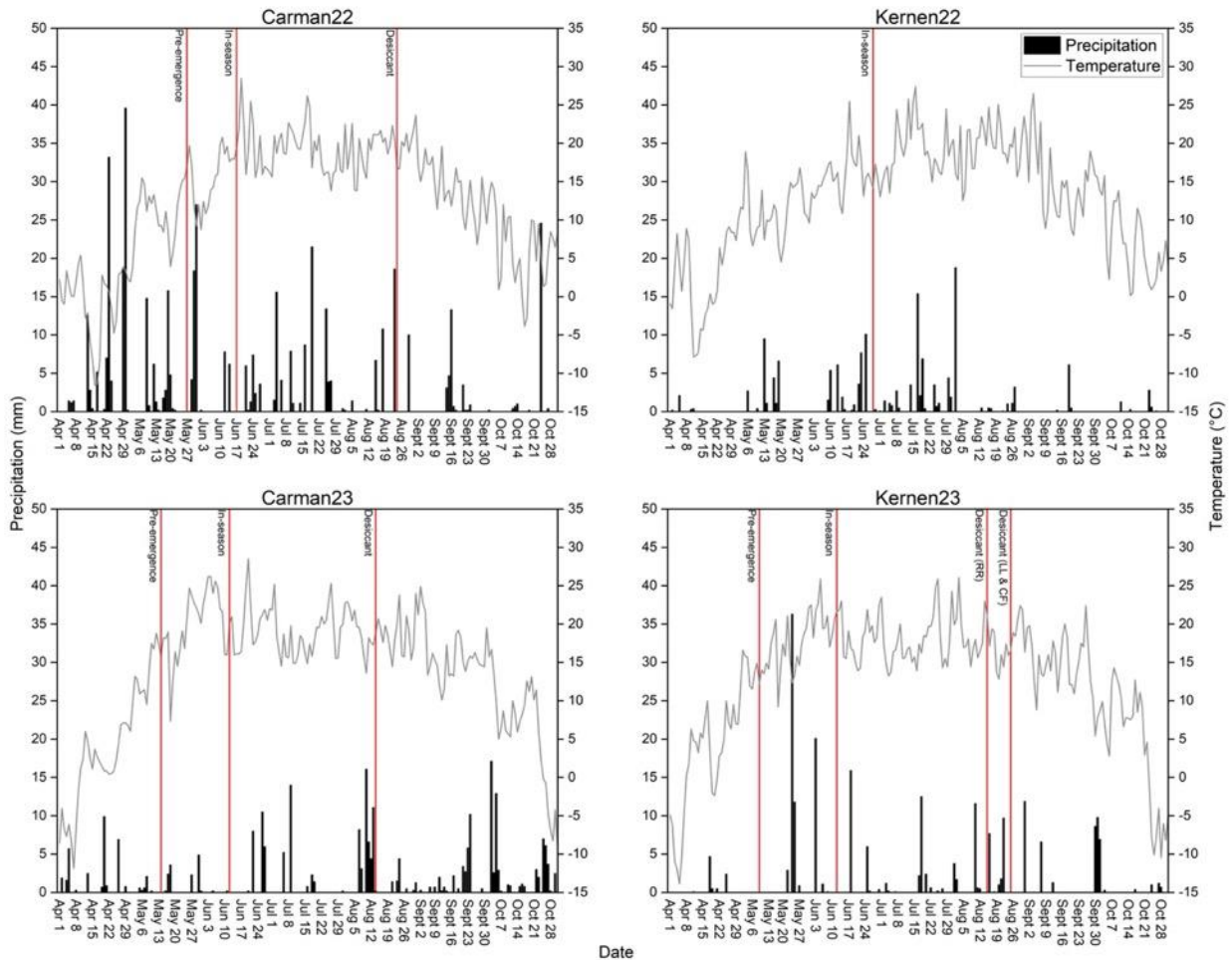


Figure 3.1. Growing season daily precipitation and daily mean temperature for Carman22, Kern22, Carman23, and Kern23. Vertical red lines indicate herbicide applications at each location for pre-emergence, in-season, or desiccant treatments.

3.4.2 Cover Crop

3.4.2.1 Cover Crop Emergence

To achieve the benefits associated with the use of cover crops, early and uniform establishment is essential for subsequent performance. The emergence of cover crop species was observed to be consistent across canola herbicide tolerance systems. Cover crop emergence varied between sites and years, largely influenced by yearly growing conditions and climate (Section 3.4.1), as well as increases made to the 2023 cover crop seeding rate. In this study, the main effect of year and location, and their interaction, were statistically significant for cover crop emergence (Table 3.8).

Table 3.8. Analysis of variance of the dependent variable, cover crop emergence taken 3 weeks after seeding for the main effects of year (Y), location (L), herbicide tolerance system (HTS), and their interactions. Bolded values indicate significance at the 0.05 probability level.

Sources of variation	df	<i>p</i> -value
Year (Y)	1	<0.0001
Location (L)	1	0.0024
Herbicide Tolerance System (HTS)	2	0.5638
Y*L	1	<0.0001
Y*HTS	2	0.1826
L*HTS	2	0.5468
Y*L*HTS	2	0.7849

In 2022, cover crop emergence in Carman was 13 plants m⁻², which was well below the target stand of 40 plants m⁻². Kernen, however, exceeded the target with an average stand of 67 plants m⁻². Due to limited cover crop establishment at Carman as well as low fall cover crop biomass at both sites in 2022, the cover crop seeding rate was increased to 100 plants m⁻² for both sites in 2023. This change in seeding rate explains part of the effect of year on cover crop emergence. In 2023, cover crop stand emergence was 124 plants m⁻² and 110 plants m⁻², respectively, in Carman and Kernen. The herbicide tolerance system treatment had no impact on

cover crop emergence, as canola was at the one-leaf stage at the time of counts, and no in-season herbicides had been applied.

The differences in cover crop emergence across locations and years can also be attributed to meteorological conditions during the experiment. Stored soil moisture and in-season rainfall are critical factors for cover crop establishment. In 2022, Carman's accumulated winter precipitation prior to the establishment of the experiment was similar to the 30-year climate normal (Table 3.7), whereas all other site-years received only 43 to 50% of the expected precipitation. Though stored soil moisture is crucial for supporting cover crop establishment, timely rainfall events are also necessary (Obour et al., 2021). In 2022, Carman received 99 mm of precipitation in May, with the majority occurring during several rainfall events after seeding. These saturated soil conditions likely resulted in oxygen deprivation around the seeds, delaying germination and emergence, which may have also increased the risk of cover crop stand loss (Government of Manitoba, n.d. b). All other site-years received less than the normal amounts of precipitation in the spring months, but still had successful establishment due to timely rainfall events following seeding. In 2022, spring temperatures in May were cooler than normal (Table 3.7) at both sites, which has also been shown to slow the germination of species in the Northern Great Plains (Obour et al., 2021).

Emergence for individual species in the cover crop mix was assessed for Carman22 and Carman23. Emergence varied by year (Table 3.9) and was influenced by seeding rates of each species (Table 3.5). Emergence counts were primarily comprised of clovers in both 2022 and 2023 at Carman (Table 3.9), reflecting the cover crop mixture proportions. Clover emergence of 106 plants m⁻² averaged across all treatments in 2023 was nearly 10 times the amount in 2022, which can be attributed to the tripled seeding rates of clover species, although emergence

exceeded the target population of 60 plants m⁻² by 46 plants m⁻². Italian ryegrass emergence of 6 plants m⁻² was nearly 3 times higher in 2023, but was still lower than the target population of 10 plants m⁻². Similarly, alfalfa emergence was lower than the expected target stand. No alfalfa emerged in 2022 at Carman, which may be attributed to high soil moisture conditions (University of Minnesota Extension, 2021). In 2023, alfalfa emergence was 10 plants m⁻², which was one-third of the target stand (30 plants m⁻²). At the seedling stage, alfalfa and clover species look similar, and misidentification could have resulted in lower counts for alfalfa seedlings.

Table 3.9. Cover crop establishment by species in June for Carman22 and Carman23.

Site-year	Cover Crop Species		
	Clovers	Alfalfa	Italian ryegrass
	plants m ⁻²		
Carman22	10.7 b ^a	0.0 b	2.4 b
Carman23	105.5 a	9.7 a	6.1 a
Source of variation			
Year	<0.0001	<0.0001	<0.0001

^a means followed by the same letter are not significantly different within a cover crop species column at $p < 0.05$.

Establishing forage crops, such as alfalfa or red clover, with a companion crop of canola is challenging, as canola is competitive and allows for little light penetration (Johnston & Bowman, 2000). However, limited peer-reviewed literature is available about establishing cover crops within a canola canopy. Previous experiments conducted across Manitoba have found differing results when intercropping cover crops with canola. Although all intercropped cover crops tested established slowly, alfalfa was observed to be more successful than red and white clover in one experiment near Roblin, MB, in 2020 (Parkland Crop Diversification Foundation, 2021). Studies looking at red clover seeded as a monoculture or with canola in Melfort, Saskatchewan, found a 30% reduction in clover establishment when intercropped with canola (McInnes & Slowski, 2020). Additional studies conducted with crimson, subterranean, and white

clover observed similar results with greater stand densities when sown as a monoculture due to decreased competition with canola (North Peace Applied Research Association, 2023).

3.4.2.2 Herbicide Damage Ratings

Herbicide damage ratings provide a quantitative assessment of cover crop tolerance to in-season herbicide applications to facilitate future herbicide selection. It should be noted that in Canada, glufosinate and imazamox+ imazethapyr, specifically Clearfield® Ares, herbicides are not registered for weed control use on any of the cover crop species used in this experiment. Imazamox and imazethapyr are however registered individually for use in alfalfa (Manitoba Agriculture, 2025). Glyphosate is not registered for use on any of the cover crop species, with the exception of Roundup Ready® alfalfa, where it is registered for weed control (Manitoba Agriculture, 2025).

Analysis of variance for herbicide damage ratings, taken 3 to 14 days after herbicide application, was conducted by cover crop species in 2023 at both study locations. A significant three-way interaction occurred between location, herbicide tolerance system, and days after application for both clovers and alfalfa. Herbicide damage ratings for Italian ryegrass were only conducted in Kernen due to limited plant establishment in Carman. At Kernen, the interaction of herbicide tolerance system and days after application was significant for herbicide damage ratings in Italian ryegrass (Table 3.10). Treatment means for the highest-order significant interactions are presented in Table 3.11.

Table 3.10. Analysis of variance (ANOVA) of the dependent variable herbicide damage ratings for the main effects of location (L), herbicide tolerance system (HTS), days after application (DAA), and their interactions for clover, alfalfa, and Italian ryegrass cover crops. Bolded values indicate significance at the 0.05 probability level.

Sources of variation	Cover crop species		
	Clovers	Alfalfa	Italian ryegrass [†]
Location (L)	0.0230	0.0090	-
Herbicide tolerance system (HTS)	<0.0001	<0.0001	0.0002
Days after application (DAA)	0.0044	0.1352	<0.0001
L*HRS	0.0217	0.3641	-
L*DAA	0.6315	0.5019	-
HRS*DAA	<0.0001	<0.0001	<0.0001
L*HRS*DAA	<0.0001	<0.0001	-

[†] Damage ratings for Italian ryegrass were recorded and analyzed only for Kernen23.

Herbicide damage ratings for cover crop species were influenced by the in-season herbicide applied (Table 3.2). In Carman, glufosinate resulted in severe injury with ratings greater than 30% at 14 DAA for all cover crop species rated (Table 3.11). In contrast, acceptable damage ratings up to 10% occurred in alfalfa treated with glyphosate and for all cover crops treated with imazamox+ imazethapyr. In Kernen, herbicide damage ratings were rated as severe damage for all cover crops at 14 DAA, regardless of the herbicide applied. To further examine the variability in injury among cover crop species (Figure 3.2 and Figure 3.3), trends in damage ratings are presented for each herbicide type.

Table 3.11. Herbicide damage ratings by percent injury as determined by the CWSS-SCM rating scale for crop tolerance for each cover crop species (clovers, alfalfa, and Italian ryegrass) treated with glufosinate, glyphosate, or imazamox+ imazethapyr. Ratings were taken 3, 7, and 14 days after application (DAA) for Carman23 and Kernen23. A rating of 0% indicates no damage, whereas a rating of 100% indicates complete plant death.

Herbicide	Carman23			Kernen23		
	3 DAA	7 DAA	14 DAA	3 DAA	7 DAA	14 DAA
	% injury					
	Clovers^a					
Glufosinate	63 cd ^b	79 ab	83 a	66 abc	79 ab	65 bc
Glyphosate	29 f	45 de	44 de	7 g	41 ef	79 ab
Imazamox+ imazethapyr	0 g	0 g	1 g	3 g	11 g	35 ef
	Alfalfa					
Glufosinate	41 d	62 cd	73 cd	76 bc	91 a	72 cd
Glyphosate	9 d	16 d	23 d	3 d	51 d	90 ab
Imazamox+ imazethapyr	0 d	0 d	0 d	2 d	3 d	48 d
	Italian ryegrass^c					
Glufosinate	-	-	-	53 a	47 a	33 a
Glyphosate	-	-	-	2 b	86 ab	100 a
Imazamox+ imazethapyr	-	-	-	2 b	11 ab	86 a

^a Clovers were rated as a group and included red, white, subterranean, and Persian clovers as individual plants for species could not be distinguished from one another at the time of rating.

^b a-g means values followed by the same letter are not significantly different from one another within a cover crop species (clovers, alfalfa, Italian ryegrass) at $p < 0.05$.

^c Italian ryegrass ratings were recorded and analyzed for Kernen only due to poor emergence in Carman.

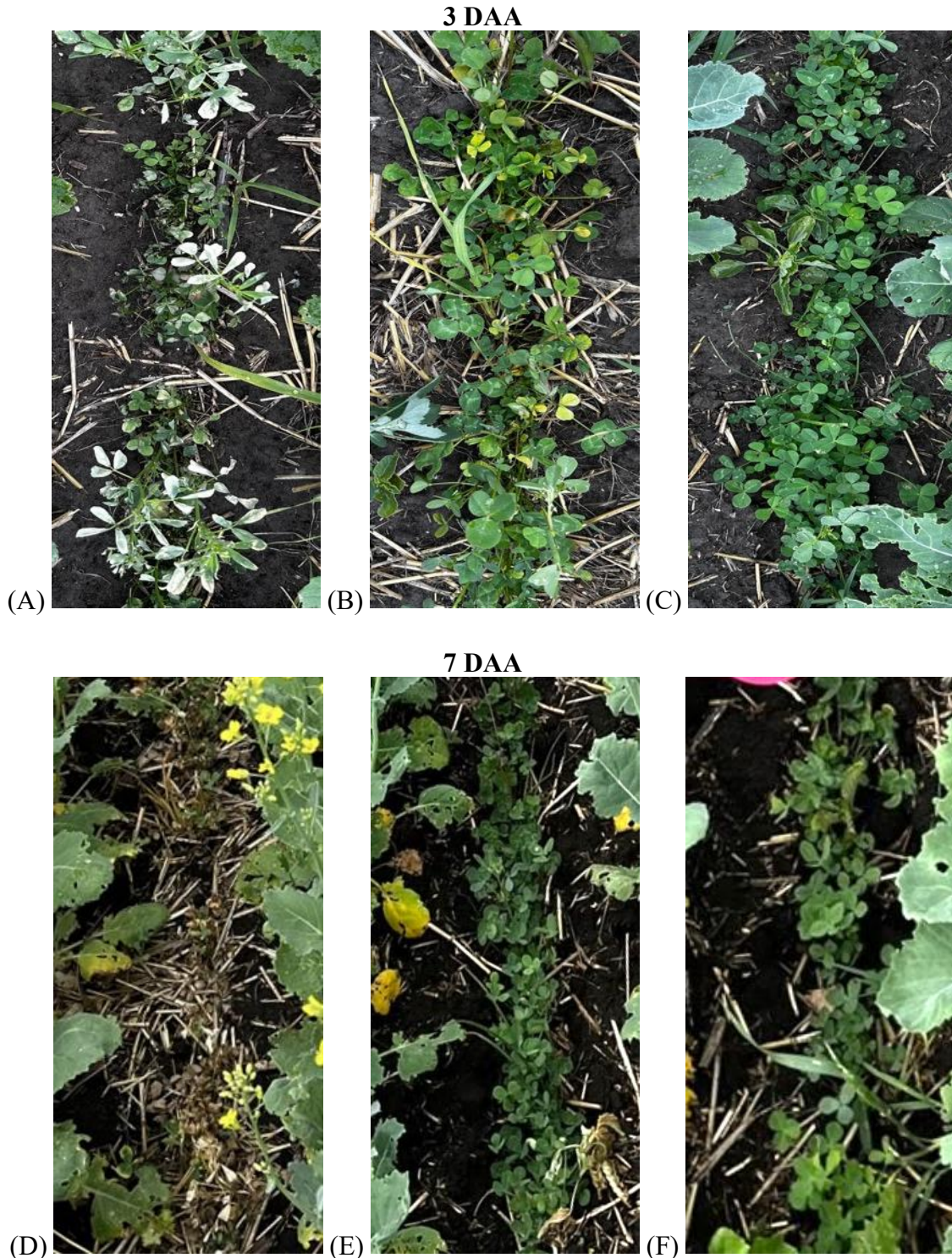


Figure 3.2. Herbicide injury 3 and 7 days after application (DAA) in Carman23 to the cover crop mixture (including red clover, white clover, subterranean clover, Persian clover, alfalfa, and Italian ryegrass) from three herbicides (glufosinate, glyphosate, and imazamox+ imazethapyr). From top to bottom: (A)-(C) 3 DAA, (D)-(F) 7 DAA. From left to right: (A) and (D) glufosinate, (B) and (E) glyphosate, and (C) and (F) imazamox+ imazethapyr.

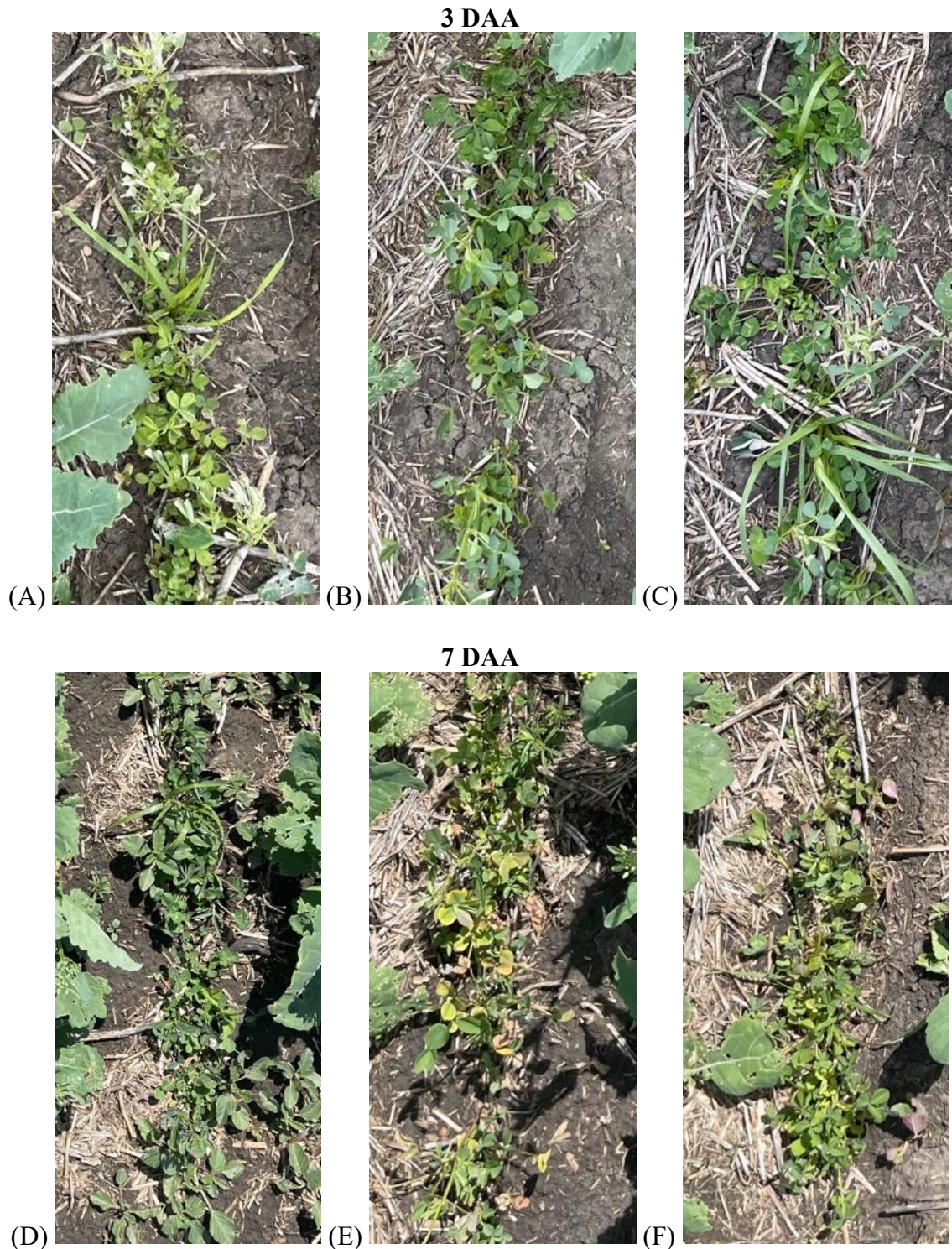


Figure 3.3. Herbicide injury 3 and 7 days after application (DAA) in Kern23 to the cover crop mixture (including red clover, white clover, subterranean clover, Persian clover, alfalfa, and Italian ryegrass) from three herbicides (glufosinate, glyphosate, and imazamox). From top to bottom: (A)-(C) 3 DAA, (D)-(F) 7 DAA. From left to right: (A) and (D) glufosinate, (B) and (E) glyphosate, and (C) to (F) imazamox+ imazethapyr.

3.4.2.2.1 Glufosinate

Glufosinate caused the most significant injury to clovers and alfalfa in Carman compared to the other herbicides utilized. Symptoms in clovers and alfalfa were evident as early as 24 hours post-application, with bleaching of the uppermost leaves (Figure 3.2 A). By 3 DAA, ratings of both clovers and alfalfa were greater than 30%, indicating severe injury (Table 3.11). Ratings continued to increase for both species 7 DAA and peaked at 14 DAA with a rating of 83% injury in clovers and 73% in alfalfa. Damage ratings in this range are deemed a severe injury using the CWSS scale. At Kernen, similar symptoms were observed 3 DAA, with bleaching in the uppermost leaves (Figure 3.3 A), and greater than 30% injury at 3 DAA, which indicated a severe injury. Damage ratings taken at 3 and 7 DAA were greater in Kernen compared to Carman and were greatest at 7 DAA, with a rating of 79% in clovers and 91% in alfalfa. Damage ratings for both species decreased to 65 and 72% in clovers and alfalfa, respectively, at 14 DAA, due to new growth. Despite this regrowth, ratings of clovers and alfalfa at both locations remained greater than 30% at 14 DAA, which indicates a severe injury with minimal potential for recovery. With the growing point of clover species and alfalfa being located at the crown, which is elevated above ground in leguminous species, the species can be damaged beyond recovery. This observation of reduced cover crop stands with injury ratings greater than 30% at 21 DAA was supported by fall persistence counts that are reported in Appendix A.1.

In Kernen, where herbicide damage ratings were conducted on Italian ryegrass, it was observed that glufosinate was the least damaging of all the herbicides applied, though the rating was still severe. At 3 DAA, a severe damage rating of 53% was observed, which was similar to ratings of clovers and alfalfa. However, unlike the broadleaf species where ratings increased at 7 DAA, damage ratings to Italian ryegrass decreased to 47% at 7 DAA and further decreased to

33% at 14 DAA. The injury to Italian ryegrass was still severe despite the declining damage ratings that indicated recovery of the species.

As glufosinate is a non-systemic herbicide, injuries are prevalent in exposed tissue on the uppermost leaves. In leguminous species, injury symptoms include greyish-white bleached patches on exposed tissues (Bogdan, 2023). These symptoms were observed in alfalfa and clovers at Carman23 (Figure 3.2 A) and Kernen23 (Figure 3.3 A).

Damage ratings taken 3 DAA saw glufosinate inflicting a greater immediate injury in Kernen than in Carman. This may be a result of the higher humidity conditions at Kernen, which slows droplet evaporation and allows for greater herbicide absorption (Ramsey et al., 2002) and thus greater phytotoxicity (Anderson et al., 2006). Previous studies have reported that relative humidity is an important factor for glufosinate performance. For example, a greenhouse study by Coetzer et al. (2001) found greater injury from glufosinate in palmer amaranth (*Amaranthus palmeri* S. Watson), redroot pigweed, and common waterhemp (*Amaranthus tuberculatus* (Moq.) Sauer) at 90% RH compared to 35% RH, where low relative humidity decreased visible control of the amaranth species (Coetzer et al., 2001). Furthermore, Coetzer et al. (2001) observed similar injury ratings when glufosinate was applied at 35% relative humidity, which was similar to the humidity conditions at Carman and Kernen in 2023. In the same study, glufosinate was applied at 410 g a.i. ha⁻¹ and resulted in 89% injury to broadleaves (Coetzer et al., 2001). This rating was similar to the damage ratings observed in the current study, with ratings of 83% to clovers in Carman and 73 to 72% to alfalfa at Carman and Kernen, respectively (Table 3.11).

While glufosinate can be highly effective and cause severe injuries to annual broadleaf species, its efficacy on annual grass species is reduced due to limited translocation (Takano et al., 2019; Takano & Dayan, 2020) and minimal contact to growing points. A contrasting study had

found that glufosinate applied at canola bolting visually controlled spring-seeded Italian ryegrass by 59% relative to the untreated control at 14 days post-application (Thorne & Lyon, 2024). As the growing point of Italian ryegrass is at the base of the tiller near the soil surface, the non-systemic activity of glufosinate limits growing point damage if the herbicide does not penetrate the canopy to reach the growing point. This may have occurred at Kernen, where a severe injury of 53% was initially observed at 3 DAA, but damage ratings declined to 33% 14 DAA, indicating recovery through regrowth of new leaves from the growing point.

3.4.2.2.2 Glyphosate

Variation in glyphosate application rates contributed to differing injury levels between locations. In Carman, where the lower rate of glyphosate was applied, glyphosate was the second most damaging herbicide, with clovers and alfalfa exhibiting varying visual injuries ranging from chlorosis in clovers to a shepherd's crook in alfalfa (Figure 3.2 B). At 3 DAA, the injury to clovers was not acceptable according to the CWSS scale, with a damage rating of 29%, whereas the 9% rating to alfalfa was considered acceptable. At 7 DAA, the rating to clovers was severe at 45%, whereas the rating to alfalfa increased to 16%, indicating injury that was not acceptable. While clover ratings remained consistent from 7 to 14 DAA, ratings to alfalfa continued to increase to 23% at 14 DAA, though the injury was still not severe (Table 3.11).

At Kernen, glyphosate was the most damaging herbicide among those tested, where the ratings to clovers and alfalfa were severe and greater than those reported at Carman. Unlike at Carman, glyphosate inflicted greater injury to alfalfa than to clovers at Kernen. Slight injury was observed in both species at 3 DAA, which was unexpected due to the higher application rate. However, similar visual symptoms of chlorosis and a shepherd's crook were observed (Figure 3.3 B). By 7 DAA, injury levels were severe with damage ratings of 41% in clovers and a greater 51% in alfalfa. Damage ratings to both species increased at 14 DAA, with clover injury reaching

79% and alfalfa injury increasing to 90% (Table 3.11). This observation was supported by fall persistence counts that are reported in Appendix A.1. Italian ryegrass experienced an acceptable injury of 2% at 3 DAA, which can be attributed to the systemic translocation of the herbicide, as visual symptoms take longer to develop. However, by 14 DAA, the injury rating increased to 100%, indicating complete mortality of the species.

The difference in ratings between locations can be attributed to the higher application rate in Kernen, where a rate of 3.3 L ha⁻¹ (1782 g a.e. ha⁻¹) was applied, compared to 1.7 L ha⁻¹ (918 g a.e. ha⁻¹) in Carman. Additionally, temperatures on the day of herbicide application at both locations were greater than the optimal temperature range of 16 to 24 degrees Celsius for Roundup Weathermax (Bayer Cropscience Inc, 2020). The maximum daily temperatures of roughly 29 degrees Celsius at both locations, coupled with the lower humidity of 32.2% and 42.8% at Carman and Kernen, respectively, can result in decreased herbicide absorption and translocation (Sharma & Singh, 2001), especially with systemic herbicides including glyphosate (Everman & Anderson, 2025). The lower relative humidity at Carman could also contribute to the lower ratings at that site compared to Kernen at 14 DAA.

Broadleaf and grass cover crop termination is often achieved with the use of glyphosate. However, glyphosate has been found to be less effective on broadleaf species with an average control of 80% (Whalen et al., 2020). In the current study, the high clover damage ratings ranging from 44% in Carman to 79% in Kernen at 14 DAA matched previous field experiments in Oklahoma by Nelson et al. (1991), which observed 56% control of white clover and 63% control of red clover. At a separate location however, the injury from glyphosate was reduced to 15% control in white clover and 9% in red clover, indicating varying results based on location (Nelson et al., 1991). An additional field experiment with white clover in Alabama found that an

application of glyphosate reduced leaf density and height by 57 and 48%, respectively (McCurdy et al., 2016). In greenhouse experiments by Adami et al. (2017), injury from glyphosate to white clover at the three-trifoliolate leaf stage, taken 14 DAA, was 25% when applied at a rate of 540 g a.e. ha⁻¹, but when applied at rates of 1080 or 1620 g a.e. ha⁻¹, injury ratings increased to 50 and 55%, respectively. The rates of 1080 and 1620 g a.e. ha⁻¹ used by Adami et al. (2017) were similar to the herbicide rates applied at both Carman and Kernen that resulted in injury ratings of 100% at 21 DAA under field conditions.

Although alfalfa is usually grown as a crop, it can also be considered a perennial broadleaf weed, which is controlled by applications of Roundup Weathermax (Bayer Cropscience Inc., 2020). Injury symptoms in Carman (Figure 3.2 B) and Kernen (Figure 3.3 B) included leaf chlorosis, aligning with previous reports on alfalfa seedling damage (Crop Protection Network, n.d.; Beck et al., 2017) and injury symptoms from glyphosate applications (Blackshaw et al., 2020; Gunsolus & Curran, 1999). In legumes, including alfalfa and clover, symptoms are slow to develop due to the systemic translocation of glyphosate, but are apparent in young leaves, which become chlorotic (Bogdan, 2023).

For grass cover crop species, glyphosate is considered the most effective herbicide used for control (Anderson, 2023). On a 0 to 100 scale with 100 indicating complete cover crop death, glyphosate resulted in 85% visible control of annual ryegrass at the tillering stage and 94% control of cereal rye at the heading stage when evaluated 28 DAA (Whalen et al., 2020). The findings from Whalen et al. (2020) align with herbicide damage ratings in the current study, which saw glyphosate as the most damaging herbicide to Italian ryegrass and resulted in complete plant death at 14 DAA. Previous studies by Thorne and Lyon (2024) confirm

glyphosate effectively controlled Italian ryegrass, with 88 to 100% control 14 days after a late post-emergence application in canola.

3.4.2.2.3 Imazamox+ Imazethapyr

Imazamox+ imazethapyr (Clearfield® Ares) was the most successful herbicide application for supporting legume cover crop growth through reduced herbicide damage ratings at both locations. At Carman, clovers and alfalfa experienced minimal injury from in-season herbicide application, both visually (Figure 3.2 C) and numerically, as reported as herbicide damage ratings based on the CWSS scale (Table 3.11). Even after 14 DAA, imazamox+ imazethapyr (Clearfield® Ares) resulted in a damage rating of 1% to clovers from slight discoloration to the uppermost leaves, whereas alfalfa had no visible damage at Carman and had a rating of 0%.

At Kernen, however, clovers and alfalfa suffered severe injury following the in-season application of imazamox+ imazethapyr (Clearfield® Ares). Up to 7 DAA, minimal injury was observed in both species, with a damage rating of 11% in clovers and 3% in alfalfa. By 14 DAA, ratings increased and resulted in damage ratings of 35% in clovers and 48% in alfalfa, as both species experienced symptoms of chlorosis (Figure 3.3 F) and stunted growth, matching previously reported injury symptoms in broadleaves to imazethapyr and imazamox (Canevari et al., 2007; Crop Protection Network, n.d.). Italian ryegrass damage ratings at Kernen were similar to clovers and alfalfa, with acceptable injury observed at 7 DAA, which then increased to severe injury with a rating of 86% at 14 DAA (Table 3.11).

The difference in ratings between locations may be explained by differences in temperature and relative humidity. At Carman, the average temperature was 24.6°C with a maximum of 29.4°C whereas in Kernen, the average temperature was lower at 23.2°C but

experienced a similar maximum of 29.9°C. When high temperature is coupled with lower humidity, absorption and translocation are decreased (Sharma & Singh, 2001), especially with systemic herbicides including imazamox+ imazethapyr (Everman & Anderson, 2025). The lower relative humidity of 32.2% at Carman may account for the lower injury ratings when compared to Kernen, which had a higher relative humidity of 42.8% on the day of application.

At this time, Clearfield® Ares, a formulation of imazamox+ imazethapyr used in this current study, is not registered for use on forages, including clovers and alfalfa (Manitoba Agriculture, 2025). However, other group 2 herbicides, including formulations of imazamox+ imazethapyr, are recommended for post-emergence applications when legume seedlings, including clovers and alfalfa, are beyond the second trifoliolate stage (Michigan State University, 2024). At both sites, legumes were approximately at this stage, which should have minimized the risk of injury. Additionally, both imazamox and imazethapyr are individually registered for use on seedling alfalfa (Canevari et al., 2007).

The Clearfield® herbicide tolerance system, which represents the lowest seeded acres of the three systems used for canola in Canada (Canola Council of Canada, n.d.), has limited published research describing the effects of this system on intercropped leguminous cover crop species or Italian ryegrass in canola. Unpublished field experiments near Melita, Manitoba, had observed that when rated 1 and 2 weeks after application, injury to red clover was 35 and 10%, respectively. In the same experiment, a greater rating of 35 and 25% was observed in alfalfa 1 to 2 weeks after herbicide application (Westman Agricultural Diversification Organization, 2024). These results contrast with the findings of the current experiment at Carman but were similar to those reported in Kernen.

Field studies have demonstrated varying levels of tolerance of legumes to either imazamox or imazethapyr. For example, a study by Lins et al. (2005) found red clover tolerance to imazamox, while a study by Enloe et al. (2014) observed white clover tolerance to imazethapyr within mixed grass-clover pastures. Other field studies conducted on annual forages in Lethbridge, Alberta, found minimal visual injury of 6.6% in Persian clover following post-emergence imazethapyr applications, whereas alfalfa had no visible injuries (Fraser et al., 2003). Similarly, Wilson and Burgener (2009) reported a visual injury of 6% to alfalfa following imazamox applications. Additional field experiments in Alabama confirmed that separate applications of imazamox and imazethapyr did not reduce white clover leaf densities relative to untreated controls (McCurdy et al., 2016). Greenhouse studies have further confirmed non-severe injuries to white clover from imazethapyr with an injury rating of 15% 14 DAA when applied at 150 or 200 g a.i. ha⁻¹ (Adami et al., 2017). While the Clearfield® system, utilizing imazamox alone, has led to widespread herbicide tolerance in Italian ryegrass populations in the United States (Thorne & Lyon, 2024), other studies have demonstrated its effectiveness in controlling Italian ryegrass when applied in Clearfield® wheat (Colquhoun et al., 2003).

3.4.2.3 Cover Crop Biomass

Cover crop biomass measured in the fall is crucial for providing an integrated measure of environmental conditions, herbicide strategies, and intercrop competition impacts on cover crop performance. The main effects of year, location, herbicide tolerance system, and herbicide frequency, as well as their four-way interaction, were statistically significant for cover crop biomass (Table 3.12). Thus, treatment trends were compared within each site-year and are presented in Figure 3.4.

Table 3.12. Analysis of variance of the dependent variable fall cover crop biomass for the main effects of year (Y), location (L), herbicide tolerance system (HTS), and herbicide frequency (HF), and their interactions. Bolded values indicate significance at the 0.05 probability level.

Sources of variation	df	p-value
Year (Y)	1	<0.0001
Location (L)	1	0.0240
Herbicide tolerance system (HTS)	2	0.0049
Herbicide frequency (HF)	2	<0.0001
Y*L	1	<0.0001
Y*HTS	2	0.3590
Y*HF	2	0.0549
L*HTS	2	0.0002
L*HF	2	<0.0001
HTS*HF	4	0.0040
Y*L*HTS	2	0.0034
Y*L*HF	2	0.5919
Y*HTS*HF	4	0.0474
L*HTS*HF	4	0.3186
Y*L*HTS*HF	4	0.0187

Cover crop biomass could be measured across all site-years; however, low cover crop emergence in 2022 (Section 3.2.2.1), particularly at Carman22, resulted in low biomass production. No trends could be observed between herbicide tolerance systems treatments and herbicide frequency treatments for Carman22. Across treatments, biomass ranged from 0 to 3 kg ha⁻¹ in this site-year (Figure 3.4).

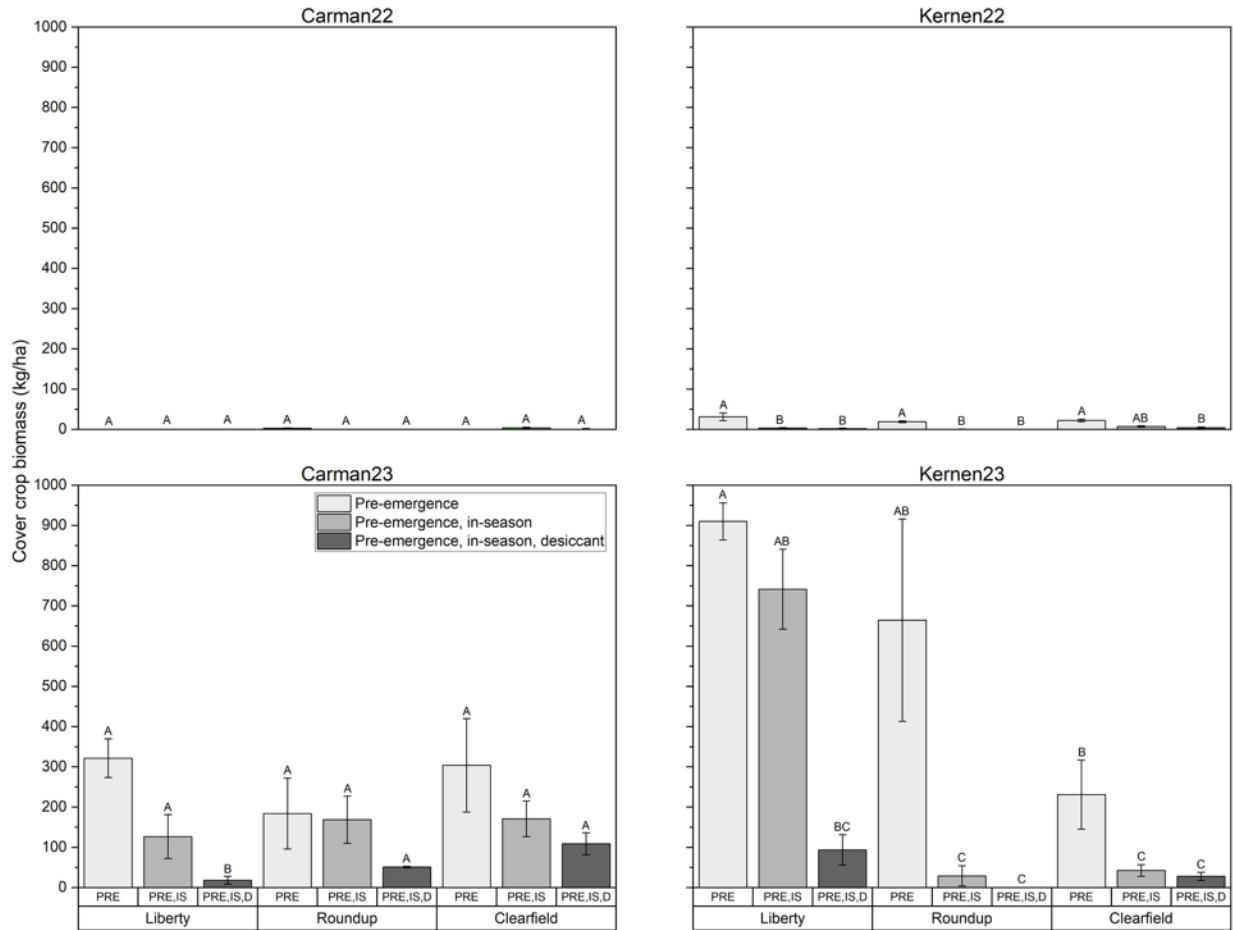


Figure 3.4. The effect of herbicide frequency (pre-emergence only (PRE), pre-emergence and in-season (PRE, IS), and pre-emergence, in-season, and desiccant (PRE, IS, D)) on mean fall cover crop biomass for three herbicide tolerance systems: Liberty, Roundup, and Clearfield for Carman22, Carman23, Kern22, and Kern23. Error bars represent ± 1 SEM. Bars with the same letters are not statistically different at the 0.05 significance level.

In contrast, cover crop biomass obtained from Kern22 was influenced by herbicide frequency in the three herbicide tolerance systems. It was observed that the greatest amount of cover crop biomass was obtained in the pre-emergence only (PRE) treatments, ranging from 31 kg ha⁻¹ in the Liberty herbicide tolerance system to 19 kg ha⁻¹ in the Roundup system. Biomass declined following the in-season (PRE, IS) application, with significant reductions observed in the Liberty and Roundup systems. Liberty had the greatest decrease in biomass with a decline of 28 kg ha⁻¹, followed by Roundup, which decreased by 18 kg ha⁻¹. Both the Liberty and Roundup

systems resulted in biomass amounts less than 2 kg ha⁻¹ following the in-season application. In the Clearfield system, biomass was numerically reduced from 22 to 7 kg ha⁻¹, resulting in the greatest biomass following the in-season treatment. The desiccant (PRE, IS, D) application further reduced cover crop biomass to negligible amounts, though these reductions in biomass did not differ statistically from the in-season (PRE, IS) treatment for each herbicide tolerance system. All three systems resulted in similar biomass amounts of less than 4 kg ha⁻¹ following the desiccant (PRE, IS, D) application.

Cover crop biomass at both sites in 2023 improved due to several factors, including improved growing conditions, increased cover crop seeding rate, and improved cover crop emergence. This allowed for greater biomass accumulation, enabling comparisons across herbicide tolerance systems and herbicide frequencies. Across all systems, the greatest biomass was observed in the pre-emergence only (PRE) treatment (231 kg ha⁻¹ in Carman to 910 kg ha⁻¹ in Kernen). Biomass declined with the additional application of an in-season herbicide (PRE, IS) and furthermore with a desiccant (PRE, IS, D) at both locations, consistent with trends observed in Kernen²². At Carman²³, the trend of cover crop biomass being greatest within pre-emergence only (PRE) treatment was apparent as the accumulated biomass ranged from 321 kg ha⁻¹ in the Liberty herbicide tolerance system to 188 kg ha⁻¹ in the Roundup system. While biomass varied numerically among herbicide tolerance systems, these differences were not statistically significant, indicating that canola variety did not impact cover crop biomass.

When an in-season herbicide (PRE, IS) was applied, cover crop biomass decreased numerically across all herbicide tolerance systems when compared to the pre-emergence only treatment (PRE) for Carman²³. Similar to the pre-emergence only (PRE) treatment, these reductions in cover crop biomass between the PRE, IS and PRE treatments were not statistically

significant. Liberty experienced the greatest decrease in cover crop biomass (-195 kg ha^{-1} deviation from pre-emergence biomass), resulting in the lowest biomass of 127 kg ha^{-1} and aligns with the highest herbicide damage ratings (Table 3.11). Biomass in the Roundup system remained similar to the pre-emergence only (PRE) treatment, decreasing to 172 kg ha^{-1} (-15 kg ha^{-1}). Clearfield resulted in similar biomass accumulation to Roundup with 171 kg ha^{-1} following an in-season (PRE, IS) application; however, it saw a greater numerical reduction (-133 kg ha^{-1}).

A further decrease in cover crop biomass at Carman23 was observed when a desiccant (PRE, IS, D) was applied following the in-season herbicide. In the Liberty herbicide tolerance system, only 18 kg ha^{-1} of biomass remained (-109 kg ha^{-1} deviation from the pre-emergence and in-season biomass), which was the lowest biomass among the herbicide tolerance systems and herbicide frequencies tested. This reduction was statistically different from the herbicide tolerance systems pre-emergence and in-season (PRE, IS) application. This statistical significance was not observed when a desiccant (PRE, IS, D) was applied to Roundup or Clearfield systems. However, the desiccant caused the greatest numerical reduction to the Roundup herbicide tolerance system (-117 kg ha^{-1}), which resulted in a biomass of 51 kg ha^{-1} . In comparison, Clearfield experienced the smallest numerical reduction (-62 kg ha^{-1}) following the desiccant application, maintaining the greatest biomass of 109 kg ha^{-1} among the three herbicide tolerance systems tested.

To determine whether these trends were consistent across sites, biomass responses were also evaluated for Kern23. Similar to observations at Kern22 and Carman23, the pre-emergence only (PRE) treatment resulted in the greatest cover crop biomass that ranged from 910 kg ha^{-1} in the Liberty herbicide tolerance system to 231 kg ha^{-1} in the Clearfield system. Although numerical differences among herbicide tolerance systems were observed, these

differences were not statistically significant, once again indicating that the canola system did not impact cover crop biomass. When compared to Carman, biomass in the Liberty and Roundup systems was greater at Kernan, whereas Clearfield achieved similar biomass at both locations.

All three herbicide tolerance systems experienced a decrease in biomass after the in-season herbicide (PRE, IS) application at Kernan23, which reflects trends previously observed in Kernan22 and Carman23, and confirms herbicide damage ratings from Kernan23 (Table 3.11). Notably, the Liberty herbicide tolerance system maintained a biomass of 741 kg ha⁻¹ (-160 kg ha⁻¹ deviation from pre-emergence biomass) and was the only treatment that remained statistically similar to its pre-emergence (PRE) treatment biomass. In contrast, biomass in the Roundup and Clearfield systems was statistically different when compared to their pre-emergence (PRE) biomass. The in-season (PRE, IS) application of glyphosate in the Roundup herbicide tolerance system led to the greatest reduction in cover crop biomass (-636 kg ha⁻¹) and resulted in the lowest reported cover crop biomass of 29 kg ha⁻¹ among the three herbicide tolerance systems tested. The Clearfield system resulted in cover crop biomass of 43 kg ha⁻¹ following an in-season application, which was similar to the Roundup herbicide tolerance systems. However, the Clearfield system at Kernan23 experienced a lower reduction (-188 kg ha⁻¹) in cover crop biomass than the other two systems tested with an in-season (PRE, IS) application.

The subsequent application of a desiccant (PRE, IS, D) further numerically decreased the biomass of all three herbicide tolerance systems at Kernan23. Following desiccation, biomass within the Liberty system was numerically the greatest at 94 kg ha⁻¹. However, this herbicide tolerance system experienced the greatest biomass reduction (-648 kg ha⁻¹ deviation from pre-emergence and in-season (PRE, IS) biomass) following the desiccant treatment. In Kernan23, the

application of the desiccant (PRE, IS, D) to the Roundup system resulted in no cover crop biomass remaining (-29 kg ha^{-1}). In the Clearfield system, the desiccant caused a small numerical reduction in cover crop biomass (-15 kg ha^{-1}), resulting in the second greatest cover crop biomass at 28 kg ha^{-1} for Kernens23.

The agronomic benefits derived from cover crops are directly related to the amount of biomass accumulated. Minimum biomass thresholds have been identified for specific ecosystem services, including 1000 kg ha^{-1} for nitrate retention, 2000 kg ha^{-1} for increasing soil organic matter, whereas greater amounts of 3000 kg ha^{-1} are needed for weed suppression (McGuire, 2025). In the present study, no treatment achieved the minimum threshold of 1000 kg ha^{-1} to observe benefits achieved from cover cropping. The insufficient biomass production can be attributed to intercrop competition, in addition to herbicide damage, which are constraints to an intercropping system.

Currently, peer-reviewed research on the intercropping of cover crops into canola remains limited, though available data on this system suggests limited biomass productivity. An unpublished study in Manning, Alberta, found that a mixture of white, crimson, and subterranean clover was able to produce 12 kg ha^{-1} biomass when intercropped with canola (North Peace Applied Research Association, 2023). When comparing the available literature about intercropping for other oilseed crops, such as soybean, a published review of 14 experiments found that alfalfa and red clover produced biomass less than 252 kg ha^{-1} (Klopp, 2024). The post-harvest seeding of cover crops often results in lower legume biomass accumulation on the Canadian Prairies. In Saskatoon, biomass of berseem clover and oat seeded following canola harvest ranged from 8 to 133 kg ha^{-1} (Otchere et al., 2023). When compared to these post-harvest

cover crop seeding results, this current intercropping study shows the potential to increase cover crop biomass, likely due to the lengthened growing season.

Cover crop biomass accumulation observed in this study also mirrored in-season herbicide damage trends (Section 3.4.2.2). At both locations, all three herbicide tolerance systems showed reductions in cover crop biomass following the in-season herbicide (PRE, IS) applications. Glufosinate resulted in a severe injury rating (Table 3.11) for both clovers and alfalfa, which account for the greatest proportion of the cover crop mixture (Table 3.9). Previous studies have found that glufosinate (500 g a.i. ha⁻¹) applied in the spring to alfalfa and red clover established the preceding fall resulted in reductions of dry shoot weight ranging from 39 to 47% in alfalfa and 70 to 99% in red clover (Swanton et al., 1998). With alfalfa and clover being the only species to establish in Carman23, following the in-season herbicide (PRE, IS) application of glufosinate, inflicting damage resulted in the lowest biomass out of all systems examined. Despite Kernen reporting similar damage ratings to alfalfa and clovers, the system produced the greatest biomass. As mentioned, Italian ryegrass was able to establish in Kernen, survive the in-season glufosinate (PRE, IS) application, and was able to produce biomass, leading to greater biomass than in Carman, where there was no persistence of Italian ryegrass.

In-season (PRE, IS) glyphosate applications in this study also resulted in severe herbicide injuries to all cover crop species, except for alfalfa at Carman23. Chlorosis was evident on the uppermost leaves at both locations following glyphosate application (Figure 3.2 B and Figure 3.3 B). Previous studies have found reductions in legume biomass following glyphosate applications. When glyphosate was spring-applied at 900 g a.e. ha⁻¹ to fall-established alfalfa and red clover, reductions of dry shoot weight ranged from 35 to 97% in alfalfa and a greater range of 94 to 99% reduction in red clover (Swanton et al., 1998). When applying a lower rate of glyphosate (540 g

a.e. ha⁻¹), Adami et al. (2017) found that biomass of white clover at the third-trifoliate stage was reduced by 38%, and when higher rates equivalent to those used in this study (1080 and 1620 g a.e. ha⁻¹) were applied, white clover biomass was completely lost. Similar trends have been observed in intercropping systems. When intercropped with glyphosate-tolerant soybean, white clover biomass decreased 66% from 1480 kg ha⁻¹ when untreated to 490 kg ha⁻¹ when treated with an in-season application of glyphosate at 720 g a.e. ha⁻¹ (Schuster et al., 2015). Although clover species have been documented to recover from such injuries once they reach 8 to 10 cm in height (Smith et al., 2007), such recovery was not observed in Kernen, likely due to the severity of injury at the maximum rate applied in this study. Additionally, Italian ryegrass establishment was greater at Kernen, where it experienced the most severe injury with a damage rating of 100%. Comparable results have been observed in annual ryegrass, which produced 80 kg ha⁻¹ of biomass following a glyphosate application at a rate of 1350 g a.e. ha⁻¹ compared to 2200 kg ha⁻¹ in the untreated control (Soltani et al., 2020).

Although not as severely damaged by the in-season (PRE, IS) application of imazamox+ imazethapyr, cover crop biomass decreased numerically for Carman23 within the Clearfield® tolerance system, even with non-severe ratings reported in Carman (Table 3.11). This reduction in cover crop biomass observed within our experiment at Carman23 may have been due to competition with canola as reflected in the decreased persistence counts of the pre-emergence only (PRE) treatment (Appendix A.1). Previous studies have found that red clover yield has been shown to decline from 1064 kg ha⁻¹ as a monocrop to 614 kg ha⁻¹ in the presence of Clearfield canola in the absence of herbicides (McInnes & Slowski, 2020). Studies, however, have also found biomass reductions with the use of imazamox or imazethapyr when applied separately. Adami et al. (2017) reported reductions in white clover biomass of 1% and 18% at rates of 150

and 200 g a.i. ha⁻¹ of imazethapyr applied at the third-trifoliate stage when compared to an untreated control. Similarly, white clover as an intercrop with soybean had a biomass of 1009 kg ha⁻¹ when treated with 100 g a.i. ha⁻¹ imazethapyr compared to 1478 kg ha⁻¹ when untreated, resulting in a 33% reduction in white clover biomass (Schuster et al., 2015). Additionally, a field study on a pure stand of Persian clover in New South Wales, Australia, was treated with 140 g a.i. ha⁻¹ of imazethapyr at the 3 to 4 leaf stage and resulted in biomass that was 79% of the untreated control (Lockley & Wu, 2008). However, when treated with 35 g a.i. ha⁻¹ of imazamox, Persian clover biomass was 87% of the untreated control (Lockley & Wu, 2008).

For all herbicide tolerance systems in this study, cover crop biomass was reduced following the desiccant (PRE, IS, D) application of Diquat Ion. Desiccants such as Diquat Ion are registered for use in forage seed crops, including alfalfa and red and white clover (Syngenta Crop Protection Canada Inc., 2014). When using a desiccant, biomass reduction is typically the result of the herbicide drying down green material through moisture reduction and leaf loss. Alfalfa has been found to have visual defoliation ranging from 38 and 48%, respectively, 3 and 7 days after the application of Diquat Ion (0.62 g a.i. ha⁻¹) (Ransom et al., 2001). Additionally, complete leaf desiccation has been observed less than 10 days after application at a rate of 500 g a.i. ha⁻¹ (Moyer et al., 1996). Diquat Ion acts as a contact desiccant, thus the roots and crowns of perennial species often survive desiccant applications due to reduced contact, allowing for regrowth (Syngenta Crop Protection Canada Inc., 2014).

3.4.3 Weeds

3.4.3.1 Weed Density

The abundance of weeds provide insight into the efficacy of canola weed management strategies that include herbicides, cultural practices, and canola varietal competitiveness, which can subsequently hinder the establishment of intercropped cover crops and limit cash crop

performance. Weed species within the experiment primarily consisted of lamb’s quarter, redroot pigweed, and green foxtail. A three-way interaction of the main effects of location, herbicide tolerance system, and herbicide frequency was statistically significant for weed density (Table 3.13). Additionally, the main effects of year, location, herbicide tolerance system, and herbicide frequency were statistically significant. Treatment means for the highest-order significant interaction are presented in Figure 3.5. Note that the pre-emergence, in-season, and desiccant treatment (PRE, IS, D) was not included in the analysis for weed density, as the desiccant had not been applied at the time the measurement was taken.

Table 3.13. Analysis of variance of the dependent variable weed density at the canola vegetative stage and weed biomass at canola pod-fill for the main effects of year (Y), location (L), herbicide tolerance system (HTS), and herbicide frequency (HF), and their interactions. Bolded values indicate significance at the 0.05 probability level.

Sources of variation	df	Response variable	
		Weed density	Weed biomass
		p value	
Year (Y)	1	<0.0001	0.1911
Location (L)	1	0.0002	0.0075
Herbicide resistance system (HRS)	2	0.0199	0.0007
Herbicide frequency (HF)	2	<0.0001	<0.0001
Y*L	1	<0.0001	<0.0001
Y*HRS	2	0.9890	0.0231
Y*HF	2	<0.0001	0.5153
L*HRS	2	0.0247	0.4033
L*HF	2	0.2243	0.2274
HRS*HF	4	0.0765	0.4362
Y*L*HRS	2	<0.0001	0.0030
Y*L*HF	2	0.4407	0.6093
Y*HRS*HF	4	0.3008	0.0478
L*HRS*HF	4	0.0239	0.1573
Y*L*HRS*HF	4	0.1212	0.0207

Weed density averaged over the two years was greater in Carman than in Kernen for both herbicide frequencies. In Carman, weed density in the pre-emergence (PRE) treatment ranged from 506 plants m⁻² in the Liberty tolerance system to 430 plants m⁻² in the Clearfield system

(Figure 3.5). For all three herbicide tolerance systems, the application of an in-season herbicide (PRE, IS) resulted in weed densities that were statistically different than the pre-emergence treatment densities. Among all the systems evaluated, Liberty maintained the highest weed density of 215 plants m^{-2} following an in-season (PRE, IS) application of glufosinate, despite observing a reduction in weed density of 312 plants m^{-2} compared to pre-emergence (PRE) treatment. The Clearfield system resulted in a lower weed density of 134 plants m^{-2} with a 296 plants m^{-2} reduction in weed density when compared to the pre-emergence only (PRE) treatment. This reduction in the Clearfield system was similar to that of the Liberty system. The lowest weed density was observed in the Roundup tolerance system, with a density of 71 plants m^{-2} , and was associated with the greatest reduction in weed density (-428 plants m^{-2}) compared to the pre-emergence (PRE) treatment. Across all herbicide tolerance systems, the presence of a cover crop did not statistically reduce weed density when compared to the no cover crop control treatment that received the pre-emergence and in-season herbicide (PRE, IS) applications.

In contrast, no significant differences in weed density were detected among treatments in Kern. Weed density was lower at Kern and ranged from 108 plants m^{-2} to 40 plants m^{-2} for all treatments (Figure 3.5). The trend observed at Carman for the Liberty and Roundup herbicide tolerance systems, with weed density being reduced with in-season herbicide (PRE, IS) applications, was also observed at Kern, though this reduction was not statistically significant. Similar to Carman, the presence of cover crops did not statistically reduce weed density relative to the no cover crop control treatment that received the pre-emergence and in-season herbicide (PRE, IS) application.

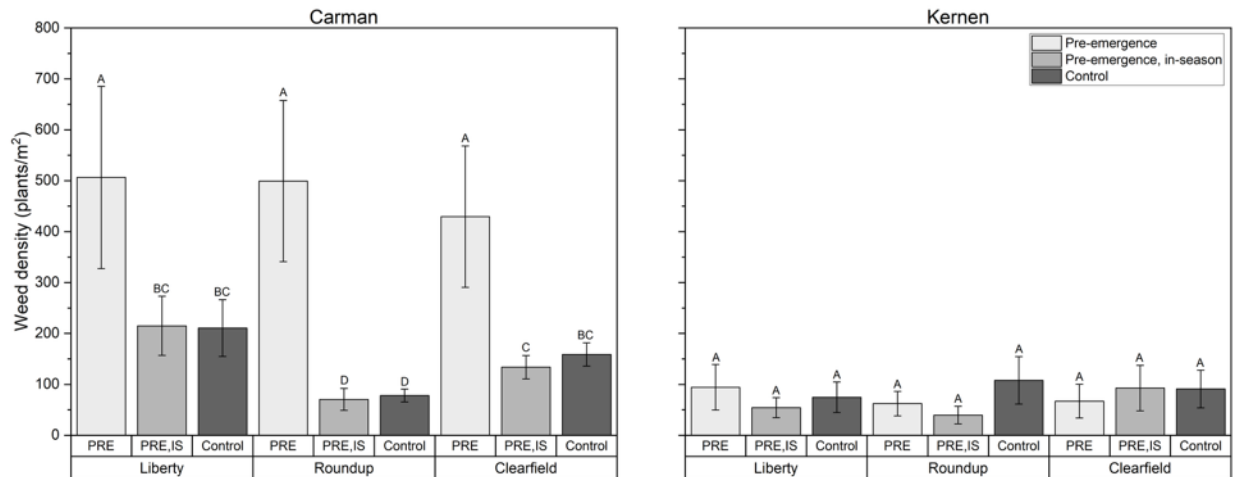


Figure 3.5. The effect of herbicide frequency (pre-emergence only (PRE) and pre-emergence and in-season (PRE, IS) on mean weed density averaged over 2022 and 2023, taken at the canola vegetative stage for three herbicide tolerance systems: Liberty, Roundup, and Clearfield in Carman and Kernen. A control with no cover crops that received a pre-emergence and in-season application was seeded for each canola herbicide tolerance system. Error bars represent ± 1 SEM. Bars with the same letters are not statistically different at the 0.05 significance level within locations.

Previous studies have demonstrated the inverse relationship between weed density and cover crop biomass (Osipitan et al., 2019; Smith et al., 2014; Weisberger et al., 2023; Kumar et al., 2024). One meta-analysis summarizing findings from the humid subtropical climate of the Southeast United States found that cover crops reduced weed density by an average of 44% (Weisberger et al., 2023). Another meta-analysis of 41 field studies conducted across temperate regions in the United States and Canada found that cover crops reduced *Amaranthus* spp. density by an average of 58% in the early season and by 48% in the mid-season (Kumar et al., 2024). However, in the United States Midwest, which experiences a similar climate to the Eastern Canadian Prairies, a meta-analysis by Nichols et al. (2020) found that cover crops did not reduce weed density in corn and soybean systems. These findings by Nichols et al. (2020) align with findings from the present experiment, where cover crops did not reduce weed density, indicating that weed suppression from cover crops is less consistent in shorter-season environments of the

United States Midwest and the Canadian Prairies. Weisberger et al. (2023) determined that 6600 kg ha⁻¹ of cover crop biomass was required to achieve a 50% reduction in weed density in the southeastern United States. In our present study, cover crop biomass accumulation remained well below this threshold, which likely contributed to the absence of significant reductions in weed density in the presence of cover crops.

3.4.3.2 Weed Biomass

Although weed density reflects initial weed emergence and establishment, weed biomass provides a more comprehensive measure of subsequent weed growth and their competitive ability within the intercropping system. A statistically significant four-way interaction between the main effects of year, location, herbicide tolerance system, and herbicide frequency occurred for weed biomass ($p= 0.0207$). Furthermore, the main effects of location, herbicide tolerance system, and herbicide frequency were statistically significant for weed biomass, whereas the main effect of year was not significant (Table 3.13). Weed species within the experiment primarily consisted of lamb's quarter, redroot pigweed, and green foxtail.

Weed biomass taken at canola pod-fill was the greatest in Carman22 compared to all other site-years (Figure 3.6). Weed biomass in the pre-emergence only (PRE) treatment was the greatest across all herbicide tolerance systems because weeds were not controlled with an in-season herbicide. Across the three herbicide tolerance systems tested, weed biomass ranged from 5754 kg ha⁻¹ in the Roundup system to 4728 kg ha⁻¹ in the Liberty system.

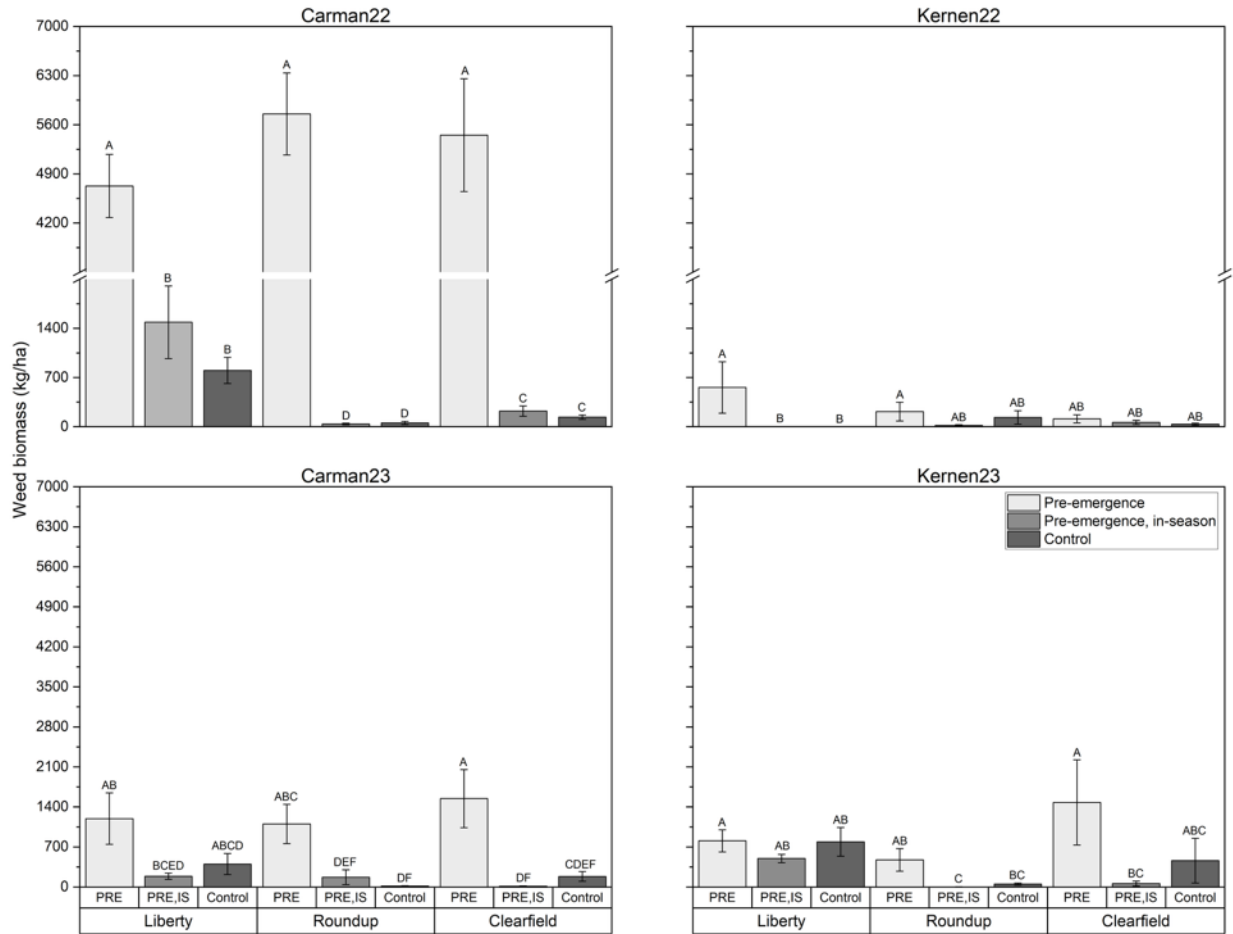


Figure 3.6. The effect of herbicide frequency (pre-emergence only (PRE) and pre-emergence and in-season (PRE, IS) on mean weed biomass for three herbicide tolerance systems: Liberty, Roundup, and Clearfield in Carman22, Carman23, Kernen22, and Kernen23. A control with no cover crops that received a pre-emergence and in-season application was seeded for all canola herbicide tolerance systems. Error bars represent ± 1 SEM. Bars with the same letters are not statistically different at the 0.05 significance level within site-years.

When weeds were controlled with in-season herbicides (PRE, IS), weed biomass statistically decreased across all herbicide tolerance systems when compared to the pre-emergence only (PRE) treatments in Carman22. The greatest reduction was observed in the Roundup system, where weed biomass declined by 5716 kg ha⁻¹ and resulted in the lowest biomass of 24 kg ha⁻¹. Clearfield also had a high reduction in weed biomass with a decline of 5229 kg ha⁻¹ following the in-season (PRE, IS) application, although the system had a greater biomass of 353 kg ha⁻¹. These larger reductions in weed biomass in the Roundup and Clearfield

systems may be attributed to the numerically greater biomass observed in the pre-emergence only (PRE) treatment when compared to the Liberty system. The in-season (PRE, IS) application of Liberty resulted in the lowest reduction in weed biomass of 3240 kg ha⁻¹ despite having the greatest herbicide damage ratings to cover crops (3.4.2.2) and resulted in the greatest weed biomass of 620 kg ha⁻¹. These results were consistent with previous studies comparing canola herbicide tolerance systems that found the greatest weed control occurred with glyphosate, followed by imazamox+ imazethapyr, and then by glufosinate (Harker et al., 2000; Harker et al., 2004). When cover crops were present, no statistical differences in weed biomass were observed when compared to the no cover crop control that received the pre-emergence and in-season herbicide (PRE, IS) application.

Weed biomass in Kern22 was the lowest across all site-years (Figure 3.6). Similar to Carman22, the greatest weed biomass was observed in the pre-emergence only (PRE) treatment, where no in-season weed control occurred. Weed biomass in the pre-emergence only treatment ranged from 558 kg ha⁻¹ in the Liberty tolerance system to 112 kg ha⁻¹ in the Clearfield system. The application of the in-season herbicides (PRE, IS) once again numerically reduced weed biomass across all herbicide tolerance systems. Liberty resulted in the greatest reduction in weed biomass, which was statistically significant, after an in-season (PRE, IS) application where no weeds remained. The application of Roundup or Clearfield, however, resulted in statistically similar weed biomass to the pre-emergence only (PRE) treatment. Roundup resulted in the second greatest decline in weed biomass, where it numerically decreased from 215 to 18 kg ha⁻¹ following an in-season application of glyphosate. In the Clearfield system, weed biomass was also reduced with an in-season application by 53 kg ha⁻¹, resulting in a weed biomass of 60 kg ha⁻¹. Due to no cover crops remaining in the Liberty system after the in-season glufosinate (PRE,

IS) application, it could not be identified if cover crops reduced weed density when compared to the no cover crop control. However, in the Roundup and Clearfield systems where weeds were present, the presence of cover crops did not statistically reduce weed biomass relative to the no cover crop control treatment that received the pre-emergence and in-season herbicide application (PRE, IS).

At Carman23, weed biomass was once again greatest within the pre-emergence only (PRE) treatments, confirming the trend observed at both locations in 2022. Weed biomass in the pre-emergence only treatment ranged from 1546 kg ha⁻¹ in the Clearfield herbicide tolerance system to 1102 kg ha⁻¹ in the Roundup system. Following an in-season herbicide (PRE, IS) application, weed biomass numerically decreased for all herbicide tolerance systems and was statistically significant for Roundup and Clearfield. The greatest reduction in weed biomass was seen in the Clearfield system, where weed biomass decreased to 13 kg ha⁻¹ (-1533 kg ha⁻¹ compared to pre-emergence only (PRE) treatment. Weed biomass in the Liberty and Roundup herbicide tolerance systems was similar, with weed biomass of 188 kg ha⁻¹ and 171 kg ha⁻¹, respectively. Relative to their pre-emergence (PRE) treatment weed biomass, reductions were also similar, where glufosinate reduced weed biomass by 1008 kg ha⁻¹, and glyphosate led to a 931 kg ha⁻¹ reduction. However, when cover crops were present, there were no statistical differences in weed biomass when compared to the no cover crop control.

Pre-emergence only (PRE) treatments for Kernen23 also saw the greatest weed biomass, which ranged from 1480 kg ha⁻¹ in the Clearfield herbicide tolerance system to 474 kg ha⁻¹ in the Roundup system. Weed biomass once again was statistically reduced with the in-season (PRE, IS) application of imazamox+ imazethapyr, where weed biomass decreased to 61 kg ha⁻¹ (-1419 kg ha⁻¹ compared to pre-emergence), and 4 kg ha⁻¹ (-470 kg ha⁻¹) following the application of

glyphosate. Unlike 2022, the in-season (PRE, IS) application of glufosinate resulted in statistically similar weed biomass of 497 kg ha⁻¹ to the pre-emergence only (PRE) treatment (807 kg ha⁻¹). Furthermore, when cover crops were present, no statistical differences in weed biomass were observed when compared to the no cover crop control that received the pre-emergence and in-season herbicide (PRE, IS) application.

Generally, cover crop biomass is inversely related to weed biomass (Osipitan et al., 2019; Nichols et al., 2020; Kumari et al., 2024; McKenzie-Gopsill et al., 2022). Baraibar et al. (2017) looked at this relationship for specific cover crop families. Based on three site-years of data in Pennsylvania, only brassica cover crop (tillage radish and canola) biomass was negatively correlated with weed biomass ($R^2= 0.40$). The same study found that there was no relationship between the biomass of grass cover crops (oat and cereal rye) or cover crop mixtures and weed biomass.

When looking at intercropped cover crops, a meta-analysis found that when cover crops were intercropped into soybean, average weed biomass was 846 kg ha⁻¹ compared to 1621 kg ha⁻¹ in treatments with no weed control (Klopp et al., 2024). Furthermore, an additional study in Breton, Alberta, found reduced weed biomass when mustard was intercropped with broadcasted red, white, and Persian clover and drilled rye when compared to the no intercrop control (Ross et al., 2001). When clovers were used, weed biomass suppression ranged from 38 to 63%, where white clover had greater weed suppression than Persian or red clover (Ross et al., 2001). Weed biomass suppression in the study by Ross et al. (2001) was greatest from rye, where weed biomass was suppressed by 86%.

Results from this current experiment and previous studies suggest that cover crops as a sole tool for weed management may not be sufficient and should be coupled with other chemical

or weed management strategies (Fernando & Shrestha, 2023). Bunchek et al. (2020) found reduced weed biomass within cover crop treatment levels in a corn and a soybean field experiment when a post-emergence herbicide was used, compared to a pre-emergence herbicide treatment. Thus, the results of Bunchek et al. (2020) and this study support that herbicide strategies were the driving factor for weed biomass suppression and should be used with cover crop strategies to maximize weed suppression in conventional grain systems. Similarly, when cover crops were combined with post-emergence herbicides, weeds were reduced when compared to a single or mixed cover crop species alone (Osipitan et al., 2019). Both studies align with results produced in the current experiment, where the greatest reduction in weed biomass was observed following the in-season herbicide application, whereas our cover crop mixture was unable to provide statistical suppression of weed biomass. In rye and small grain intercropping systems, weed suppression from the cover crops alone was inadequate and post-emergence herbicide programs were needed to achieve maximum crop yields (Rajalahti et al., 1999; De Bruin et al., 2005). This corresponds with results observed in all site-years of the present experiment, where for all herbicide tolerance systems, the greatest weed biomass was observed within the pre-emergence only (PRE) treatment (Figure 3.6).

When comparing the three herbicide tolerance systems, field studies in Alberta by Harker et al. (2004) found greater monocot weed biomass in glufosinate and imazamox+ imazethapyr tolerance systems when half the rate of the herbicide was used. Median weed biomass within these two systems ranged from 200 to 400 kg ha⁻¹. Harker et al. (2004) observed that monocot plant biomass was low irrespective of rate or timing of application due to the efficacy of glyphosate on monocot weeds. This aligns with results in the present experiment, where weed biomass was lowest in the Roundup herbicide tolerance system out of all systems tested in two

out of four site-years (Figure 3.6). Conversely, the greatest dicot and monocot weed biomass was observed when treated with glufosinate (Harker et al., 2004). This agrees with our findings that following an in-season herbicide (PRE, IS) application, the Liberty tolerance system had the greatest weed biomass in three out of four site-years.

3.4.4 Canola

3.4.4.1 Canola Yield

Canola yield is the primary metric to evaluate the effects of the presence of cover crops and herbicide frequency treatments on crop performance. The significant three-way interaction for year, location, and herbicide frequency (Table 3.14) was evaluated by comparing mean canola yields, averaged over herbicide tolerance system treatments within each site-year. The three-way interaction between year, location, and herbicide tolerance system was not evaluated, as yield differences were expected due to varietal differences.

Canola yield in the pre-emergence only (PRE) treatment at Carman22 was the lowest yield among all site-years at 1146 kg ha⁻¹ (Figure 3.7) due to high weed pressure (Figure 3.6). With the application of an in-season (PRE, IS) herbicide, canola yields increased to 3087 kg ha⁻¹. The application of a desiccant (PRE, IS, D) did not statistically increase yields relative to the in-season treatment and yielded 3195 kg ha⁻¹. Additionally, the direct comparison of the PRE, IS, D treatments with and without cover crops did not differ statistically.

Table 3.14. Analysis of variance of canola yield and canola oil content for the main effects of year (Y), location (L), herbicide tolerance system (HTS), and herbicide frequency (HF), and their interactions. Bolded values indicate significance at the 0.05 probability level.

Sources of variation	df	Response variable	
		Canola grain yield	Canola oil content
		p value	
Year (Y)	1	<0.0001	<0.0001
Location (L)	1	0.0363	<0.0001
Herbicide tolerance system (HTS)	2	0.0285	0.0026
Herbicide frequency (HF)	3	<0.0001	0.0120
Y*L	1	0.0160	0.0005
Y*HTS	2	0.6024	0.0169
Y*HF	3	<0.0001	0.2243
L*HTS	2	0.0163	0.6440
L*HF	3	<0.0001	0.1370
HRS*HF	6	0.8367	0.7600
Y*L*HTS	2	0.0333	0.0413
Y*L*HF	3	<0.0001	0.1307
Y*HTS*HF	6	0.7433	0.9003
L*HTS*HF	6	0.7476	0.7120
Y*L*HTS*HF	6	0.7335	0.6697

At Kernen22, there were no statistical differences between canola yields, likely as a result of low cover crop and low weed biomass among treatments (Figure 3.7). Yield for the Kernen22 site-year was lower than at Carman22, with yields ranging from 2672 kg ha⁻¹ in the pre-emergence only (PRE) treatment to 2785 kg ha⁻¹ in the pre-emergence and in-season (PRE, IS) application. Similar to Carman22, the application of a desiccant (PRE, IS, D) did not increase canola yields as the crop had reached physiological maturity at the time of the desiccant application. As cover crop biomass was low for Kernen22, there was no statistical difference in canola yields when cover crops were present, when compared to the treatment receiving the desiccant (PRE, IS, D) without cover crops.

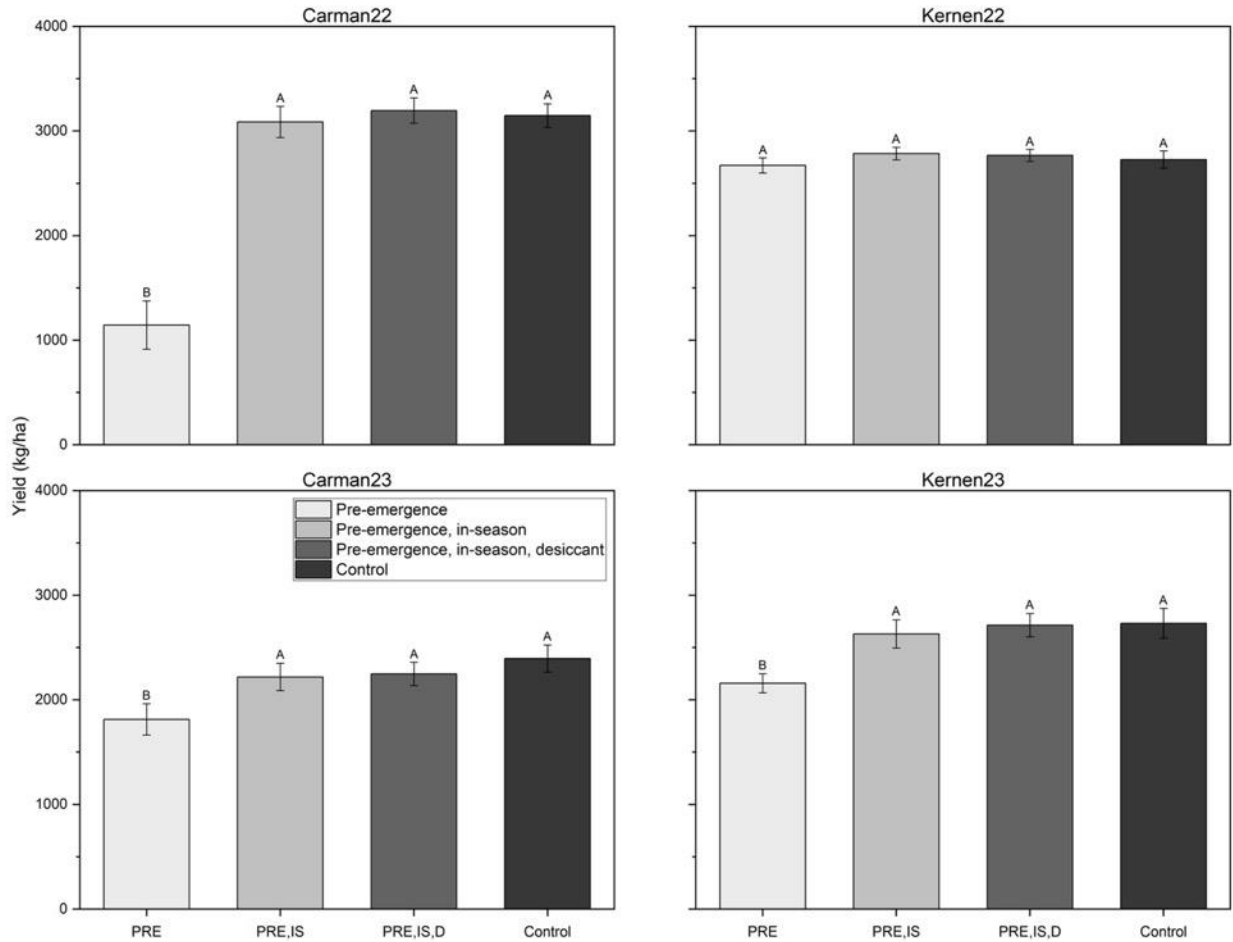


Figure 3.7. The effect of herbicide frequency (pre-emergence only (PRE), pre-emergence and in-season (PRE, IS), and pre-emergence, in-season, and desiccant (PRE, IS, D) on mean canola yield for Carman22, Carman23, Kernen22, and Kernen23. A control with no cover crops was included within each canola herbicide tolerance system main plot that received a pre-emergence, in-season, and desiccant application. Error bars represent ± 1 SEM. Bars with the same letters are not statistically different at the 0.05 significance level within site-year.

Statistical differences in yield were observed in 2023 following the increase in cover crop seeding rate and establishment. In Carman23, there were statistical differences in yields with the pre-emergence only (PRE) treatment yielding lower than those treated with an in-season herbicide application, as seen at Carman22. Canola yield in the pre-emergence treatment was 1814 kg ha^{-1} and decreased relative to treatments receiving the in-season (PRE, IS) application. This is likely a result of greater cover crop biomass ($184\text{-}321 \text{ kg ha}^{-1}$) and high weed biomass ($1102\text{-}1546 \text{ kg ha}^{-1}$) in the pre-emergence only (PRE) treatment. The reduction in yield

compared to the PRE, IS treatment (-405 kg ha⁻¹) was not as severe as Carman22 (-1941 kg ha⁻¹), as less weed biomass accumulation led to lower competition between cover crops, weeds, and canola. Yield for Carman23 was 2219 kg ha⁻¹ following an application of an in-season herbicide (PRE, IS) and did not statistically differ following an application of a desiccant (PRE, IS, D). Additionally, cover crops in the PRE, IS, D treatment did not statistically decrease yield compared to the no cover crop control. Canola yield in Carman23 may have been reduced due to swathing of the canola, which was required to facilitate dry down of the crop due to the high weed pressure. A previous study by Liu et al. (2014) observed seed yield reductions of 19% when using swathing compared to straight cutting canola. Additionally, in 2023, canola was seeded below the target stand of 110 plants m⁻² with a cumulative stand of 82 plants m⁻² at Carman. Although canola is known to compensate for lower plant stand through other yield components (Angadi et al., 2003), this lower stand may have contributed to the lower canola yield at Carman when compared to Kernen.

Canola yield for Kernen23 was statistically lower in the pre-emergence only (PRE) treatment when compared to treatments with post-emergence applications (PRE, IS and PRE, IS, D), with a yield of 2159 kg ha⁻¹, which was similar to the yields of the pre-emergence only treatments at Carman22 and Carman23. Yield increased to 2631 kg ha⁻¹ following an in-season herbicide application. The application of a desiccant (PRE, IS, D) did not statistically increase yields. When cover crops were present in the pre-emergence, in-season, and desiccant treatment, yields did not differ compared to the no cover crop control, as the influence of cover crops was marginal.

In the pre-emergence (PRE) treatments, yields were statistically reduced in three out of four site-years. There are previous reports documenting that living understory cover crops can

suppress cash crop yield when intercropped (Brandsæter et al., 1998; Sheaffer et al., 2002) as a result of competition for nutrients (Teasdale et al., 2007). When intercropped into oilseed crops, such as soybean, relative soybean yield was 80% with alfalfa, 90% with red clover, and 95% with cereal rye (Klopp, 2024). Additionally, cover crops planted at the same time as the soybean cash crop were found to reduce yield to 80% of the relative crop yield (Klopp, 2024), as it coincided with the critical weed-free period of soybean. In canola, the critical interference prevention period ranges from 25 to 60 days after emergence and is the period when weeds must be controlled to prevent significant yield losses (Brandler et al., 2021). When emerging together, turnip competition at the density of 4 plants m⁻² reduced canola yield by 9 to 11%, and when increased to 64 plants m⁻², canola yield was reduced by 77 to 91% (Brandler et al., 2021). Additionally, when looking at other brassica species such as cabbage (*Brassica oleracea* L.), when intercropped with white or subterranean clover, cabbage yield was suppressed to 2159 and 2150 g head⁻¹, respectively, when compared to the no intercrop control (2413 g head⁻¹) (Brandsæter et al., 1998).

Limited research is available on the impact intercropped cover crops have on canola yield across the Canadian Prairies, but unpublished studies have found no statistical differences between monocrop and intercrop canola yields. At the Peace Region Living Lab in Alberta (2024), there were no statistical differences in yield relative to the control when cover crops were intercropped. Subterranean clover and crimson clover drilled at the same time as canola resulted in canola yields of 950 kg ha⁻¹ and 1118 kg ha⁻¹, respectively, which were both lower than the no cover crop control of 1230 kg ha⁻¹ (Peace Region Living Lab, 2024). When white clover was drilled at the same time as canola, however, it resulted in canola yields greater than the no cover crop control at 1,400 kg ha⁻¹ (Peace Region Living Lab, 2024). An unpublished field experiment

in northeast Saskatchewan by McInnes & Slowski (2020) also found canola yields to be not statistically different when they were seeded as a monocrop or as an intercrop with red or alsike clover (*Trifolium hybridum* L.). In Manitoba, white, sweet, and red clover, as well as alfalfa, have been intercropped with canola and resulted in increased yields in 2020 compared to the no cover crop control, whereas in 2021, the no cover crop control outyielded all intercropped treatments (Parkland Crop Diversification Foundation, 2021). Canola yield ranged from 2633 to 2739 kg ha⁻¹ with white clover, 2571 to 2770 kg ha⁻¹ with sweet clover, 2286 to 2834 kg ha⁻¹ with red clover, and 2337 to 2829 kg ha⁻¹ with alfalfa, compared to 2202 to 3030 kg ha⁻¹ in the no-cover control (Parkland Crop Diversification Foundation, 2021). It was also observed that canola yields when intercropped with cover crops experienced less variation between years when compared to the no cover crop control (Parkland Crop Diversification Foundation, 2021). Currently, there is little evidence that cover crops cause a decrease in yield on the Canadian Prairies, which was supported in the present experiment, where there were no statistical differences in canola yield when cover crops were present and in-crop herbicides applied (PRE, IS). Decreases in yield within the cover crop treatment with the pre-emergence only (PRE) treatment was a result of uncontrolled weeds in combination with the presence of cover crops.

In-season herbicides used in conjunction with grain intercropping have been shown to result in overyielding in Manitoba. A canola-pea intercrop overyielded most consistently in the presence of herbicides with a mean land equivalent ratio of 1.22 (range of 1.16-1.28) (Szumigalski & Van Acker, 2005). Furthermore, the canola-pea intercrop was the most consistent with land equivalent values over site-years and overyielded significantly in 3 out of 6 site-years when herbicides were applied (Szumigalski & Van Acker, 2005). When herbicides

were not applied, significant overyielding occurred in 1 out of 6 site-years, where the mean LER was 1.19 with a range of 0.79 to 1.47 (Szumigalski & Van Acker, 2005).

Yield was not expected to increase following the application of a desiccant (PRE, IS, D) as the critical period for yield determination occurs during the anthesis period (Kirkegaard et al., 2018), which is before desiccant applications. When applied at the correct stage, desiccants do not decrease canola yield (Marchiori et al., 2002; Jenks et al., 2010).

3.4.4.2 Canola Grain Quality

The oil and protein content of canola grain were the two measures of grain quality within this study. Oil content is the primary quality trait for canola seed (Sabbahi et al., 2023). The main effects of herbicide frequency was statistically significant for canola oil content, and a significant three-way interaction ($p= 0.0413$) was detected between year, location, and herbicide tolerance system (Table 3.14). Oil and protein content of canola follow a linear inverse relationship (Hossain et al., 2019). Thus, the higher protein content at Carman23 likely resulted in a lower oil content compared to Carman22, whereas oil content was similar between years at Kernen. Unexpectedly, the oil content of canola was greater at Carman than at Kernen for both years (Table 3.15). This finding contrasts with previous studies in Western Canada by Duan (2006) and Dickson (2014) of which have found that sites at higher latitudes have significantly impacted canola yield. with Canola samples collected at the 49° latitudes similar to Carman had lower oil content than canola samples collected at mid-latitudes (51°-53°), similar to Kernen, likely due to the lower temperatures at higher latitudes (Duan, 2006; Dickson, 2014).

Table 3.15. Canola oil content of three herbicide tolerance systems (Liberty Link®, Roundup Ready®, and Clearfield®) averaged over herbicide frequency treatments for Carman22, Carman23, Kernen22, and Kernen23. Values with the same letters are not statistically different at the 0.05 significance level.

Herbicide tolerance system	Site-year			
	Carman22	Carman23	Kernen22	Kernen23
	%			
Liberty Link®	48.3 b	47.7 b	42.5 de	42.4 e
Roundup Ready®	49.6 a	47.7 b	43.1 cd	42.9 de
Clearfield®	49.6 a	49.3 a	43.6 c	43.6 c

Canola seed oil content is more sensitive to heat stress than to drought, with high temperatures during seed development decreasing oil content (Elferjani & Soolanayakanahally, 2018). At both sites in this study, oil content was numerically greater in 2022 than in 2023, likely due to the hot growing conditions and heat dome experienced in 2022 (Table 3.7), which negatively impacted canola seed oil content (Barthet, 2022). The hot and dry growing conditions were also experienced in 2023; however, nighttime temperatures were cooler, which resulted in greater oil contents across the Canadian Prairies (Barthet, 2023). A previous study by Aksouh-Harradji et al. (2006) reported that exposing canola to a very high temperature regime (28°C day/23 °C night) 25 to 29 days after flowering for 5 days reduced the oil content of canola seed by 5% relative to a lower control temperature regime (22°C/17°C). Similarly, a study that focused on post-anthesis heat exposure found that with every 1°C increase in post-anthesis temperature, oil content decreased by 0.7% (Si & Walton, 2004). This contrasts with the findings of the current experiment, where mean air temperatures in July and August were warmer in 2022 than in 2023 at both locations (Table 3.7), yet canola oil content was greater in 2022. Additionally, canola oil content across the Canadian Prairies was greater in 2023 than in 2022 (Barthet, 2023), which was the opposite of what was observed in this experiment.

It was expected that oil content would differ between the three canola hybrids selected for each of the three herbicide tolerance systems due to varietal differences (Sabbahi et al., 2023). In this study, Clearfield canola had higher oil content than the other two hybrids at all site-years and ranged from 49.6% in Carman22 to 43.6% in Kernen23. Oil content in the Roundup Ready hybrid ranged from 49.6% to 42.9% and resulted in the second greatest oil content, except for Carman23. Oil content within the Liberty Link hybrid was the lowest, with a range of 48.3 to 42.4% across the 4 site-years (Table 3.15).

Cover crop biomass may also account for some of the variation in oil content between years and locations. In both years, cover crop biomass was greater at Kernen than at Carman (Figure 3.4), and under nitrogen fertilizer conditions, studies have found that intercropping reduced canola oil content compared to a canola monocrop (Mirdoraghi et al., 2024). An unpublished study, however, found conflicting results. In a single-year experiment in the Peace Region of Alberta, crimson, white, or subterranean clover drilled with canola did not reduce canola seed oil content (Peace Region Living Lab, 2024). Competition from weed biomass may result in lower oil content at sites with higher weed biomass, similar to Carman22, however, oil content was greater for Carman22 than for Carman23.

The impact of the combined competition of cover crops and weeds on canola was apparent in the significant main effect of herbicide frequency on oil content. When averaged across years and locations, canola oil content was lowest within the pre-emergence only treatment at 45.4%. Canola oil content did not statistically differ between the pre-emergence (PRE) and in-season treatment (PRE, IS) (45.7%) but did differ between the pre-emergence (PRE) and pre-emergence, in-season, and desiccant treatment (PRE, IS, D) (46.0). When comparing the effect of cover crops between the treatments receiving the pre-emergence, in-

season, and desiccant application, canola oil content did not differ statistically and was 46.0% in the presence of cover crops and 46.1% when cover crops were absent.

Protein content was only measured at Carman for both years of the study and significantly differed between years ($p= 0.0384$) but did not differ between the three hybrids selected for the three herbicide tolerance systems ($p= 0.2823$) or between the herbicide frequency treatments ($p= 0.5975$). Mean protein concentration of all treatments was 24.3% at Carman22 and increased by 0.3% to 24.6% at Carman23. As protein and oil content have a strong inverse relationship, it was expected that protein content would be lower in 2022 as the oil content was greater. Although yield differences between herbicide frequencies did not result in statistical differences in protein, this agrees with previous research in Western Canada that found protein content of hybrid canola cultivars was not impacted by weed competition (Beckie et al., 2008). Thus, it is more likely that the difference in protein content between years in this study was environmentally driven.

Drought conditions such as those experienced in 2023 have been shown to shift canola seed composition, increasing protein content at the expense of oil synthesis (Gunasekera et al., 2006; Elferjani & Soolanayakanahally, 2018; Elferjani et al., 2024). Drought conditions have been shown to increase protein content in canola seed by 2.8% compared to a well-watered control treatment (Elferjani & Soolanayakanahally, 2018). The duration and timing of drought further influence this response. A meta-analysis of studies conducted under controlled conditions found that early drought stresses that occurred prior to the end of canola flowering increased protein concentration by 1.4% for a short-duration drought and increased further by 2.2% over a long-period drought relative to a well-watered control (Secchi et al., 2023). However, the magnitude of the protein content increases in these studies was greater than what was observed at

Carman. Early drought occurred at both locations during flowering and seed development, likely minimizing year-to-year differences in protein concentration (Table 3.7).

3.5 Summary and Conclusions

The objective of this study was to identify canola herbicide tolerance systems and herbicide frequencies that could enable cover crop intercropping with canola. The performance of cover crops with three herbicide tolerance systems and three herbicide frequencies were assessed by measuring establishment, herbicide damage ratings, cover crop persistence, and their impact on cash crop yield and quality.

Establishment of the cover crops varied by year and was driven by meteorological conditions. Poor cover crop establishment occurred in Carman in 2022 due to heavy rainfall events. Due to this poor performance, increased seeding rates were used in 2024, which increased cover crop establishment.

In-season herbicides had varying effects on the established cover crops. Poor establishment of cover crops in 2022 limited observations about in-season herbicide treatment trends. With increased cover crop establishment in 2023, herbicide damage ratings revealed that broadleaf cover crops (clovers and alfalfa) were severely injured by glufosinate at both locations. Glyphosate was also severely damaging to broadleaf cover crop species, except for alfalfa at Carman. Broadleaf cover crops tolerated imazamox+ imazethapyr at Carman with acceptable injuries, but not at Kernen, where severe injuries still occurred. When determining tolerance of Italian ryegrass, the opposite trend occurred, where imazamox+ imazethapyr and glyphosate were numerically the most damaging and glufosinate was the least, although all herbicides resulted in severe injuries.

Fall cover crop biomass was greatest in the pre-emergence only treatment and decreased following the use of both in-season herbicides and a subsequent desiccant application. In-season

herbicide applications reduced cover crop biomass and were consistent with the herbicide damage ratings at both locations. In Carman, biomass was most reduced with glufosinate, followed by imazamox+ imazethapyr, and glyphosate, although all the reductions were not statistically significant. At Kernen, the opposite occurred, with glufosinate causing the least reduction, followed by imazamox+ imazethapyr and glyphosate, which resulted in statistically significant reductions. Higher biomass within the glufosinate treatment at Kernen can be attributed to greater Italian ryegrass establishment, which appeared to be herbicide-tolerant, unlike at Carman, where establishment of Italian ryegrass was low. The greater establishment of Italian ryegrass at Kernen may have been attributed to greater cover crop biomass due to the species' high biomass production, rather than what was reported in Carman, where the Italian ryegrass population was minimal. Following an application of a desiccant, cover crop biomass was only statistically reduced in the glufosinate treatment at both locations in 2023, although numeric decreases were observed among all herbicide tolerance systems.

The yield of the canola cash crop was impacted by herbicide frequency, with the pre-emergence only treatment resulting in statistically lower yields in 3 out of 4 site-years. The reduction in yield in the pre-emergence only treatments was due to the high weed biomass in 2022 and 2023, respectively, and high fall cover crop biomass in 2023, which were both not controlled by in-season herbicide applications. Canola yield did not differ when a desiccant was applied, indicating a desiccant should be avoided if wanting to maintain greater cover crop biomass. As well, the presence of cover crops in the pre-emergence, in-season, and desiccant treatment did not statistically reduce yields relative to the no cover crop control when weeds were suppressed.

Weed suppression was not observed from the cover crop mixture in the experiment, but rather was attributed to the use of in-season herbicides. In 2022, weed biomass was significantly greater in Carman than in Kernen. Among all site-years, the greatest weed biomass was observed in the pre-emergence only treatment and was controlled following an in-season herbicide application. In 2023, when there was greater cover crop biomass, weed biomass was not reduced in Carman and was statistically reduced in the presence of cover crops in the glyphosate and imazamox+ imazethapyr systems in Kernen. However, when it came to weed density, the presence of cover crops had no statistical impact on the number of weeds present. As observed with weed biomass, in Carman, it was statistically high in the pre-emergence only treatment and controlled with in-season herbicides, whereas at Kernen, weed density did not differ between treatments.

Identifying a herbicide strategy that supported cover crop growth and minimized yield losses from weed pressure required the use of an in-season herbicide application in this study. The best in-season herbicide to use varied depending on the cover crop species utilized as an intercrop. If the cover crop species were broadleaves, imazamox+ imazethapyr resulted in the lowest injury, reduced weed biomass, and had the highest cover crop biomass. If the cover crop species were grasses, glufosinate was better tolerated. To maximize cover crop biomass, the application of a desiccant should be avoided, as biomass reductions occurred with the application of a desiccant and as there was no benefit from the desiccant for weed suppression or canola yield.

Future research on cover crops should focus on establishment methods and timings, and species selection, as their integration with canola is in its infancy. The timing of intercropping cover crops into canola should be further evaluated to observe if it is possible to establish a cover

crop following the in-season herbicide application as a way to minimize injury to the cover crops. Additionally, experiments are needed to determine the best seeding configuration, considering whether the cover crops should be established in mixed rows with canola or alternating, as well as the row spacings. Seeding methods should also be explored to determine if broadcasting cover crops into canola is a feasible practice. Additionally, a broader range of cover crop species should be evaluated individually and in mixtures, including grasses and broadleaf species commonly used on the Prairies, such as hairy vetch, clovers, and ryegrasses, to determine the most effective intercrop combination for canola.

Within this experiment, the three most utilized herbicide tolerance systems were evaluated, although there are other options for pre-emergence weed management within canola. Within pre-emergence weed management, the use of a herbicide with residual activity would be important to evaluate to determine its effects on the establishment of cover crops. Additionally, screenings should be done on individual cover crop species intercropped within canola to determine their tolerance to the herbicides.

This experiment is the first of its kind evaluating the intercropping of cover crops into canola. This experiment shows there is promise in getting cover crops to establish and persist within a canola canopy and endure a conventional weed management strategy.

4.0 CHALLENGES OF INTERCROPPING COVER CROPS WITH WHEAT UNDER MOISTURE-LIMITED CONDITIONS ON THE CANADIAN PRAIRIES

4.1 Abstract

The semi-arid climate of Western Canada, characterized by a short growing season and limited fall precipitation, constrains widespread adoption of fall cover crops. Intercropping presents as a potential solution by increasing the window for cover crop establishment and biomass accumulation. However, intercropping also creates challenges when using herbicides to control weeds within a spring wheat (*Triticum aestivum* L.) cash crop. Field experiments in 2022 and 2023 were conducted at two sites (Carman, Manitoba and Kernen, Saskatchewan) to compare the effect of three in-season herbicide applications commonly used in spring wheat (bentazon, tralkoxydim, and pyroxsulam) on the establishment and growth of intercropped cover crops. A cover crop mixture of red clover (*Trifolium pratense* L.), white Dutch clover (*Trifolium repens* L.), subterranean clover (*Trifolium subterraneum* L.), Persian clover (*Trifolium resupinatum* L.), alfalfa (*Medicago sativa* L.), and phacelia (*Phacelia tanacetifolia* L.) was drilled at the same time as wheat within the same row in 2022 and in alternating rows with wheat in 2023. Experiment measurements included cover crop establishment, herbicide damage ratings, aboveground fall cover crop biomass, weed density and biomass, and wheat grain yield and quality. Cover crop establishment varied by year and location, with poor establishment in 2022 due to low seeding rates, within-row arrangement, and drought conditions. The establishment of cover crops improved due to the alternate row seeding arrangement and increased seeding rate but continued to be inconsistent in 2023 due to moisture limitations. Numerically, cover crop biomass was greatest in the no herbicide control or the tralkoxydim treatment, as cover crop biomass was unaffected by in-season herbicide applications. This was reflected in the herbicide damage ratings, which showed that tralkoxydim and bentazon were tolerated by clovers, alfalfa,

and phacelia. However, the application of pyrosulam inflicted severe injuries but did not reduce cover crop biomass due to regrowth of the cover crop species. The herbicide damage ratings for pyroxsulam were mirrored in the observed weed biomass reduction when compared to the no-herbicide control. However, wheat yield was not affected by the herbicide treatments nor by the presence of the intercropped cover crop mixture. Overall, the establishment and growth of cover crops within a wheat cash crop remains a major challenge that is influenced by interspecific competition and environmental conditions. Therefore, further agronomic research in a wider range of locations is needed to identify agronomic management strategies to optimize wheat and cover crop performance for cropping systems across Western Canada.

4.2 Introduction

On the Canadian Prairies, the agricultural landscape is dominated by cereal crops, with the Prairie Provinces accounting for 90% of national wheat production (Newlands et al., 2014). Following the harvest of wheat in late August or early September, the soil is left bare for 2 months, exposing it to potential wind and rain erosion. The use of cover crops is a management practice deployed to prevent erosion by increasing ground cover and soil aggregation (Bourgeois et al., 2022; Koudahe et al., 2022) but also for the soil health (Blanco-Canqui & Ruis, 2020; Haruna et al., 2020; Šimansky et al., 2021; Blanco-Canqui et al., 2015; Adetunji et al., 2020; Muhammad et al., 2021) and weed suppressive benefits they provide (Fernando & Shrestha, 2023; Teasdale et al., 2007).

The utilization of cover crops has been increasing in recent years, driven by early adopters of the practice. A recent Prairie Cover Crop Survey conducted by Morrison and Lawley (2021) identified that shoulder-season cover crops were grown on 12,244 ha in Manitoba (105 respondents) and 6993 ha in Saskatchewan (90 respondents) in 2020. The widespread adoption of cover crops in the fall shoulder-season is constrained by the short growing season and limited

fall precipitation (Garnett & Khandekar, 2017; Wu et al., 2024), which hinders cover crop establishment and biomass production.

Establishing the cover crops as an intercrop with the cash crop presents as a potential solution by increasing the window for cover crop establishment and growth, and was reported to be used by 37% of respondents to the Prairie Cover Crop Survey (Morrison & Lawley, 2021). Unlike the fall shoulder-season, where biomass accumulation is hindered by the short growing season, intercrop competition and herbicide compatibility are the limiting factors of cover crop success within intercropping systems. Of the 281 respondents to the 2020 Prairie Cover Crop Survey, 21% identified that cover crops impacted their herbicide choice and was a challenge with adoption (Morrison & Lawley, 2021). Furthermore, intercropping legumes with a small grain crop presents a significant obstacle as legumes are sensitive to broadleaf herbicides and thus intercropped cover crops need to be selected not only for their functional traits, but also for their tolerance to herbicides.

Spring wheat was identified by 48% of respondents as the most popular cash crop grown from a recent Prairie Cover Crop Survey (Morrison & Lawley, 2021). However across the Prairies and the United States, minimal research has been conducted on cover crops intercropped into spring wheat (Wiersma et al., 2005; Pridham & Entz, 2008; Anderson, 2015; Aberle, 2024) with a greater proportion of published research looking into incorporating legume intercrops into winter wheat (Blackshaw et al., 2010; Blaser et al., 2011; Anderson, 2015; Koehler-Cole et al., 2016; Law et al., 2021).

Given the limited availability of research on the feasibility of intercropping cover crops within the Canadian Prairies, the main objective of this study was to identify compatible in-season herbicides for cover crops intercropped with wheat. It was hypothesized that 1) group 2

and 6 herbicides, which are used for broadleaf weed control, will be more damaging than group 1 grass herbicides, and 2) cover crop biomass will decrease with the application of in-season herbicides. Additionally, it was important to evaluate the impact of intercropped cover crops on wheat yield, and it was hypothesized that where cover crops and weeds were not controlled with in-season herbicides, wheat yield would decrease.

4.3 Materials and Methods

4.3.1 Site Descriptions

Small plot field experiments were conducted at the University of Manitoba Ian N. Morrison Research Station in Carman, MB (49°49' N, 98°03' W) and the University of Saskatchewan Kernen Crop Research Farm in Saskatoon, SK (52°09' N, 106°32' W) in 2022 and 2023. A new experimental area was used each year at each location, hereafter referred to as site-year. Site-year is denoted by location and the year when the cover crop was established: Carman22, Carman23, Kernen22 and Kernen23. Prior to seeding the cash and cover crops in the first year of the study, the experimental area was seeded as canola in both years in Carman and at Kernen, both experiments followed a canola- chemical fallow sequence. The soil classifications and climate characteristics can be found in Section 3.3.1.

4.3.2 Experimental Design and Treatments

The experiment was organized as a randomized complete block design with four replicates. Six treatments were designed to compare three standard wheat in-season herbicides with and without intercropped cover crops (Table 4.1). These treatments were compared to an intercropped cover crop control treatment, which received no in-season herbicide application. Individual plot sizes varied between locations based on available equipment. At Carman, individual plots were 1.9 m wide by 8 m long (15.2 m²) for both site-years. At Kernen, plots were 1.5 m wide by 8 m long (12.2 m²) in Kernen22 and 1.5 m wide by 10 m (15.2 m²) in

Kernen23. Between subplots, an unseeded buffer area of 1 m was used at Carman, and a 1.5 m buffer was used at Kernen.

Table 4.1. List of in-season herbicides and cover crop treatments for the experiment with wheat, including herbicide name, herbicide group, and which treatments included cover crops (+CC) or did not include cover crops (-CC).

Treatment	In-season herbicide		Cover crop
	Herbicide	Herbicide group	
1	Bentazon	Group 6	+CC
2	Bentazon	Group 6	-CC
3	Pyroxsulam	Group 2	+CC
4	Pyroxsulam	Group 2	-CC
5	Tralkoxydim	Group 1	+CC
6	Tralkoxydim	Group 1	-CC
7	None	None	+CC

The three in-season herbicide strategies utilized represent different herbicide groups and were applied to the wheat prior to flag leaf emergence. The in-season herbicides consisted of: tralkoxydim (Liquid Achieve™ SC, Corteva Agriscience), a group 1 grass herbicide; bentazon (Basagran® Liquid Herbicide, BASF Canada Inc.), a group 6 broadleaf herbicide; and pyroxsulam (Simplicity™, Corteva Agriscience), a group 2 broadleaf and grass herbicide. Tralkoxydim was applied at a rate of 0.5 L ha⁻¹ (200 g a.i. ha⁻¹) with an emulsifiable concentrate added to the tank mix at both locations. For Carman, the emulsifiable concentrate was Carrier® adjuvant (Nufarm Canada), used at 0.5% volume to volume (0.5 L ha⁻¹) and in Kernen, it was Turbocharge adjuvant (Corteva Agriscience), used at 0.5% volume to volume (0.5 L ha⁻¹). Pyroxsulam was applied at a rate of 0.5 L ha⁻¹ (15 g a.i. ha⁻¹) in conjunction with a non-ionic surfactant (Agral® 90, Syngenta Canada) at 0.25% volume to volume (0.25 L ha⁻¹). Bentazon was applied at a rate of 1.7 L ha⁻¹ (830 g a.i. ha⁻¹) in Carman and a rate of 2.3 L ha⁻¹ (1080 g a.i. ha⁻¹) in Kernen. All herbicides were applied at a water volume of 100 L ha⁻¹.

A mixture of cover crop species was seeded at the same time as wheat. In 2022, the seeding arrangement was a within-row intercrop and in 2023, it was seeded as an alternate row intercrop in all treatments with cover crops (Table 4.1). The species mixture included two overwintering clovers (red clover and white Dutch clover), two non-overwintering clovers (Persian clover and subterranean clover), alfalfa, and phacelia. A detailed description of the cover crop treatment and management is provided in section 4.3.4.

4.3.3 Crop Management

Crop management decisions were guided by environmental conditions in each year and the recommended practices for each province where the experiment was conducted. Spring soil tests to guide fertilizer application were conducted annually at each location prior to experiment establishment in May. Soil was sampled from 0 to 15 cm and 15 to 60 cm at 10 randomly selected locations within the experimental area using a Dutch auger at Carman. In Kernen, soil was sampled at the same depths from 5 selected locations at the NW, NE, SW, SE, and center of the experimental area using a hydraulic soil probe. At both locations, 1 composite soil sample for each depth was sent to Agvise Laboratories (Northwood, ND, USA) for Carman in both years and Kernen²³ and to A&L Canada Laboratories Inc. (London, ON, CAN) for Kernen²². Soil samples were analyzed for nitrate using the KCl method (Gelderman & Beegle, 2011) and Olsen phosphorus using sodium bicarbonate (Frank et al., 2011). Fertilizer rates for nitrogen, phosphorus, potassium, and sulphur were determined based on soil test recommendations for a target wheat yield of 4708 kg ha⁻¹ (Table 4.2). In Carman, fertilizer was banded prior to planting at a depth of 8 cm on 19 cm spacing perpendicular to the direction of seeding. In Kernen, fertilizer was banded at planting 1 cm away from the wheat seed at a depth of 3 cm.

Canada Western Red Spring (CWRS) wheat (ACC Starbuck VB) was seeded to a target population of 311 plants m⁻² in 2022 and reduced to 250 plants m⁻² in 2023. Wheat was seeded

Table 4.2. Date of spring soil sampling and soil test results for soil nitrate (N), Olsen phosphorus (P), potassium (K), sulphur (S), zinc (Z), and soil organic matter (SOM), as well as fertilizer application dates and rates (kg ha⁻¹) Carman22, Carman23, Kernen22, and Kernen23.

Site-year	Depth	Spring soil test results								Fertilizer applied				
		Sampling Date	N	S	P	K	Zn	pH	SOM	Application Date	N	P	K	S
	cm		—kg ha ⁻¹ —		——ppm——				g kg ⁻¹		——kg ha ⁻¹ ——			
Carman22	0-15	May 6	11.2	15.7	9.0	284.0	2.1	5.4	53.0	May 17	126.7	44.8	0.0	0.0
	15-60		74.0	53.8				7.0						
Carman23	0-15	May 3	11.2	17.9	12.0	325.0	2.6	5.5	58.0	May 11	156.9	22.4	0.0	0.0
	15-60		26.9	40.4				6.5						
Kernen22	0-15	May 12	34.7	16.8	19.0	519.0	2.2	7.6	46.0	May 25	89.7	22.4	0.0	0.0
	15-60		23.5	29.2				7.9						
Kernen23	0-15	May 4	43.7	27.4	11.6	476.2	0.5	7.8	50.0	May 8	89.7	22.4	0.0	0.0
	15-60		28.8	77.8				8.3						

total of 10 wheat rows per plot. In Kernen, wheat was seeded with a JT-8DMS R-Tech disc opener plot seeder (R-Tech Industries Ltd., Homewood, Manitoba) on a row spacing of 20 cm for a total of 9 wheat rows per plot. In 2023, wheat rows were reduced to 5 wheat rows per plot on a spacing of 38 cm in Carman and 40 cm in Kernen to account for the wheat and cover crops being seeded in alternating rows. Depending on soil moisture, wheat was seeded at a depth no greater than 2.5 cm. Weed control included a pre-emergence application of glyphosate (Roundup Transorb® HC, Bayer Crop Science Inc., Calgary, Alberta) at a rate of 2.5 L ha⁻¹ (1334 g a.e. ha⁻¹) for both site-years at Carman, and a rate of 1.3 L ha⁻¹ (702 g a.e. ha⁻¹) with the addition of the herbicide cargentrzone-ethyl (AIM® EC, FMC, Mississauga, Ontario) at 0.01 L ha⁻¹ (2.4 g a.i. ha⁻¹) in Kernen²³. In Kernen²², the pre-emergence application did not occur due to minimal weed presence.

Diseases and pests were monitored at each location. Environmental conditions conducive to fusarium head blight infection were monitored prior to wheat anthesis. Based on Fusarium risk maps, tebuconazole (Folicur® 250 EW, Bayer Crop Science Inc.) was applied at 125 g a.i. ha⁻¹ prior to wheat anthesis in Carman on July 13 in 2022 and June 29 in 2023 (Table 4.3). Favourable environmental conditions for infection were not observed at Kernen, and no fungicides were applied.

Individual plots were direct harvested with a Kincaid 8-XP small plot combine (Kincaid Equipment Manufacturing, Haven, Kansas) in Carman and with a Zürn 130-SE small plot combine (Zürn Harvesting GmbH & Co. KG, Baden-Württemberg, Germany) in Kernen. At the Carman site, additional management was required to mechanically harvest wheat in 2022, as lamb's quarters and redroot pigweed were large enough to interfere with direct harvest. Therefore, a desiccant application of glyphosate (Roundup Transorb HC, Bayer Cropscience

Table 4.3. Dates of field operations, herbicide applications, and measurements for Carman22, Carman23, Kernen22, and Kernen23.

Operation	Site-year			
	Carman22	Carman23	Kernen22	Kernen23
Wheat and cover crop seeding	May 27	May 13	May 25	May 8
Harvest	September 7	August 31 September 7	September 12	August 19
Herbicide applications				
Pre-season burndown	May 27	May 16	-	May 9
In-season herbicide	June 17	June 21	June 28	June 13
Measurements				
Cash crop emergence counts	June 15	May 29 May 30	June 14	May 30
Cover crop emergence counts	June 29	June 8 June 9	June 14	June 7
Herbicide damage ratings				
Rating 1 (7 DAA)	-	June 28	-	June 20
Rating 2 (14 DAA)	-	July 5	-	June 27
Rating 3 (21 DAA)	-	July 12	-	July 4
Weed counts	July 7	July 12	July 11	June 12
Weed biomass	August 15	August 9	August 23 August 26	August 17
Cover crop biomass	October 5	October 7	October 13	October 26

Inc.) at a rate of 1.7 L ha⁻¹ (918 g a.e. ha⁻¹) was applied to all plots to facilitate harvest, as cover crop persistence was low. For Carman23, due to a combine malfunction, wheat harvest occurred on August 31 for reps 1 and 2 and on September 7 for reps 3 and 4.

4.3.4 Cover Crop Management

The cover crop mixture of red clover, white Dutch clover, Persian clover, subterranean clover, alfalfa, and phacelia was seeded to a target stand of 40 plants m⁻² in 2022 (Table 4.4). Due to low establishment of cover crops in 2022, the target stand was increased to 100 plants m⁻² in 2023. Seeding rates varied by species, with adjustments made for seed lot germination and thousand kernel weight.

Table 4.4. Cover crop species, target stand, and seeding rates of the cover crop mixture for the 2022 and 2023 experiments.

Cover crop species	Target stand		Seeding rate	
	2022	2023	2022	2023
	plants m ⁻²		kg ha ⁻¹	
Red clover	5	15	0.252	0.756
White Dutch clover	5	15	0.112	0.336
Subterranean clover	5	15	0.785	2.355
Persian clover	5	15	1.401	4.203
Alfalfa	10	30	0.308	0.924
Phacelia	10	10	0.897	0.897
Mix total	40	100	3.755	9.471

Cover crops were seeded with disc plot seeders (Section 4.3.3) in the same row as wheat in 2022 on a row spacing of 19 cm in Carman and 20 cm in Kernen. In 2023, cover crops were seeded in an alternate-row arrangement with wheat to increase cover crop establishment. Cover crops were drilled on 38 cm row spacing in Carman and 41 cm in Kernen, resulting in 5 cover crop rows per plot. The cover crops were drilled in alternating rows with wheat on a row spacing of 19 cm between wheat and cover crop rows in Carman and 20 cm between rows in Kernen.

The cover crop mixture was seeded at the same depth as the wheat into moisture at a depth no deeper than 2.5 cm.

4.3.5 Data Collection

4.3.5.1 Cover Crop

Cover crop performance was assessed by measuring plant emergence, herbicide damage ratings, and aboveground biomass. Plant counts were conducted in the spring, one to three weeks after seeding, to assess cover crop emergence counts. To avoid edge effects, plant counts were taken at least 1 m from the plot edge, and no counts were taken from the outer rows of the plot. Cover crop plant counts were measured from two adjacent one-meter rows at both the front and back of the treatment plot.

Cover crop biomass samples were taken in early to mid-October, prior to the first predicted killing frost. Biomass was sampled from two adjacent one-meter cover crop rows at the front of the plot at Carman22, Carman23, and Kernen22. In Kernen23, biomass samples were taken from two adjacent 0.5-meter rows. For all site-years, cover crop biomass was cut at the soil surface and oven dried at 60°C for 48 hours, or until constant dry weights were obtained. Herbicide damage ratings for cover crops were recorded following the in-season herbicide application. Ratings were conducted 7, 14, and 21 days after application (DAA) to assess the injury to cover crops. The observation period was based on the timing of expected herbicide injury symptoms for the three herbicides included in the study: Bentazon and Tralkoxydim (Corteva Agriscience, n.d. b), 10 to 14 DAA, and Pyroxsulam 7 to 21 DAA (Corteva Agriscience, n.d. c). Cover crops in each treatment were visually evaluated and compared to the pre-emergence only treatment for each herbicide group. Plots were rated using a 0 to 100 rating scale for crop phytotoxicity adapted from the Canadian Weed Science Society (2018) as described within section 3.3.5.2 (Table 3.6). Damage ratings were taken for each individual plot,

with ratings performed separately for alfalfa and phacelia, while clover species were grouped together. Specific symptoms, including chlorosis, necrosis, stunting, and wilting, were described for each species.

Cover crop biomass samples were taken in early to mid-October, prior to the first predicted killing frost. Biomass was sampled from two adjacent one-meter rows at the front of the plot at Carman22, Carman23, and Kern22. In Kern23, biomass samples were taken from two adjacent 0.5-meter rows. For all site-years, cover crop biomass was cut at the soil surface and oven dried at 60°C for 48 hours or until constant dry weights were obtained.

4.3.5.2 Weeds

Weed counts were taken after the in-season herbicide application had taken effect during the vegetative stage of the wheat crop. A 0.25 m² quadrat was placed at the front and back of each plot, positioned so the cover crop row was centred. The number of new and surviving weeds within the quadrat were counted. Common species within the experimental area were recorded.

Weed biomass was collected when the wheat crop reached maturity. An area of 0.381 m² was sampled using a quadrat at the front of each plot. Quadrats were positioned so that the cover crop row was centred and the edges of the plot were avoided when sampling. Weed biomass within the quadrat was cut at the soil surface and oven dried at 60°C for 48 hours until constant dry weights were obtained.

4.3.5.3 Wheat

Wheat was harvested in early to mid-September using a plot combine (Section 4.3.3.). Grain samples were dried with ambient air before being cleaned. In Carman, plot samples were cleaned using a grain cleaner (Clipper M2BC, Bluffton, IN). Clean weights were recorded, and the samples were analyzed for grain moisture using a GAC 2500-INTL Grain Analysis

Computer (Dickey-John, Auburn, IL, USA). In Kernen, plot samples were individually cleaned using a dockage tester (AG60-2023, Carter Day International, Minneapolis, MN, USA). Grain samples from both locations were analyzed for protein and moisture using near infrared (NIR) spectroscopy (Foss Infratec™ 6008 9470/ Rev. 1, Hilleroed, Denmark) for near infrared (NIR) analysis at a wavelength range of 570 to 1100 nm.

4.3.6 Statistical Analysis

Statistical analysis was performed using SAS 9.4 (SAS Institute Inc., Cary, NC). The PROC GLIMMIX procedure was utilized to conduct an analysis of variance (ANOVA) to evaluate the treatment effects on dependent variables. The models accounted for location and treatment, and their interactions, as fixed effects. Year was not included as a fixed effect in the model, except for the analysis on cover crop emergence, as there were low cover crop populations at both sites in 2022. The random effect included replication nested within location to account for random variation at the location level. Data distributions were either Gaussian for wheat yield, lognormal for cover crop and weed biomass, and Poisson for weed density. Link functions were selected according to the specified error distribution: an identity link for Gaussian distributions and a log link for lognormal Poisson distributions. Models with Gaussian and log normal error distributions were estimated using the restricted maximum likelihood (REML), while models with the Poisson distribution were fit using the default pseudo-likelihood (ML-based) method. Results were back-transformed prior to reporting.

Default options for the GLIMMIX procedure were included using the link statement, the Satterthwaite method to determine denominator degrees of freedom, and the compound symmetry covariance structure. To further investigate differences among treatment means, the LSmeans statement was used for pairwise comparisons between means of the treatment groups with Tukey's honest Significant Difference (HSD) adjustment at a probability of 5% ($p < 0.05$).

Assumptions for ANOVA were evaluated using PROC UNIVARIATE to test the normality of residuals with the Shapiro-Wilk W test and by visually inspecting histograms of each response variable. Homogeneity of variances was tested by visual inspection of a plot of residuals, where residuals should not form a pattern.

Cover crop emergence was analyzed using an ANOVA with the PROC GLIMMIX procedure and an adjusted model statement, which included year. The model, therefore accounted for year, location, and treatment. Due to increased cover crop establishment in 2023, to determine if there were differences based on location and treatments, a reduced model was further run on 2023 establishment counts without the fixed effect of year. Since the data did not follow a normal distribution, a Poisson transformation was applied prior to statistical analysis and back-transformed for presentation.

Herbicide damage ratings were subjected to a repeated measures ANOVA conducted by each of the species rated: clovers, alfalfa, or phacelia. The PROC GLIMMIX procedure was utilized with a model that included location, herbicide, and day after application, as well as their interactions, were included as fixed effects in the model. The model's error distribution was estimated using the default pseudo-likelihood (ML-based) method. The denominator degrees of freedom were calculated using the Kenward-Roger method (1997) to account for repeated measures with non-normal data. As ratings were a percentage value, the beta distribution with the logit link function was utilized for all species. Data was back-transformed for presentation. Random statements were used to specify the repeated measures structure. Day after application was a random effect within the model to determine if ratings taken on different days were independent from one another. Day was grouped within the combination of location and herbicide, which was nested within replication to account for variation among days within each

experimental condition. The compound symmetry covariance structure was utilized to account for equal spacing between ratings. To further investigate differences among treatment means, the LSmeans statement was used for pairwise comparisons between means of the treatment groups with Tukey's Honest Significant Difference (HSD) adjustment at a probability of 5% ($p < 0.05$).

4.4 Results and Discussion

4.4.1 Meteorological Conditions

Environmental conditions for all of the site years of the experiment, including average temperature, precipitation, and climate normals, were previously described within Section 3.4.1. On the day the in-season herbicides were applied in 2023, weather conditions varied between locations (Figure 4.1). In Carman, the average daytime temperature was 16.2°C with a peak of 26.1°C. Average relative humidity (RH) was 73.1% with a dewpoint of 16.3°C with 0.2 mm of precipitation received the day prior to application and 7.4 mm of precipitation occurring the day after application. In Kernen, the average temperature was greater than in Carman at 23.1°C and had a greater peak at 29.3°C. The relative humidity and dew point were lower than Carman at 49.3% RH and 11.0°C with no precipitation occurring 24 hours before or after the herbicide application.

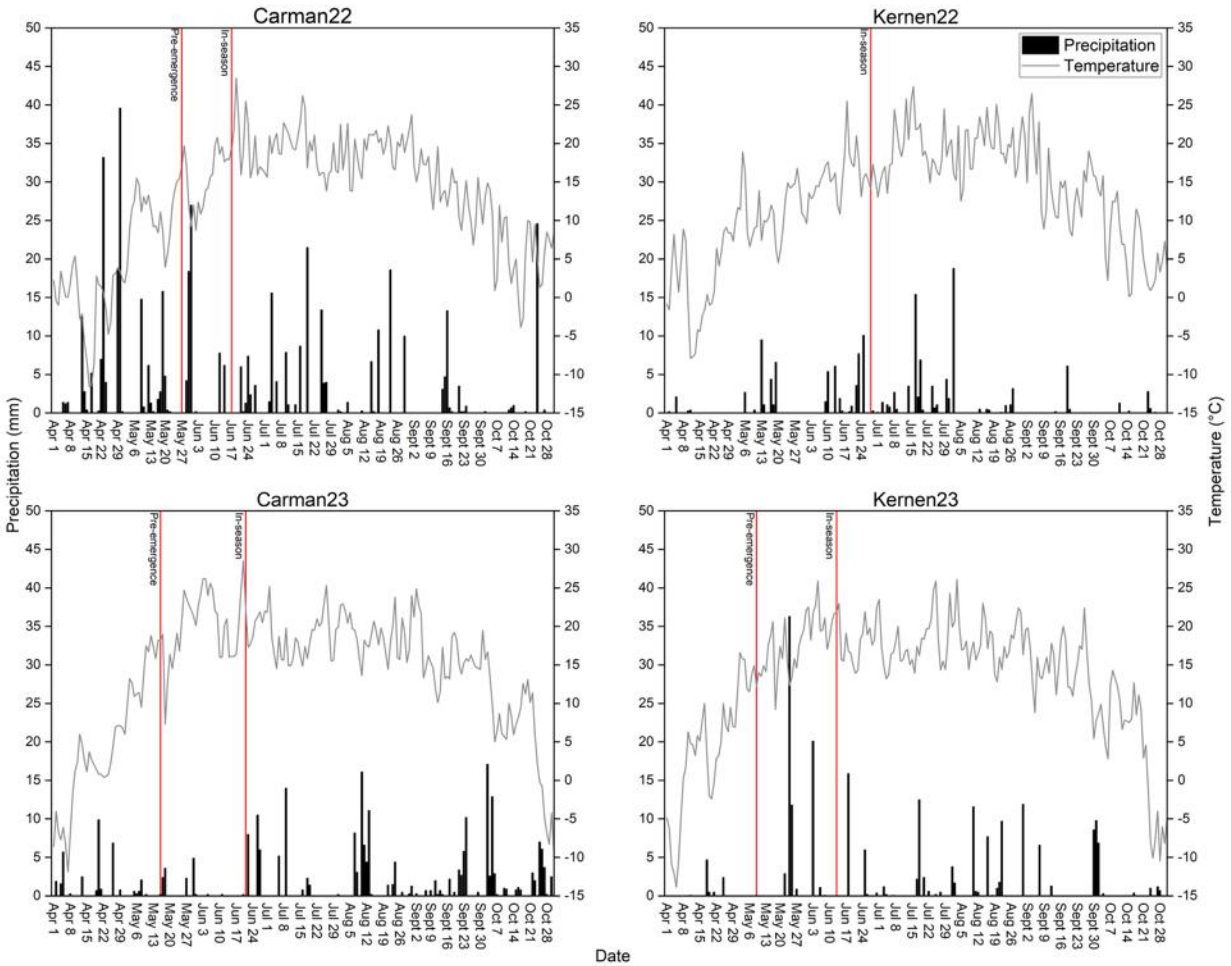


Figure 4.1. Growing season daily precipitation (mm) and daily mean temperature (°C) for Carman22, Kernen22, Carman23, and Kernen23. Vertical red lines indicate pre-emergence or in-season herbicide applications at each location.

4.4.2 Cover Crop

4.4.2.1 Cover Crop Emergence

Cover crop benefits are maximized when stands emerge rapidly and establish evenly within a field. The emergence of cover crop species was consistent across treatments but differed by year and by location. The main effects of year and location were statistically significant for cover crop emergence, and there were no statistically significant interactions between the main effects (Table 4.5).

Table 4.5. Analysis of variance of the dependent variable cover crop emergence for the main effects of year (Y), location (L), herbicide treatment (T), and their interactions. Bolded values indicate significance at the 0.05 probability level.

Sources of variation	df	<i>p</i> -value
Year (Y)	1	<0.0001
Location (L)	1	<0.0001
Herbicide treatment (T)	6	0.6992
Y*L	1	0.4872
Y*T	6	0.6223
L*T	6	0.7290
Y*L*T	6	0.6194

In 2022, cover crop emergence was well below the target stand of 40 plants m⁻² at both locations. In Carman, cover crop emergence was minimal at 5 plants m⁻², whereas Kernen had slightly greater emergence of 9 plants m⁻². Due to limited cover crop establishment and low cover crop persistence in the fall at both locations in 2022, the cover crop seeding rate was increased to 100 plants m⁻² in 2023. This change in seeding rate explains part of the effect of year on cover crop emergence.

To determine if in 2023, there were differences based on location and treatment, a reduced model was run on the 2023 emergence counts. Similar to the complete data set, cover crop emergence was found to vary based on location ($p < 0.0001$) but once again was not statistically significant for treatment ($p = 0.3479$) or their interaction ($p = 0.9681$). In 2023, the cover crop stand was still below the target in Carman at 77 plants m⁻², whereas at Kernen the stand of 121 plants m⁻² exceeded the target stand.

In arid regions of North America, forage crops can often fail even when sown with a cereal companion crop (Kilcher & Heinrichs, 1960). Additionally, it is often advised that when there are limitations to moisture availability, cereal and forage legumes should not be established simultaneously (Kilcher & Heinrichs, 1960).

The differences in emergence across locations and years can be partially attributed to meteorological conditions, with soil moisture and rainfall being critical factors for cover crop establishment. In 2022, Carman's accumulated winter precipitation amounts were similar to the 30-year climate normal (Table 3.7), whereas all other site-years received only 43 and 50% of the expected precipitation. Though soil moisture is crucial for supporting establishment, timely rainfall events are necessary to achieve optimum establishment (Obour et al., 2021). In 2022, Carman received 99 mm of precipitation in May, with the majority occurring immediately after seeding. These saturated soil conditions likely resulted in oxygen deprivation around the seeds, delaying germination and emergence, which increased the risk of stand loss (Government of Manitoba, n.d. b). In contrast, Kernen22 received less than the normal amount of precipitation in the spring months and experienced similar establishment after experiencing a timely rainfall. Temperature is also a critical factor for germination and in 2022, temperatures in May were 1-degree Celsius lower than the 30-year climate normal (Table 3.7) at both sites. A difference of this size has been shown to hinder germination of seeds in the Northern Great Plains, as observed in a review by Obour et al. (2021). In 2023, spring conditions at both sites were 5°C warmer than the spring temperatures in 2022, likely increasing cover crop establishment. For example, Butler et al. (2014) reported that alfalfa germination was 73% at 10°C increasing to 86% at 15°C. Additionally, the germination of arrowleaf clover (*Trifolium vesiculosum* Savi) was 51 and 66% at 10 and 15°C, respectively (Butler et al., 2014),

Establishment of clover and alfalfa may have been hindered in both years due to suboptimal seeding depths. In Carman, suboptimal emergence of clover and alfalfa may be attributed to inappropriate seeding depth. Seeding depth of the drill was set for the ideal depth for wheat at 2-3 cm, exceeding the 1-1.5 cm recommended maximum depth for small-seeded

species like clover and alfalfa (Sheaffer et al., 2022). Previous unpublished experiments on companion seeding alfalfa with wheat found poor establishment when seeded at a depth of 1.29 cm and greater establishment with broadcasting. In the same experiment, clovers performed similarly for both seeding methods (Westman Agricultural Diversification Organization, 2017). Additionally, a controlled experiment by Chu et al. (2022) found that when seeded at 1 cm, white clover emergence was 55% compared to 77% emergence when broadcast on the soil surface.

Competition with the wheat crop may have also played a factor in decreasing establishment, especially in 2022 when wheat and the cover crops were seeded within the same row. During establishment, there is early-season competition for solar radiation by the wheat crop, which can decrease the establishment of legume species, such as red clover, though clover is considered a shade-tolerant species (Gaudin et al., 2013). Red clover has been found to establish easily under the canopy of a grass companion crop (Government of Ontario, 2022). However, there are cultivar differences as Canadian grown cultivars of mammoth red clover, such as Altaswede clover, do not tolerate the competition and shading from wheat as well as Michigan Mammoth, an American cultivar (Hudson et al., 2011). Increasing the interrow spacing can improve the amount of solar radiation available for legume species, allowing for greater establishment (De Notaris et al., 2019).

Additionally, when clovers are simultaneously seeded with spring cereals, they can be at a disadvantage due to the rapid aboveground growth and substantial rooting system of spring species, which can outcompete clover seedlings (Garand et al., 2001). However, when evaluating grass companion crops, wheat was found to be less competitive with a forage mixture of brome grass (*Bromus secalinus* L.), alfalfa, and crested wheatgrass (*Agropyron cristatum* (L.) Gaertn.) as compared to oat, rye, and barley (Kilcher & Heinrichs, 1960). Other field

experiments in Carman, Manitoba, within organic wheat production were able to achieve red clover stands ranging from 93 to 172 plants m⁻² (Pridham & Entz, 2008). When intercropped with wheat in Minnesota, the establishment of alfalfa and red clover was 129 plants m⁻² and 118 plants m⁻², respectively, when seeded at 6.7 and 5.6 kg ha⁻¹ (Wiersma et al., 2005). Cover crops have also been established as an intercrop within other small grain crops. When seeded with an oat crop at a density of 100 plants m⁻², berseem clover stand was reduced to 404 plants m⁻² compared to its establishment as a monocrop at a density of 632 plants m⁻² (Ross et al., 2003). When seeded with barley, red clover was able to establish with a stand of 210 plants m⁻² when seeded at 17 kg ha⁻¹ (Johnson & Hansen, 2014).

Plant densities per species at emergence varied by year and were related to the seeding rates of each species (Table 4.4). In 2022, poor emergence was experienced with overall densities of less than 3 plants m⁻², irrespective of cover crop species. In 2022 and 2023, the emergence counts were predominantly comprised of clovers in Carman, followed by alfalfa and phacelia (Table 4.6), reflecting the proportions of the cover crop mixture (Table 4.4). An unpublished experiment conducted by Frey and Thiessen Martens (2024) found success in establishing individual legume species in the same row as wheat. They found alfalfa establishment ranged from 90 to 103 plants m⁻², red clover from 12 to 128 plants m⁻², and white clover from 22 to 206 plants m⁻² (Frey & Thiessen Martens, 2024). In their study, Frey and Thiessen Martens (2024) used higher seeding rates than in the present study, which may have been a crucial factor in achieving higher emergence values.

Table 4.6. Cover crop establishment by species for Carman22 and Carman23.

Site-year	Cover crop establishment		
	Clovers	Alfalfa	Phacelia
		plants m ⁻²	
Carman22	3 b ^a	2 b	0 b
Carman23	65 a	8 a	4 a
Sources of variation			
Year	<0.0001	<0.0001	<0.0001

^a a-b least square mean values followed by the same letter are not significantly different from one another for cover crop species within a column at $p < 0.05$.

4.4.2.2 Herbicide Damage Ratings

Herbicide damage ratings are an assessment of cover crop tolerance to in-season herbicides, offering a practical basis for selecting compatible herbicide strategies. It should be noted that in Canada, bentazon is registered for post-emergence use on clovers and alfalfa, and tralkoxydim is the only graminicide registered for use in cereals underseeded to clovers and alfalfa.

Analysis of variance for herbicide damage ratings was conducted by cover crop species. A significant two-way interaction between herbicide and days after application was highly significant for all cover crop species, and the two-way interaction between location and herbicide was significant for alfalfa and phacelia (Table 4.7). The main effect of herbicide was highly significant in the ANOVA for the herbicide damage ratings of all cover crop species. Furthermore, the main effect of location was significant for alfalfa and phacelia damage ratings, while days after application was not significant.

Table 4.7. Analysis of variance for the main effects of location (L), herbicide treatment (T), days after application (DAA), and their interactions for clover, alfalfa, and phacelia herbicide damage ratings in 2023. Bolded values indicate significance at the 95% confidence interval.

Sources of variation	Response variable		
	Clover rating	Alfalfa rating	Phacelia rating
Location (L)	0.1993	<0.0001	0.0100
Herbicide treatment (T)	<0.0001	0.0004	<0.0001
Days after application (DAA)	0.0848	0.5997	0.5196
L*T	0.5237	0.0020	0.0223
L*DAA	0.5100	0.0586	0.2297
T*DAA	<0.0001	0.0025	<0.0001
L*T*DAA	0.4586	0.1054	0.2586

Table 4.8. Mean herbicide damage ratings expressed as percent injury using the CWSS-SCM rating scale for crop tolerance for each cover crop species (clovers, alfalfa, and phacelia) treated with bentazon (group 6), tralkoxydim (group 1), or pyroxsulam (group 2) herbicides were taken 7, 14, 21 days after application (DAA) in 2023. A rating of 0% indicated no damage, whereas a rating of 100% indicates complete plant death.

Herbicide	Herbicide group	Days after application (DAA)		
		7	14	21
		% injury		
		Clovers^a		
Bentazon	Group 6	1.4 c ^b	0.8 c	0.0 c
Tralkoxydim	Group 1	0.0 c	0.0 c	0.4 c
Pyroxsulam	Group 2	0.5 c	17.3 b	33.5 a
		Alfalfa		
Bentazon	Group 6	9.5 a	2.1 ab	0.0 b
Tralkoxydim	Group 1	0.0 b	0.0 b	0.0 b
Pyroxsulam	Group 2	0.4 ab	0.7 ab	1.4 a
		Phacelia		
Bentazon	Group 6	12.5 b	6.8 bc	2.0 bcd
Tralkoxydim	Group 1	0.4 cd	0.1 d	0.0 d
Pyroxsulam	Group 2	5.7 b	30.7 a	41.7 a

^a Clovers were rated as a group and included red, white, subterranean, and Persian clovers as individual plants for species could not be distinguished from one another.

^b a-e means values followed by the same letter are not significantly different from one another within a cover crop species (clovers, alfalfa, Italian ryegrass) at $p < 0.05$.

(Table 4.1). Greater effects of herbicide damage were observed 21 days after application (DAA) compared to 7 DAA for pyroxsulam, whereas bentazon showed decreased herbicide damage at 21 DAA compared to 7 and 14 DAA. For tralkoxydim, damage ratings were minimal

for all cover crop species, with ratings being less than 0.4% regardless of DAA. To further examine the variability in injury among cover crop species, trends in damage ratings are presented for each in-season herbicide treatment (Table 4.8).

4.4.2.2.1 Bentazon

Bentazon caused no injury to any of the legume cover crop species at the last rating taken 21 DAA. Among the legumes, clovers experienced the lowest injury of 1.4% 7 DAA which was outgrown and decreased to a rating of 0% by 21 DAA. Alfalfa was initially more injured than clovers with an acceptable rating of 9.5% 7 DAA, which decreased to 2.1% 14 DAA, and further to 0% at 21 DAA, indicating it was also able to outgrow the injury. Phacelia was the most damaged by the application and experienced an injury that was not acceptable 7 DAA with a rating of 12.5%. However, similar to the legume species, it was able to outgrow its injuries with a rating that decreased to an acceptable injury of 2% by 21 DAA (Table 4.8).

As a contact herbicide, bentazon injuries manifest as chlorosis and necrosis on the uppermost leaves, with symptoms being outgrown by legumes if the injury is non-severe (BASF, n.d. a). Due to its low injury potential, it has been regarded as the industry standard for post-emergence applications in established red clover (Johnson et al., 2007). Field experiments in Oregon applied bentazon at 1120 g a.i. ha⁻¹ to red clover and reported injuries ranging from 0 to 3% 10 DAA. This injury rating increased to a range of 0 to 5% at 20 DAA (Lins et al., 2005). When applied at the same rate in another field study in Alabama, crimson clover exhibited 15% injury, whereas white clover control was lower at 5% relative to the untreated control 6 weeks after application (McCurdy et al., 2013). In a complementary greenhouse experiment, Ceballos et al. (2004) found that bentazon at 1200 g a.i. ha⁻¹ produced the greatest phytotoxicity out of all herbicides tested, with 46% of clovers experiencing severe foliar injuries, which decreased from 10 to 30 days after application. Similar injury and recovery were observed in clovers within the

present experiment. Other studies on subterranean clover yielded similar results as our experiment, with visible injuries ranging from 0 to 6% up to 3 weeks after application when applied at 800 g a.i. ha⁻¹, which was the rate utilized in Carman, and injury ratings increased to 5 to 8% when the application rate was increased to 1700 g a.i. ha⁻¹ (Evers et al., 1993).

The experiment conducted by Ceballos et al. (2004) also found red clover treated with bentazon had a 30% increase in plant height, which can be a proxy for cover crop biomass, relative to the untreated control. Other experiments observing plant height reported varying results on clovers treated with bentazon. A greenhouse experiment also reported a similar 30% increase in white clover height but found a 2% reduction in crimson clover height (McCurdy et al., 2013). A subsequent field experiment by McCurdy et al. (2016) found no reduction in height or leaf densities relative to the untreated control. Thus, white clover was determined to be tolerant of bentazon (McCurdy et al., 2016).

Bentazon is currently approved for use within seedling forage legumes, including alfalfa (BASF Canada Inc., n.d. a). However, when applied on hot, humid days as experienced in 2023, temporary leaf yellowing and burning can appear in alfalfa, but plants often outgrow the damage within 10 days (BASF Canada Inc., n.d. a). These observations align with herbicide damage ratings from this study, which observed decreasing injury by 14 and 21 DAA. Harvey et al. (1991) reported that over eight years of field experiments in Wisconsin, the average injury from bentazon was 8% on seedling alfalfa 10 DAA, which did not result in decreased alfalfa growth. When using bentazon at a rate of 800 g a.i. ha⁻¹, which was the rate applied at Carman, alfalfa injury was of 9% 10 DAA (Harvey, 1991). In the same study, the higher rate of 1100 g a.i. ha⁻¹, which was applied in Kernen, reported a greater injury of 13% 10 DAA (Harvey, 1991). Tonks et al. (1991) also observed similar alfalfa injury ratings ranging from 3 to 8% in Utah field

experiments when bentazon was applied at 800 g a.i. ha⁻¹. In contrast, a greenhouse experiment by Hijano et al. (2013) found alfalfa phytotoxicity rating of 70% 14 DAA when bentazon was applied at the recommended rate. These injuries were attributed to widespread leaf necrosis at 21 DAA (Hijano et al., 2013).

Currently, there are no herbicides registered for use with phacelia in Canada (Manitoba Agriculture, 2025). Furthermore, there is minimal research on the tolerance of phacelia to bentazon (Westman Agricultural Diversification Organization, 2021). Preliminary experiments in California have found that a post-emergence bentazon application at a rate of 562 g a.i. ha⁻¹ resulted in a 5% reduction in ground cover of seedling phacelia when compared to an untreated control (Hill & Moretti, 2024).

4.4.2.2.2 Tralkoxydim

The application of the group 1 herbicide, tralkoxydim, resulted in no visible injuries to the legume cover crop species up to 14 DAA. At 21 DAA, alfalfa still had no visible injuries, whereas clover had an acceptable injury rating of 0.4%. In phacelia, acceptable ratings were also observed, though it experienced a greater initial injury rating of 0.4% 7 DAA, which then decreased to a rating of 0% by 21 DAA (Table 4.8). These minimal injury ratings to the species in the cover crop mixture can be attributed to the fact that group 1 herbicides, including tralkoxydim, inhibit the acetyl-CoA carboxylase (ACCase) enzyme in grass species and do not affect broadleaf species, as their ACCase enzyme is insensitive to the herbicide (Bayer Group, n.d.). The cover crop mixture seeded in this experiment consisted of two leguminous species (clovers and alfalfa) as well as herbaceous species (phacelia), which were all unaffected by tralkoxydim. No information was available on phacelias tolerance to tralkoxydim, or other group 1 herbicides, as there is minimal research on phacelias tolerance to herbicides.

Tralkoxydim is approved for use in cereals underseeded with alfalfa and clovers (Pest Management Regulatory Agency, 2011). In Ontario, spring-seeded red clover intercropped with winter wheat saw no reductions in density when treated with 200 g a.i. ha⁻¹ of tralkoxydim applied two months post red clover seeding (Robinson et al., 2014). A greenhouse experiment conducted by Dear et al. (2006) reported that tralkoxydim applied to subterranean clover at 150 g a.i. ha⁻¹ resulted in a rating of 1 (no effect) at 15 and 30 days after application, using the European weed research council rating scale for plant tolerance. Their experiment also observed no reductions in subterranean clover foliage compared to the untreated control following the application of tralkoxydim (Dear et al., 2006). Sethoxydim, a herbicide in the same family as tralkoxydim, resulted in 83% crop vigour when applied to seedling alfalfa at a rate of 250 g a.i. ha⁻¹ compared to 81% vigor in a weedy control, indicating the tolerance of alfalfa to this herbicide group (Malik & Waddington, 1990).

4.4.2.2.3 Pyroxsulam

The group 2 herbicide, pyroxsulam, inflicted the greatest injury to all cover crop species, with injuries increasing over the rating period. The leguminous species experienced contrasting ratings. Both clovers and alfalfa experienced acceptable ratings of 0.5 and 0.4% injury, respectively, at 7 DAA. However, the injury rating to clovers continued to increase substantially with the following ratings, whereas the ratings to alfalfa remained acceptable. At 14 DAA, the injury rating to clovers was 17.5%, which is considered not acceptable, and further increased to 34%, which is considered a severe rating at 21 DAA. Visible symptoms included stunting and reddening of foliage followed by necrosis. Alfalfa was unexpectedly the least injured out of all the cover crop species with a rating of 1.4% at 21 DAA, which indicated acceptable injury. Injury from pyroxsulam was apparent to phacelia at 7 DAA with an acceptable rating of 5.6%. This increased to severe injury with a rating of 30.7% at 14 DAA. Phacelia observed to be

stunted, and leaf tissue appeared burnt and necrotic. At 21 DAA, the damage rating for phacelia increased to 41.7%, which was the greatest injury rating recorded of all species in the experiment. This level of injury for phacelia was severe, with the plants being unable to recover (Table 4.8).

Legumes, including clovers and alfalfa, are highly susceptible to injury from pyroxsulam, which is not recommended for use with underseeded legumes (Corteva Agriscience, n.d. c; Manitoba Agriculture, 2025). Pyroxsulam is registered in Canada for use to control white clover, indicating greater phytotoxicity of clover species than alfalfa (Corteva Agriscience, n.d. c). When pyroxsulam was spring applied at 18 g a.i. ha⁻¹ to spring-seeded red clover in winter wheat, red clover had an injury rating greater than 90% after winter wheat harvest (Powell & Sprague, 2016). Extension recommendations from Michigan State University (2019) further advise against pyroxsulam applications to red clover in the spring when frost seeding into winter wheat. Injury symptoms reported in other leguminous species, such as soybean, include necrosis and stunting (Eley, 2006) which agrees with observations in this study of visual injury symptoms to clovers and phacelia.

When comparing pyroxsulam to other group 2 herbicides from the same (triazolopyrimidine) and differing (sulfonyleurea) chemical families, similar patterns of phytotoxicity have been observed. Alfalfa is tolerant to flumetsulam, a group 2 herbicide from the same triazolopyrimidine family (Zandstra et al., 2004), consistent with the injury ratings of 1% to alfalfa in the current study (Table 4.8). In greenhouse experiments conducted by Ceballos et al. (2004), flumetsulam applied to red clover seedlings at a rate of 39 g a.i. ha⁻¹ resulted in phytotoxicity ratings ranging from 2 (88% of plants) to 3 (13%) on a scale of 1 (no injury) to 5 (complete plant death) at 20 DAA. However, the red clover was not severely damaged by the

application and subsequently recovered, with plant height increasing by 57% relative to the untreated control 30 DAA (Ceballos et al., 2004).

Group 2 herbicides from the sulfonylurea family report similar phytotoxicity as the triazolopyrimidine chemical family. Nicosulfuron, a group 2 herbicide from a differing sulfonylurea family, applied at 70 g a.i. ha⁻¹ to 1 cm tall red and white clover seedlings resulted in injury ratings of 5 and 9, respectively, on a 0 (no injury) to 10 (complete plant death) scale (Greenland, 2004). In a field experiment conducted by McCurdy et al. (2013) on crimson and white clover, an application of metsulfuron at a rate of 20 g a.i. ha⁻¹ resulted in 93 and 88% injury relative to the untreated control when rated 6 weeks after application. In the same experiment, an application of trifloxysulfuron at 30 g a.i. ha⁻¹ produced similar results of 95% injury to crimson clover and 89% injury to white clover (McCurdy et al., 2013).

Limited information was available on phacelia's tolerance to pyroxsulam or other group 2 herbicides as there is minimal research on phacelia's tolerance to herbicides as no herbicides are registered for use with phacelia (Westman Agricultural Diversification Organization, 2021). One study, however, observed that rimsulfuron had a 36% reduction in ground cover of phacelia (Hill & Moretti, 2024).

4.4.2.3 Cover Crop Biomass

Due to minimal cover crop persistence in 2022, statistical analysis was only conducted on the data obtained from 2023. The main effect of location was significant ($p= 0.0172$), whereas the effect of herbicide treatment was not significant ($p= 0.0797$). Their interaction ($p= 0.0462$) was statistically significant for cover crop biomass. In 2023, when measurable biomass was obtained at Carman, the biomass decreased numerically following an in-season application for all herbicides tested and following the bentazon and pyroxulsam applications at Kernen (Figure 4.2).

At Carman, the untreated control resulted in the greatest cover crop biomass numerically, with 116 kg ha⁻¹. When bentazon, tralkoxydim or pyroxsulam in-season herbicides were applied, cover crop biomass did not statistically differ when compared to the untreated control. Cover crop biomass in these treatments ranged from 46 to 30 kg ha⁻¹ (Figure 4.2). No trends could be correlated between herbicide damage ratings and cover crop biomass due to low biomass and persistence counts as reported in Appendix B.1.

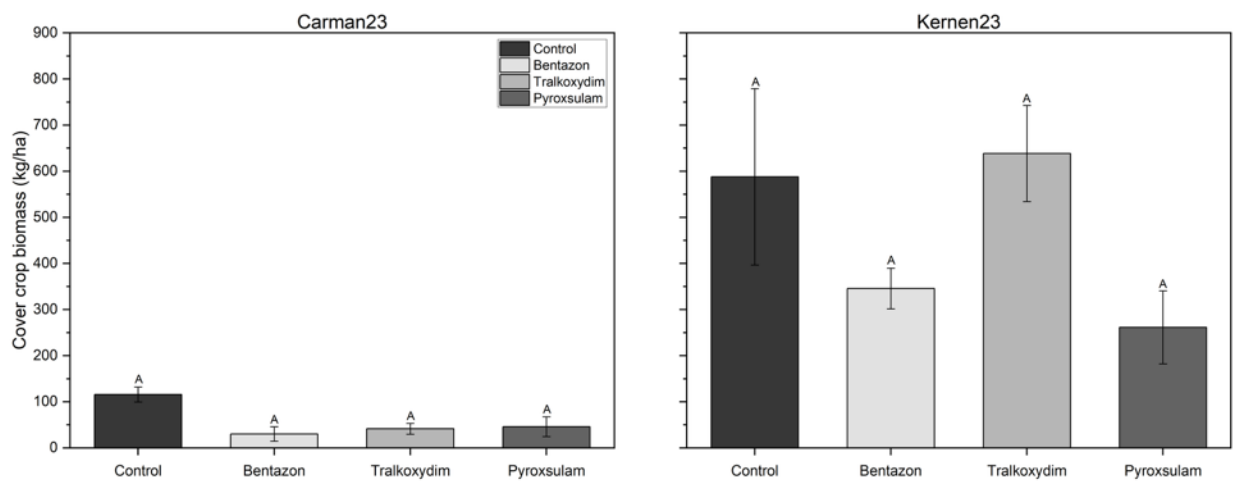


Figure 4.2. Mean fall cover crop biomass following in-season herbicide applications of three herbicides: bentazon (group 6), tralkoxydim (group 1), and pyroxsulam (group 2), and a control which received no herbicides for Carman23 and Kernen23. Error bars represent ± 1 SEM. Bars with the same letters are not statistically different at the 0.05 significance level.

In Kernen, cover crop biomass was greater than the biomass obtained in Carman ($p=0.0172$). With variability in cover crop biomass among treatment replications, a larger error was observed at Kernen, limiting the treatment differences. At Kernen, cover crop biomass was statistically the same as the untreated control (589 kg ha⁻¹) following the bentazon, tralkoxydim, or pyroxsulam in-season applications. Biomass in these treatments ranged from 639 kg ha⁻¹ to 262 kg ha⁻¹. The lowest cover crop biomass numerically was observed when treated with pyroxsulam, with 262 kg ha⁻¹ of biomass, which correlates with the greatest herbicide damage ratings.

Previous research across the Prairie provinces has reported variable cover crop biomass production in the absence of in-season herbicides. Results from unpublished experiments in Manitoba found that red clover intercropped with wheat produced 592 kg ha⁻¹ of biomass, while intercropped alfalfa resulted in a lower biomass of 272 kg ha⁻¹ (Parkland Crop Diversification Foundation, 2021). A multi-site experiment across Manitoba conducted by Frey and Thiessen Martens (2024) found biomass of alfalfa intercropped with wheat ranged from 158 kg ha⁻¹ to 557 kg ha⁻¹ across the 4 sites. In the same experiment, when it came to clovers, 3 out of 4 locations were unable to produce measurable biomass. In the location where biomass was measurable, intercropped red clover biomass was 339 kg ha⁻¹ and intercropped white clover biomass was 118 kg ha⁻¹ (Frey & Thiessen Martens, 2024). Within the present experiment, cover crop biomass in Kernen23 was comparable to these values. In Saskatchewan, Bowren et al. (1969) measured red clover and alfalfa biomass accumulation at wheat maturity when cross-seeded with wheat at two locations in Saskatchewan. In Melfort, red clover and alfalfa produced 1112 and 753 kg ha⁻¹ of biomass, respectively, whereas in Whitefox, biomass was higher with 1303 kg ha⁻¹ for red clover and 1449 kg ha⁻¹ for alfalfa.

Similar variability in the biomass of intercropped cover crops has been documented in the United States. In Minnesota, Wiersma et al. (2005) found that when intercropped with wheat, red clover biomass was 766 kg ha⁻¹, and alfalfa biomass was 429 kg ha⁻¹. In Wisconsin, when seeded as an intercrop with oat, red clover biomass ranged from 1020 kg ha⁻¹ to 2080 kg ha⁻¹, and alfalfa biomass ranged from 180 kg ha⁻¹ to 890 kg ha⁻¹ (Stute & Posner, 1993).

Cover crop biomass following in-season herbicide applications generally followed trends observed with herbicide damage ratings within the current experiment (Table 4.8). In a greenhouse trial, red clover biomass was 53% of the untreated control 10 days after a bentazon

application and by 30 DAA, red clover biomass was similar to the untreated control, indicating recovery from the herbicide application (Ceballos et al., 2004). An additional greenhouse experiment found differing results, with biomass of red clover treated with bentazon being only 73% of the untreated control at 30 DAA (Ceballos et al., 2009). When looking at the biomass of ball, crimson, small hop, and white clover, bentazon applied at 1120 g a.i. ha⁻¹ led to a 36% reduction in biomass 4 weeks after application (McCurdy et al., 2013). A follow-up experiment conducted by McCurdy et al. (2016) found that bentazon applied to white clover resulted in 34% defoliation, contributing to a decrease in biomass. Similar findings were reported in Brazil by Schuster et al. (2015), where bentazon applied at 600 g a.i. ha⁻¹ to white clover intercropped in soybean, reduced biomass to 950 kg ha⁻¹ when compared to 1480 kg ha⁻¹ in the control (Schuster et al., 2015). When applied to alfalfa in an experiment in Utah, bentazon resulted in yields ranging from 60 to 79% of the untreated monoculture (Tonks et al., 1991). These results are consistent with the current study's findings at Carman23, where bentazon led to the lowest cover crop biomass (30 kg ha⁻¹). In contrast, bentazon applied at Kernan23 caused no significant reduction in biomass, indicating herbicide impact on cover crop biomass can be site-specific.

Fewer studies could be identified that quantified the impact of tralkoxydim and pyroxsulam on intercropped cover crops. Tralkoxydim applied at 200 g a.i. ha⁻¹ at winter wheat booting reduced red clover cover crop biomass by 60 kg ha⁻¹ in 2009 and further reduced biomass by 30 kg ha⁻¹ in 2010 when averaged across 3 southern Ontario locations (Robinson et al., 2014). Similarly, in the present experiment, cover crop biomass when treated with tralkoxydim was statistically the same as the untreated control, demonstrating the mixture's tolerance to the herbicide, which was observed with herbicide damage ratings (Table 4.8). When comparing pyroxsulam to similar group 2 herbicides, metsulfuron resulted in an 84% reduction in

clover biomass, whereas trifloxysulfuron had a lower biomass reduction of 68% (McCurdy et al., 2013). A similar experiment found metsulfuron defoliated white clovers by 64% and height by 53%, whereas nicosulfuron resulted in a lower defoliation of 28% and a lesser reduction in height of 35%, resulting in reduced biomass (McCurdy et al., 2016). Biomass following the pyroxsulam application at Carman23 was statistically similar to the untreated control, whereas in Kernen23 biomass was numerically reduced when compared to the untreated control, reinforcing that the efficacy of herbicides was site-specific, consistent with the literature findings.

4.4.3 Weeds

4.4.3.1 Weed Density

Weed density reflects the effectiveness of in-season herbicide weed management strategies in wheat-cover crop systems, which can influence both the success of intercropped cover crops and the performance of wheat. Weed species within the experiment primarily consisted of lamb’s quarter, redroot pigweed, and green foxtail. The main effect of location was significant, whereas herbicide treatment was not significant for the variable of weed density. However, the interaction between the two main effects was statistically significant (Table 4.9). Treatment means for the highest-order significant interaction are presented in Figure 4.3.

Table 4.9. Analysis of variance for the main effects of location (L), herbicide treatment (T), and their interactions for weed density and weed biomass in 2023. Bolded values indicate significance at the 95% confidence interval.

Sources of variation	Response variable	
	Weed density	Weed biomass
Location (L)	0.0082	0.0037
Herbicide treatment (T)	0.1295	0.0038
L*T	<0.0001	0.3498

Weed density at Carman was greater than at Kernen. Weed density ranged from 107 plants m⁻² in the no herbicide control to 160 plants m⁻² following the in-season (IS) tralkoxydim

treatment with the addition of cover crops (Figure 4.3). However, there were no statistical differences in weed density between treatments at Carman23. Numerically, the greatest weed density was observed in the treatments that received the tralkoxydim application and within these two treatments, weed density was greater by 16 plants m⁻² when cover crops were present. A similar trend was observed when treated with pyroxsulam, where weed density was numerically increased by 13 plants m⁻² in the presence of cover crops. In contrast, treatments receiving an application of bentazon experienced a numerical decrease in weed density from 143 plants m⁻² when cover crops were absent to 108 plants m⁻² with cover crops.

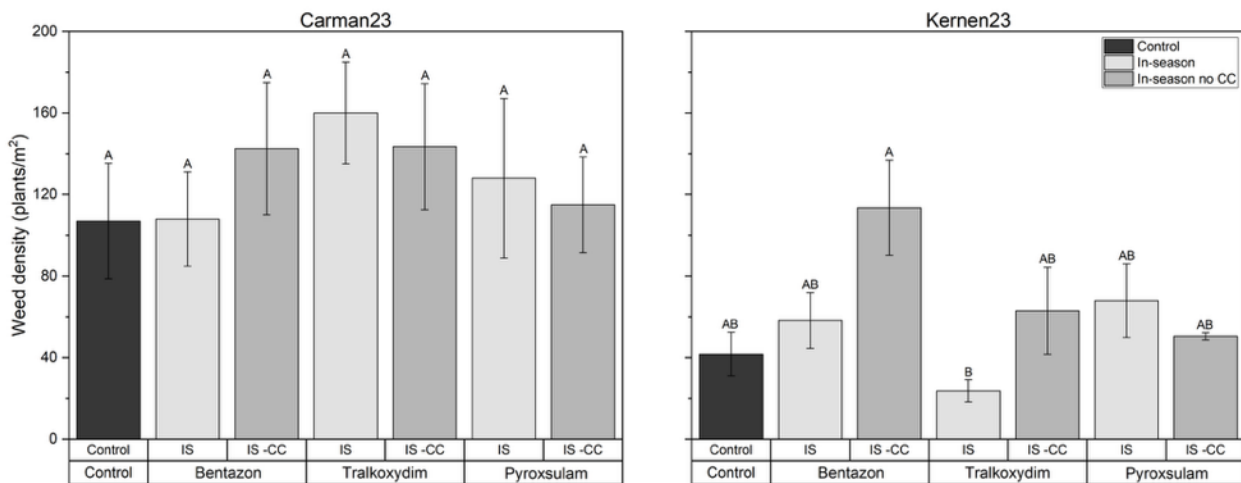


Figure 4.3. Mean weed density following in-season herbicide applications from three herbicide groups: bentazon (group 6), tralkoxydim (group 1), and pyroxsulam (group 2) for Carman23 and Kernen23. A control with no cover crops (-CC) was present for each herbicide group. A control was seeded with cover crops and received no herbicide applications. Error bars represent ± 1 SEM. Bars with the same letters are not statistically different at the 0.05 significance level.

At Kernen the cover crop control treatment had the second lowest weed density of 42 plants m⁻² numerically which was similar to what was observed in Carman23. The lowest weed density in Kernen occurred with the tralkoxydim treatments, where the presence of cover crops numerically reduced weed density to 24 plants m⁻² compared to the absence of cover crops,

where weed density was 63 plants m⁻². A numerical reduction also occurred in treatments with the bentazon herbicide, where weed density was reduced by 56 plants m⁻² when cover crops were present. The same trend however did not occur in the pyroxsulam treatments, where like Carman, weed density was greater when cover crops were present at 68 plants m⁻² compared to 51 plants m⁻² in the absence of cover crops. This increase in weed density, however, was not statistically significant. All treatments were statistically similar to the untreated control.

The differences in weed density between locations could be attributed to the amount of cover crop biomass produced. Cover crop biomass was higher in Kernen (Figure 4.2) and thus weed suppression from cover crops was more effective. Despite the differences in densities, at both locations, the cover crop control treatment, which received no in-season herbicides, had lower weed densities than those treated with in-season applications, except for the tralkoxydim treatment in Kernen. A recent meta-analysis conducted in the Southeast United States found cover crops reduced weed density by 44% (Weisberger et al., 2023). A meta-analysis conducted by Nichols et al. (2020) in the Midwest United States found no reduction in weed density, which indicates the suppressive effects of cover crops vary spatially.

In organic systems, where weed control is not reliant on the use of herbicides, intercropping has produced mixed results on weed density suppression. Previous studies in Manitoba conducted by Pridham and Entz (2008) found that wheat intercropped with red clover had greater weed density in 2 out of 3 years when compared to monoculture spring wheat when herbicides were not applied. In conventional winter wheat systems, Blaser et al. (2006) found that red clover at any density reduced weed densities, however there was greater suppression with increases in red clover density. In the study, weed density was reduced by an average 38% with red clover when compared to the winter wheat monoculture control (Blaser et al., 2006). In

South Dakota, red clover was able to reduce volunteer winter wheat densities by 98%, lowering weed densities to less than 1 plant m⁻² compared to 50 plants m⁻² in the no cover crop control (Anderson, 2015). Additional experiments have found that when alfalfa and red clover were frost-seeded into winter cereals, weed densities were reduced by 50 and 71%, respectively, compared to the no legume intercrop control (Blaser et al., 2011).

In the current study, the only in-season herbicide treatment that outperformed the no herbicide control with cover crops was the tralkoxydim treatment at Kernen, which resulted in the lowest weed density. Due to the high population of redroot pigweed and lamb's quarters in Carman and Kernen, it was anticipated that bentazon would provide the greatest control. A study by Soltani et al. (2021) found that bentazon reduced the density of redroot pigweed by 7 plants m⁻² and lamb's quarters by 25 plants m⁻² compared to the untreated control (Soltani et al., 2021). At Carman, the presence of green foxtail, a species that has resistance to group 1 herbicides, can account for the high weed density within this treatment as compared to Kernen, where tralkoxydim resulted in the lowest density. Due to the anticipated group 1 resistance at Carman, it was expected that pyroxsulam would perform greater than both tralkoxydim and bentazon. Zagar et al. (2020) found pyroxsulam controlled redroot pigweed by 65% 4 weeks after application, whereas Satchivi et al. (2017) found pyroxsulam control of green foxtail was less than 81%. The results by Satchivi et al. (2020) align with our results at Carman, where the weed population, primarily composed of redroot pigweed and green foxtail, was not controlled with the in-season application of pyroxsulam when compared to the untreated control.

4.4.3.2 Weed Biomass

While weed density provides insight into weed emergence, weed biomass reflects weed growth and competitive ability within wheat-cover crop intercrops. The main effects of location ($p= 0.0037$) and herbicide treatment ($p= 0.0036$) were significant. Their interaction ($p= 0.3498$)

however, was not significant for weed biomass (Table 4.9). Weed species within the experiment primarily consisted of lamb's quarter, redroot pigweed, and green foxtail. Across all treatments, weed biomass was greater in Carman, where average biomass was 1552 kg ha⁻¹, compared to Kernen where weed biomass was 245 kg ha⁻¹.

When combined across locations, the cover crop control treatment, which received no in-season herbicides, had the greatest numerical weed biomass of 1318 kg ha⁻¹ (Figure 4.4). However, it was not statistically different from weed biomass in treatments (IS) receiving bentazon or tralkoxydim. In contrast, a statistically significant reduction in weed biomass was observed when pyroxsulam was applied, which reduced biomass to 380 kg ha⁻¹ relative to the untreated control. In the presence of cover crops (IS), there were no statistically significant reductions in weed biomass observed when compared to the no cover crop treatment (IS – CC) for any of the in-season herbicides tested.

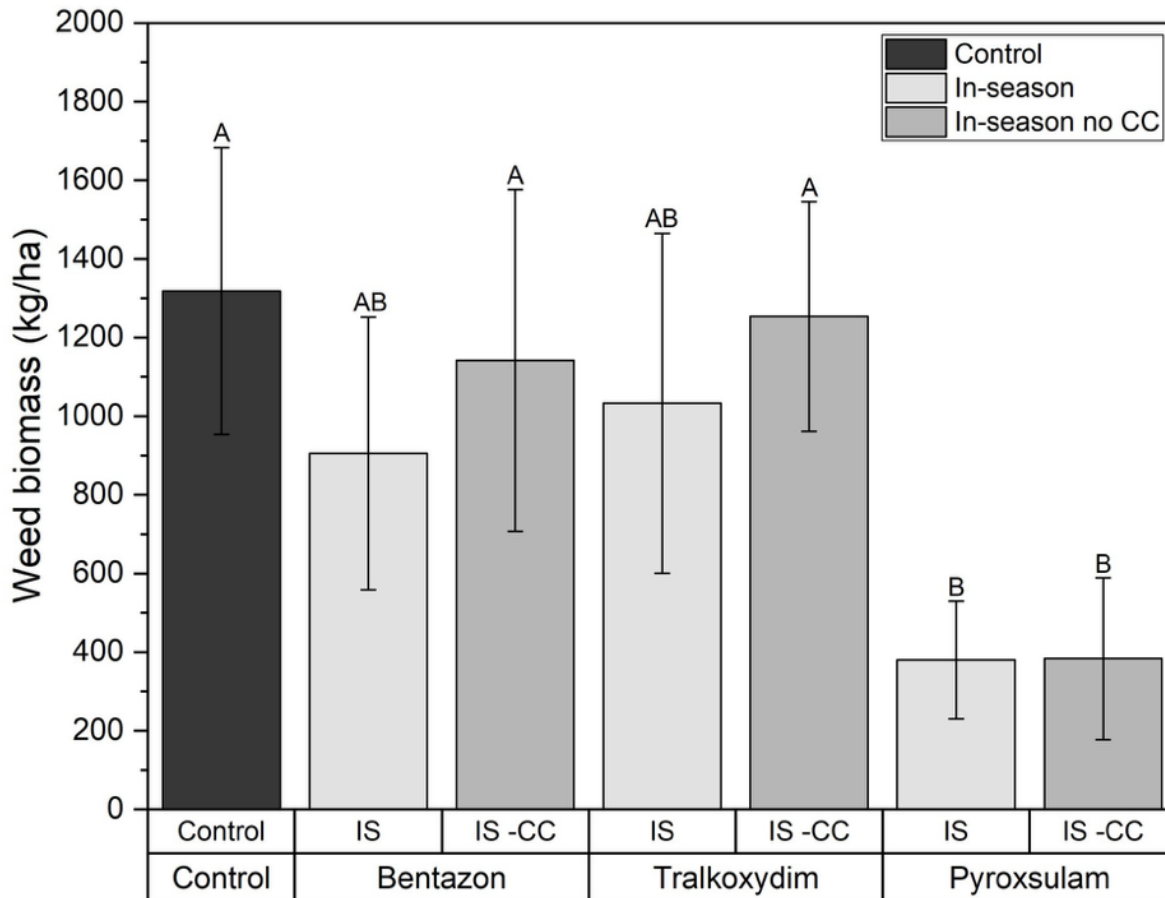


Figure 4.4. Mean weed biomass following the in-season application of three herbicides: bentazon (group 6), tralkoxydim (group 1), and pyroxsulam (group 2) for Carman23 and Kernen23. A control with no cover crops (-CC) was present for each herbicide treatment. A control was seeded with cover crops and received no herbicide applications. Error bars represent ± 1 SEM. Bars with the same letters are not statistically different at the 0.05 significance level.

These trends of numerical weed suppressive benefits of cover crops in this experiment contrasts other experiments on spring wheat-red clover intercrops in Manitoba. When intercropped with wheat, Pridham & Entz (2008) found that red clover increased weed biomass from 390 to 560 kg ha⁻¹. This was likely attributed to the legume nitrogen-fixation of red clovers producing more favourable conditions for weed species (Szumigalski & Van Acker, 2005; Kocira et al., 2020). While research on intercropped cover crops in spring wheat is limited, more research is available on intercropping with winter wheat across the United States, however, with

mixed results on its impact on weed biomass. A three-year study in New York found that red clover intercropped into winter wheat reduced weed biomass by 24 and 327 kg ha⁻¹ in two out of three site-years. However, in one site-year red clover increased weed biomass by 94 kg ha⁻¹ when compared to a winter wheat monoculture (Law et al., 2021). In Michigan, Mutch et al. (2003) found red clover frost-seeded into winter wheat significantly suppressed common ragweed (*Ambrosia artemisiifolia* L.) by 600 kg ha⁻¹ in 1998 and by 600 to 900 kg ha⁻¹ in 1999. Following winter wheat harvest in South Dakota, weed biomass of green and yellow foxtail (*Setaria pumila* (Poir.) Roem. & Schult.), lamb's quarters, and redroot pigweed in plots containing red clover was less than 1 kg ha⁻¹ compared to the control, which had 600 kg ha⁻¹ (Anderson, 2015). The findings of Law et al. (2021) were consistent with those observed within the current study, whereas the weed suppressive effects found by Mutch et al. (2003) and Anderson (2015) were greater than those observed in the current experiment.

A study comparing seeding rates of red clover found that weed biomass did not differ between seeding rates of 6.7, 10.1, and 13.5 kg ha⁻¹, with an average weed biomass of 1009 kg ha⁻¹ in the intercrop treatments compared to 1569 kg ha⁻¹ in the no cover crop control (Hudson et al., 2011). A study by Koehler-Cole et al. (2016) on the suppressive ability of legume species intercropped in winter wheat found an intercrop with red clover had a weed biomass of 500 kg ha⁻¹ compared to a weed biomass of 750 kg ha⁻¹ when white clover was used. A study by Volkman et al. (2022) in Montana, however, reported an increase in weed biomass when sweetclover was utilized. The experiment found broadleaf weed biomass was 577 kg ha⁻¹ in the presence of sweet clover compared to 338 kg ha⁻¹ in the no cover crop control. In the same study, grass weeds were less prominent and thus weed biomass was similar in the presence of sweet clover compared to the no intercrop control (Volkman et al., 2022).

Previously, studies have reported an inverse relationship between cover crop biomass and weed biomass (Osipitan et al., 2019; Nichols et al., 2020; Kumari et al., 2024; McKenzie-Gopsill et al., 2022). Nichols et al. (2020) identified a biomass threshold of 5000 kg ha⁻¹ to achieve 40% weed suppression. Cover crop biomass in the present study fell well below this threshold in all site-years. Consequently, the observed reductions in weed biomass within this study were likely driven by the in-season herbicide applications, rather than by cover crops.

Previous studies have found that cover crops alone are often insufficient for effective weed control, and the addition of chemical or mechanical weed management strategies were needed (Fernando & Shrestha, 2023). For example, Bunchek et al. (2020) found that in a corn and a soybean field experiment weed biomass was reduced when a post emergence herbicide was used compared to a pre-emergence herbicide only (Bunchek et al., 2020). Thus, they determined that herbicide strategies were required for weed biomass reduction and additional weed suppressive benefits of a smaller magnitude were experienced when coupled with cover crops (Bunchek et al., 2020). Likewise, Osipitan et al. (2019) found that combining cover crops with a post-emergence herbicide suppressed weeds to a greater extent when compared to a single or mixed cover crop species. Additionally, within rye and small grain intercropping systems, weed suppression from the cover crops alone was inadequate and post-emergence herbicide programs were needed to reduce weed biomass (Rajalahti et al., 1999; De Bruin et al., 2005). This was observed within the present experiment, where the greatest weed suppression occurred following a pyroxsulam application, despite having the lowest cover crop biomass, indicating the reduction in weed biomass was instead a result of the herbicide.

4.4.4 Wheat

4.4.4.1 Wheat Yield

Assessing wheat yield is essential for determining the impact of intercropped cover crops on wheat productivity and agronomic performance. The main effects of location ($p= 0.0864$), herbicide treatment ($p= 0.3847$), and their interaction ($p= 0.7784$) were not statistically significant for wheat yield. Mean wheat yield across all treatments and locations was 3644 kg ha^{-1} , indicating that intercropped cover crops did not statistically impact spring wheat yield in this study.

Although cover crop biomass within the current experiment was low, these findings are consistent with previous research indicating limited impact on wheat yield when intercropped with legumes. An unpublished multi-location experiment across Manitoba by Frey & Thiessen Martens (2024) found no wheat yield reductions when intercropped in the same row with alfalfa ($2623\text{-}5918 \text{ kg ha}^{-1}$), red clover ($2219\text{-}6120 \text{ kg ha}^{-1}$), or white clover ($2690\text{-}6322 \text{ kg ha}^{-1}$), relative to the no-cover crop control ($2488\text{-}6254 \text{ kg ha}^{-1}$). In an experimental site-year where fall cover crop biomass was measured, biomass of alfalfa (557 kg ha^{-1}), red clover (339 kg ha^{-1}), and white clover (118 kg ha^{-1}), which was similar to the current study, did not reduce wheat yield (Frey & Thiessen Martens, 2024). Similarly, an unpublished study in Alberta found intercrops of white, crimson, and subterranean clovers drilled simultaneously with spring wheat did not have an impact on grain yield (Peace Region Living Lab, 2024). When intercropped cover crops were included with in-season weed control in Minnesota, Wiersma et al. (2005) found similar results that intercropped alfalfa (biomass of 429 kg ha^{-1}), or red clover (biomass of 766 kg ha^{-1}) did not affect wheat yields compared to a wheat monoculture.

Previous experiments have also reported a decrease or increase in wheat yield when intercropped with cover crops. In South Dakota, Anderson (2015) wheat yield decreased by 17%

when red clover was intercropped simultaneously with spring wheat. In an unpublished study in Melita, Manitoba, spring intercropping of alfalfa or sweet clover with wheat under moisture-limited conditions led to reduced wheat yields, likely a result of increased interspecific competition (Westman Agricultural Diversification Organization, 2017). Conversely, a subsequent unpublished experiment near Roblin, Manitoba in 2020 observed that wheat yield did not differ statistically but increased numerically when seeded with clover intercrops. In a second Manitoba experiment, the monocrop wheat yielded 3598 kg ha⁻¹, and increased to 3901 kg ha⁻¹, 4096 kg ha⁻¹, and 4445 kg ha⁻¹ when seeded with red clover, alfalfa, or white clover, respectively (Parkland Diversification Foundation, 2021b). The same results were found in an unpublished study in Alberta, where wheat intercropped with red clover yielded 2219 kg ha⁻¹ with a land equivalent ratio based on biomass yield of 1.5, indicating wheat overyielding relative to a monocrop (North Peace Applied Research Association, 2020).

4.4.4.2 Wheat Grain Quality

Grain protein was used to quantify the impact of the experiment treatments on wheat grain quality. Grain protein differed by location ($p= 0.0002$) but was not significant for herbicide treatment ($p= 0.6021$) or their interaction ($p= 0.5798$). Both locations produced grain protein that was greater than the 2023 average for Canadian spring wheat of 13.8% and the 10-year Canadian average of 13.7% (Canadian Grain Commission, 2023), with protein in Carman being 15.5% and greater in Kernen at 16.7%.

Nitrogen-fixing legumes have the potential to enhance grain protein through increasing soil available nitrogen released from root exudates. However, other studies have confirmed the same findings of this study, where wheat protein, when intercropped with legumes, was similar to that of a wheat monocrop. With Kernen having greater cover crop establishment and persistence than Carman, grain protein may have seen an increase as nitrogen-fixing legumes are

important for increasing protein in water or nitrogen-limited environments (Miller et al., 2018). However, previous research has provided varying results. In Minnesota, field studies conducted on alfalfa and red clover intercrops saw no significant effect on wheat protein; both treatments resulted in 14.6% grain protein, whereas the no-cover crop control had a protein content of 14.5% (Wiersma et al., 2005). Similar unpublished studies in Alberta using white, crimson, and subterranean clover intercrops drilled simultaneously with wheat reported no statistical differences in grain protein (Peace Region Living Lab, 2024). A single-year experiment in Manitoba found that sweet clover and alfalfa broadcast pre- or post-seeding did not influence wheat protein (Westman Agricultural Diversification Organization, 2017). In contrast, an unpublished multi-site field study in Manitoba found varying impacts of legume-wheat intercrops on grain protein. Across 4 sites in Manitoba, protein content in the wheat-only control ranged from 12-15% and was similar to intercropped legumes of alfalfa (12-14.2%), red clover (11.8-15.1%), and white clover (12-15.1%) (Frey & Thiessen Martens, 2024). Differences in grain protein can be attributed to environmental conditions and locations, as opposed to cover crops.

In general, the protein content of Canadian spring wheat is greater than that of winter wheat (Entz & Fowler, 1991), but the influence of legume cover crops on grain protein remains relevant between the different wheat classes. In winter wheat, grain protein was also seen not to be influenced by a legume intercrop. For example, Blackshaw et al. (2010) reported no impact of spring-seeded alfalfa or red clover on winter wheat grain yield in Alberta. Similarly, a three-year study in Nebraska found that when white or red clover was frost-seeded into winter wheat, grain protein was statistically similar to the no-cover crop control in two out of three site-years (Koehler-Cole et al., 2016). Although in one year, grain protein was reduced to 11.7% when

intercropped with red clover compared to 12% of the no cover crop control (Koehler-Cole et al., 2016). A field experiment in central Italy found that temporary intercropping of Persian clover with wheat was able to increase winter wheat protein by 1.5% compared to a wheat monocrop (Pellegrini et al., 2021).

4.5 Summary and Conclusions

The objective of this small plot experiment was to identify compatible herbicides and frequencies of applications for cover crops intercropped in wheat. The performance of cover crops was assessed by measuring establishment, herbicide damage ratings, and persistence and their impact on the cash crop was explored. The research also assessed the effects of cover crops on weed suppression. Cover crop establishment varied by year, driven by meteorological conditions and differences in seeding rates. In 2022, cover crops were seeded in the same row as the wheat, resulting in poor establishment and a loss of the cover crops. To account for the poor establishment, in 2023 the cover crop seeding rate was increased and was seeded in alternating rows with wheat. There was success in cover crop establishment at Kernen, however, it was still a challenge to get the cover crops to establish with wheat at Carman. This can be attributed to the moisture-limited conditions experienced during early growth in June for both years of the study and competition with wheat, which has a shallow rooting system and depleted the available moisture.

In-season herbicides had varying effects on the established cover crops. Based on the herbicide mode of action, it was expected that tralkoxydim would not affect the broadleaf cover crops (clovers and alfalfa) as it is selective to grass species, and this was confirmed with acceptable herbicide damage ratings for cover crops. The in-season application of bentazon also resulted in acceptable damage ratings for the cover crop species. Pyrosulam had varying impacts on clovers and alfalfa. For clovers, a severe rating was observed, whereas an acceptable rating

was observed in alfalfa, which was unexpected. As phacelia had not been previously exposed to or evaluated for tolerance to the herbicides used in this experiment, its response was uncertain. Following the in-season application, tralkoxydim and bentazon were tolerated by phacelia, whereas pyroxsulam resulted in a severe injury.

The yield of the wheat crop was not impacted by herbicides or the herbicide frequency and remained consistent among treatments. This could be explained by similar weed pressure experienced among treatments. The weed density was statistically similar to the no-herbicide control when treated with all three in-season herbicides. The only difference observed in weed pressure was a decrease in weed biomass following an in-season application of pyroxsulam, whereas bentazon and talkoxydim applications resulted in weed biomass similar to the no-herbicide control.

When it comes to identifying a herbicide strategy that supports cover crop growth while minimizing potential wheat yield losses from weed pressure, in-season herbicides are required. The selection of in-season herbicide used will depend on the cover crop species utilized as an intercrop. If the cover crop species are broadleaf species, such as alfalfa, clovers, and phacelia, bentazon and tralkoxydim resulted in the lowest injury, reduced weed biomass, and the highest cover crop biomass.

Considerable challenges were observed in this study and correspond to experiences by early adopters of cover cropping on the Canadian Prairies. Cover crop establishment and biomass accumulation varied across years and locations, driven by climatic and soil conditions. Cover crop establishment was increased in 2023, due to an increase in seeding rate and an alternate-row intercrop arrangement. Intercrop competition could also be a challenge to the success of intercropped cover crops due to the competitive nature of wheat as its shallow rooting system

depleted the available moisture which was limited due to drought conditions and resulted in mortality of the cover crop mixture.

This highlights several areas for future cover crop research in the areas of establishment method, cover crop species, and herbicide use. Additional experiments are needed to determine the best seeding configuration for intercropped cover crops, taking into account whether the cover crops should be established in mixed rows with wheat or alternating rows, and the optimal row spacing. Though the failure of cover crops to establish at both locations of this study in 2022 could be attributed to the low seeding rate, further experiments need to be conducted to evaluate the relative importance of seeding rates versus row arrangement. Seeding methods should also be explored to determine if broadcasting cover crops into wheat is a feasible practice to establish cover crops following in-season herbicide applications if selective herbicides are used.

A greater range of cover crop species should also be evaluated for their ability to be intercropped within wheat. This experiment examined six cover crop species within a mixture. Thus, individual evaluation should be conducted with a wider range of broadleaf and brassica species to determine optimal intercrop mixtures. On the Canadian Prairies, special consideration should be taken to pea, hairy vetch, radish, and turnip as they were identified as the most commonly utilized species in the 2020 Prairie Cover Crop Survey (Morrison & Lawley, 2021) and are potentially complimentary to the wheat cash crop.

Within this study, three non-residual selective herbicides were evaluated. Further experiments are needed to screen a wider range of cover crop species, including clovers, alfalfa, and phacelia, for tolerance to commonly used in-season herbicides for spring wheat. A further range of herbicide groups should be considered during this screening. It would be important to include commonly used herbicides with residual activity for weed control in wheat on the

Canadian Prairies. Additionally, pre-emergence weed management strategies should be evaluated to determine their effects on the establishment of cover crops.

Although challenges were experienced during this study, this experiment is the first of its kind, evaluating the intercropping of cover crops into spring wheat on the Canadian Prairies. The challenges to establish cover crops and to get them to persist within a wheat canopy were identified as key areas of agronomic research that are needed for advancing the practice.

5.0 GENERAL DISCUSSION AND CONCLUSIONS

This research was conducted to provide agronomic information about the intercropping of cover crops into two of the most abundant crops on the Canadian Prairies. Weed management is one of the most important agronomic decisions producers make to optimize crop yield in wheat and canola crops. The lack of regionally specific research on how intercropped cover crops intersect with herbicidal weed management remains as a barrier to the adoption of the practice. Despite this challenge, cover crop adoption is increasing, and producers are turning to intercropping as a strategy to maximize the benefits received from cover crops.

The evaluation of cover crops intercropped within wheat or canola showed contrasting results. In both years of the study, cover crops were successfully established and produced biomass at both locations when intercropped with canola. However, when it came to intercropping with wheat, establishment and biomass production only occurred in the second year of the study. Despite using the same seeding rates in the wheat and canola experiment, cover crop establishment and biomass production were always greater within the canola experiment, even within the treatments which received no in-season herbicides when seeded in alternating rows. Superior performance of the intercropped cover crops with canola over wheat can be attributed to the differences between brassica and grass species. Grass species are more competitive during the seedling stage, with their rapid establishment that could have outcompeted the cover crop seedlings compared to the less competitive tap-rooted canola. Even in an alternate-row arrangement, the fibrous rooting system of wheat outcompeted the cover crop species. This may have been attributed to competition for soil moisture in the surface soil layers, however future research is needed to evaluate the impact of cover crops on soil moisture on the Canadian Prairies.

The greater cover crop establishment and the resulting biomass accumulation, however, had negative impacts on canola. Yield penalties were observed when no in-season herbicides were applied in canola. The observed reductions in canola yield could also be attributed to the limited weed suppressive ability of the cash and cover crops. In the canola experiment, cover crops did not provide any weed suppression and decreases in weed biomass and density were instead attributed to the in-season herbicide use, which were necessary to maintain canola yield. In the wheat experiment, no yield penalties were observed. In the wheat experiment, weed biomass and density in the no herbicide control were similar to those in the in-season herbicide treatments. Due to minimal establishment of intercropped cover crops in wheat, this weed suppression is likely attributed to the competitive nature and rooting system of the wheat crop.

While the herbicide management strategies tested in this experiment show potential for cover crops intercropped with canola, the challenges faced over the experiment make it difficult to make conclusive decisions on what strategies are best suited for intercropping in wheat. These results highlight a fundamental challenge in these systems surrounding balancing effective weed control with successful cover crop establishment. Achieving adequate cover crop biomass is necessary to provide benefits such as weed suppression, however herbicide applications are needed for weed control and can restrict cover crop growth. Conversely, when cover crop biomass is sufficient, weed pressure may be reduced and can reduce the dependence on post-emergence herbicides. The challenge of getting cover crops established, as discussed in the two experiments, mirrors the experiences of the early adopters of intercropped cover crops on the Canadian Prairies. These challenges are often driven by variable environmental conditions and indicate that further research under a range of prairie growing conditions is required to identify management strategies that balance weed control with reliable cover crop establishment.

There are several areas for future cover crop research that emerged from this project. The areas include establishment methods and timings for intercropped cover crops, cover crop species, and herbicide evaluation. For example, the timing of intercropping of cover crops into annual cash crops should be further evaluated to observe if it is possible to establish a cover crop following the in-season herbicide application to minimize injury to the cover crops. Additionally, experiments are needed to determine the best seeding configuration of cash crops and cover crops in mixed rows with the annual cash crop or alternating, as well as the optimal row spacings.

A greater range of cover crop species should also be evaluated for their ability to be intercropped within annual cash crops. This experiment examined the cover crop species grown as a mixture. Individual evaluation should be conducted with a wider range of grass and broadleaf species to enable a more precise determination of optimal species as monoculture or as intercrop mixtures. On the Prairies, special consideration should be taken to evaluate pea, hairy vetch, and ryegrasses as they are identified as the most utilized species in the 2020 Prairie Cover Crop Survey (Morrison & Lawley, 2021).

Within these experiments, only a narrow range of herbicide groups were evaluated. A wider range of herbicides need to be explored as cover crops as a sole management tool for weed suppression is currently unreliable. Within pre-emergence weed management, the use of herbicides with residual activity would be important to evaluate to determine their effects on the establishment of cover crops. Additionally, herbicide screenings through the use of herbicide damage ratings should be conducted on individual cover crop species and mixtures intercropped within annual cash crops to determine their tolerance to the herbicides.

This experiment is one of the first of its kind, evaluating the intercropping of a cover crop mixture into annual cash crops on the Canadian Prairies with specific attention to herbicide interaction. This experiment shows there is promise in getting cover crops to establish and persist within annual cash crops. However, further agronomic research is needed to address the challenges that were experienced during this study.

6.0 LITERATURE CITED

- Abdalla, M., Hastings, A., Cheng, K., Yue, Q., Chadwick, D., Espenberg, M., Truu, J., Rees, R.M., & Smith, P. (2019). A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity. *Global Change Biology*, 25 (8.), 2530-2543. <https://doi.org/10.1111%2Fgcb.14644>
- Aberle, E. (2024). *Summary: timing of cover crop establishment in spring cereals*. North Dakota State University. <https://www.ndsu.edu/agriculture/sites/default/files/2025-03/24%20Timing%20of%20Cover%20Crops.pdf>
- Acton, D.F., & Gregorich, L.J. (1995). *The health of our soils: toward sustainable agriculture in Canada*. Centre for Land and Biological Resource Research.
- Adami, M.F.F., Modolo, A.J., Adami, P.F., Dutra de Moraes, P.V., Pitta, C.S.R., Rossi, P., & Batista, V.V. (2017). White clover tolerance to herbicides applied at different rates and phenological stages. *African Journal of Agricultural Research*, 12 (28.), 2336- 2341. <https://doi.org/10.5897/AJAR2016.11905>
- Adetunji, A.T., Ncube, B., Mulidzi, R., & Lewu, F.B. (2020). Management impact and benefit of cover crops on soil quality: a review. *Soil and Tillage Research*, 204, 104717. <https://doi.org/10.1016/j.still.2020.104717>
- Agriculture and Agrifood Canada. (2021). *30-year average growing degree days (GDD), base 5*. Government of Canada. <https://open.canada.ca/data/en/dataset/3b9c09f3-e5cd-41f4-a603-76ba8c7a4c60>
- Aksouh-Harradj, N.M., Campbell, L.C., & Mailer, R.J. (2006). Canola response to high and moderately high temperature stresses during seed maturation. *Canadian Journal of Plant Science*, 86 (4.), 967-980. <https://doi.org/10.4141/P05-130>
- Alberta Grains, Sask Wheat, SaskBarley, & Manitoba Crop Alliance. (2025). *Managing lodged cereal grains*. SaskWheat. <https://saskwheat.ca/managing-lodged-cereal-crops/>
- Alberta Pulse Growers (n.d.). *Lentil weed control*. Alberta Pulse Growers. <https://albertapulse.com/lentilweedcontrol/#:~:text=Resistant%20weeds%20can%20have%20a,there%20are%20limited%20herbicide%20options>

- Anderson, D.M., Swanton, C.J., Hall, J.C., & Mersey, B. (2006). The influence of temperature and relative humidity on the efficacy of glufosinate-ammonium. *Weed Research*, 33 (2.), 139-147. <https://doi.org/10.1111/j.1365-3180.1993.tb01927.x>
- Anderson, M. (2023). *Cover crop termination review for 2023*. Iowa State University Extension and Outreach. <https://crops.extension.iastate.edu/post/cover-crop-termination-review-2023>
- Anderson, R.L. (2015). Suppressing weed growth after wheat harvest with underseeded red clover in organic farming. *Renewable Agriculture and Food Systems*, 31 (3.), 185-190. <https://doi.org/10.1017/S1742170515000022>
- Anderson, R. L. (2017). Interseeding berseem clover in winter wheat. *Renewable Agriculture and Food Systems*, 3 (6.), 573-575. <https://doi.org/10.1017/S1742170517000023>
- Angadi, S.V., Cutforth, H.W., McConkey, B.G., & Gan, y. (2003). Yield adjustments by canola when grown at different plant populations under semiarid conditions. *Crop Science*, 43 (4.), 1358-1366. <https://doi.org/10.2135/cropsci2003.1358>
- Antosh, E., Liebig, M. A., Archer, D. W., & Luciano, R. (2022). Cover crop interseeding effects on aboveground biomass and corn grain yield in western North Dakota. *Crop, Forage, and Turfgrass Management*, 8 (1.), 20148. <https://doi.org/10.1002/cft2.20148>
- Asrari, E., Masoudi, M., & Afroogh, E. (2011). Analyzing spatial and temporal pattern of humid, normal and drought years using percent of normal precipitation index (PNPI) in fars province, Iran. *Journal of Applied Sciences in Environmental Sanitation*, 6 (3.), 299-308.
- Ayisi, K. K., Putnam, D. H., Vance, C. P., Russelle, M. P., & Allan, D. L. (1997). Strip intercropping and nitrogen effects on seed, oil, and protein yields of canola and soybean. *Agronomy Journal*, 89 (1.), 23-29. <https://doi.org/10.2134/agronj1997.00021962008900010004x>
- Bagg, J., Ball, B., Banks, B., Baute, T., Bohner, H., Brown, C., Cowbrough, M., Dyck, J., Ferguson, T., Follings, J., Hall, B., Hayes, A., Johnson, P., Kyle, J., McDonald, I., Moran, M. Munroe, J., Quesnel, G., Rabe, N., ... Verhallen, A. (2022). Spring and winter canola. In C. Brown et al., (Eds.), *Agronomy guide for field crops*. (pp. 157-172). Ontario Ministry of Agriculture, Food, and Rural affairs. <https://www.ontario.ca/files/2022-10/omafra-agronomy-guide-for-field-crops-en-2022-10-13.pdf>

- Bailey-Elkin, W., Carkner, M., & Entz, M.H. (2021). Intercropping organic field peas with barley, oats, and mustard improves weed control but has variable effects on grain yield and net returns. *Canadian Journal of Plant Science*, 102 (3.), 515-528. <https://doi.org/10.1139/cjps-2021-0182>
- Bainard, J.D., Serajchi, M., Bainard, L.D., Schellenberg, M.P., & Lamb, E.G. (2020). Impact of diverse annual forage mixtures on weed control in a semiarid environment. *Frontiers in Sustainable Food Systems*, 4 (92.). <https://doi.org/10.3389/fsufs.2020.00092>
- Baraibar, B., Hunter, M.C., Schipanski, M.E., Hamilton, A., & Mortensen, D.A. (2017). Weed suppression in cover crop monoculture mixtures. *Weed Science*, 66, 121-133. <https://doi.org/10.1017/wsc.2017.59>
- Baraibar, B., Mortensen, D.A., Hunter, M.C., Barbercheck, M.E., Kaye, J.P., Finney, D.M., Curran, W.S., Bunchek, J. & White, C.M. (2018). Growing degree days and cover crop type explain weed biomass in winter cover crops. *Agronomy for Sustainable Development*, 38 (65.). <https://doi.org/10.1007/s13593-018-0543-1>
- Barthet, V.J. (2022). *Quality of western Canadian canola 2022* (Publication No. A92-14-2022-eng). Canadian Grain Commission. https://publications.gc.ca/collections/collection_2023/ccg-cgc/A92-14-2022-eng.pdf
- Barthet, V.J. (2023). *Quality of western Canadian canola 2023* (Publication No. A92-45-2023-eng). Canadian Grain Commission. https://publications.gc.ca/collections/collection_2024/ccg-cgc/A92-45-2023-eng.pdf
- BASF Canada Inc. (n.d.)a. *Basagran® Liquid Herbicide*. BASF Canada Inc. https://agriculture.basf.ca/content/dam/cxm/agriculture/canada/english/agriculture/west/products/documents/product-documents/Basagran_label.pdf
- BASF Canada Inc. (n.d.)b. *Liberty® 150 SN Herbicide*. BASF Canada Inc. https://agriculture.basf.ca/content/dam/cxm/agriculture/canada/english/agriculture/west/products/documents/product-documents/Liberty150SN_Product_Label.pdf
- Basu, S., Sauchyn, D.J., & Anis, M.R. (2020). Hydrological extremes in the Canadian Prairies in the last decade due to the ENSO teleconnection- a comparative case study using WRF. *Water*, 12 (11.), 2970. <https://doi.org/10.3390/w12112970>

- Bayer Cropscience Inc. (2020). *Roundup WeatherMAX® with transorb 2 technology liquid herbicide*. Bayer Cropscience Inc. https://www.cropscience.bayer.ca/-/media/Bayer-CropScience/Country-Canada-Internet/Products/Roundup-WeatherMAX/27487_LE-Change_WeatherMax_ENG_Label_12-13-21_ac.ashx
- Bayer Group. (n.d.). *Understanding Cereal Herbicide Modes of Action*. Bayer Crop Science. <https://www.cropscience.bayer.ca/articles/mix-it-up/understanding-cereal-herbicide-modes-of-action>
- Beck, L., Marsalis, M., & Lauriault, L. (2017). *Managing weeds in alfalfa*. New Mexico State University Cooperative Extension Service. <https://lubbock.tamu.edu/files/2018/03/Managing-Weeds-in-Alfalfa-NMSU-2017-A-325.pdf>
- Beckie, H.J., Johnson, E.N., Blackshaw, R.E., & Gan, Y. (2008). Productivity and quality of canola and mustard cultivars under weed competition. *Canadian Journal of Plant Science*, 88 (2.), 367-372. <https://doi.org/10.4141/CJPS07152>
- Belfry, K.D., & Van Eerd, L.L. (2016). Establishment and impact of cover crops intersown into corn. *Crop Science*, 56 (3.), 1245-1256. <https://doi.org/10.2135/cropsci2015.06.0351>
- Bennett, C. (2021). *Intercropping gains more interest from US farmers*. AgWeb. <https://www.agweb.com/news/crops/crop-production/intercropping-gains-more-interest-us-farmers>
- Bich, A.D., Reese, C., Kennedy, A.C., & Clay, D.E. (2014). Corn yield is not reduced by mid-season establishment of cover crops in Northern Great Plains environments. *Crop Management*, 13 (1.). <https://doi.org/10.2134/CM-2014-0009-RS>
- Blackshaw, R.E. (2008). Agronomic merits of cereal cover crops in dry bean production systems in western Canada. *Crop Protection*, 27 (2.), 208-214. <https://doi.org/10.1016/j.cropro.2007.05.006>
- Blackshaw, R.E., Molnar, L.J., & Moyer, J.R. (2010). Suitability of legume cover crop-winter wheat intercrops on the semi-arid Canadian Prairies. *Canadian Journal of Plant Science*, 90 (4.), 479-488. <https://doi.org/10.4141/CJPS10006>

- Blackshaw, R., Sowiak, V., Hall, L., Kowalchuk, N., Gabert, K., Glover, M., & Brook, H. (2020). *Herbicide action and injury*. Government of Alberta Agriculture and Forestry. <https://open.alberta.ca/dataset/091900c6-0a1e-41bc-a6e4-d740464149af/resource/826424cf-6973-44ba-a157-86bceb75fefd/download/af-herbicide-action-and-injury-2020.pdf>
- Blanco, H. (2023). Cover crops and biomass production. In H. Blanco (Eds.), *Cover Crops and Soil Ecosystem Services* (pp. 12-34). ASA, CSSA, and SSSA. <https://doi.org/10.1002/9780891186403.ch2>
- Blanco-Canqui, H. (2013). Crop residue removal for bioenergy reduces soil carbon pools: how can we offset carbon losses? *Bioenergy Research*, 6, 358-371. <https://doi.org/10.1007/s12155-012-9221-3>
- Blanco-Canqui, H. & Jasa, P.J. (2019). Do grass and legume cover crops improve soil properties in the long term? *Soil Science Society of America Journal*, 83 (4.), 1181-1187. <https://doi.org/10.2136/sssaj2019.02.0055>
- Blanco-Canqui, H. & Ruis, S.J. (2020). Cover crop impacts on soil physical properties: a review. *Soil Science Society of America Journal*, 84 (5.), 1527-1576. <https://doi.org/10.1002/saj2.20129>
- Blanco-Canqui, H., Holman, J.D., Schlegel, A.J., Tatarko, J., & Shaver, T.M. (2013). Replacing fallow with cover crops in a semiarid soil: effects on soil properties. *Soil Science Society of America Journal*, 77 (3.), 1026-1034. <https://doi.org/10.2136/sssaj2013.01.0006>
- Blanco-Canqui, H., Ruis, S.J., Koehler-Cole, K., Elmore, R.W., Francis, C.A., Shapiro, C.A., Proctor, C.A., & Ferguson, R.B. (2023). Cover crops and soil health in rainfed irrigated corn: what did we learn after 8 years? *Soil Science Society of America Journal*, 87 (5.), 1174-1190. <https://doi.org/10.1002/saj2.20566>
- Blanco-Canqui, H., Shaver, T.M., Lindquist, J.L., Shapiro, C.A., Elmore, R.W., Francis, C.A., & Hergert, G.W. (2015). Cover crops and ecosystem services: insights from studies in temperate soils. *Agronomy Journal*, 107 (6.), 2449-2474. <https://doi.org/10.2134/agronj15.0086>
- Blaser, B.C., Gibson, L.R., Singer, J.W., & Jannick, J. (2006). Optimizing seeding rates for winter cereal grains and frost-seeded red clover intercrops. *Agronomy Journal*, 98 (4.), 1041-1049. <https://doi.org/10.2134/agronj2005.0340>

- Blaser, B.C., Singer, J.W., & Gibson, L.R. (2011). Winter cereal canopy effect on cereal and interseeded legume productivity. *Agronomy Journal*, 103 (4.), 1180-1185. <https://doi.org/10.2134/agronj2010.0506>
- Bodah, B.W., Ullman, J.L., Mccool, D. (2011, September 18-21). *Impacts of chemical fallow practices in conservation tillage management systems on runoff and erosion in the pacific northwest* [Paper presentation]. 2011, International Symposium on Erosion and Landscape Evolution, Anchorage, AK. <https://doi.org/10.13031/2013.39249>
- Bogdan, J. (2023). *Herbicide injury in pulse crops*. Saskatchewan Pulse Growers. <https://saskpulse.com/resources/herbicide-injury-in-pulse-crops/?download-pdf>
- Bonanomi, G., Sicurezza, M.C., Caporaso, S., Esposito, A., & Mazzoleni, S. (2005). Phytotoxicity dynamics of decaying plant materials. *The New Phytologist*, 169 (3.), 571-578. <https://doi.org/10.1111/j.1469-8137.2005.01611.x>
- Bourgault, M., Wyffels, S.A., Dafoe, J.M., Lamb, P.F., & Boss, D.L. (2021). Introducing cover crops as a fallow replacement in the norther great plains: II. Impact on following wheat crop. *Renewable Agriculture and Food Systems*, 37 (4.), 303-312. <https://doi.org/10.1017/S1742170521000508>
- Bourgeois, B., Charles, A., Van Erd, L.L., Tremblay, N., Lynhc, D., Bourgeois, G., Bastien, M., Bélanger, V., Landry, C., & Vanasse, A. (2022). Interactive effects between cover crop management and the environment modulate benefits to cash crop yields: a meta-analysis. *Canadian Journal of Plant Science*, 102, 656-678. <https://doi.org/10.1139/cjps-2021-0177>
- Bowren, K.E., Cooke, D.A., & Downey, R.K. (1969). Yield of dry matter and nitrogen from tops and roots of sweetclover, alfalfa and red clover at five stages of growth. *Canadian Journal of Plant Science*, 49, 61-68. <https://doi.org/10.4141/cjps69-007>
- Brandler, D., Galon, L., Mossi, A.J., Pilla, T.P., Tonin, R.J., Forte, C.T., Bianchessi, F., de Oliveira Rossetto, E.R., & Tironi, S.P. (2021). Weed interference in canola. *Communications in Plant Sciences*, 11, 1-8. <https://doi.org/10.26814/cps2021001>
- Brandsæter, L.O., Netland, J. & Meadow, R. (1998). Yields, weeds, pests and soil nitrogen in a white cabbage–living mulch system. *Biological Agriculture & Horticulture*, 16 (3.), 291–309. <https://doi.org/10.1080/01448765.1998.10823201>

- Brhel, J., Elmore, E., Proctor, C., Melvin, S., & Sindelar. (2019). *Interseeding cover crops into corn or soybean*. University of Nebraska-Lincoln. <https://cropwatch.unl.edu/2019/interseeding-cover-crops-corn-or-soybean/>
- Brooker, A.P., Renner, K.A., & Sprague, C.L. (2020). Interseeding cover crops in corn. *Agronomy Journal*, 112 (1.), 139-147. <https://doi.org/10.1002/agj2.20046>
- Brooker, R.W., Bennett, A.E., Cong, W.F., Daniell, T.J., George, T.S., Hallett, P.D., Hawes, C., Iannetta, P.P.M., Jones, H.G., Karley, A.J., Li, L., McKenzie, B.M., Pakeman, R.J., Paterson, E., Schöb, C., Shen, J., Squire, G., Watson, C.A., White, P.J., ... Zhang, J. (2014). Improving intercropping: a synthesis of research in agronomy, plant physiology, and ecology. *New Phytologist*, 206 (1.), 107-117. <https://doi.org/10.1111/nph.13132>
- Bressler, A., & Blesh, J. (2023). A grass-legume cover crop maintains nitrogen inputs and nitrous oxide fluxes from an organic agroecosystem. *Ecosphere*, 14 (2.). <https://doi.org/10.1002/ecs2.4428>
- Bunckek, J.M., Wallace, J.M., Curran, W.S., Mortensen, D.A., VanGessel, M.J., & Scott, B.A. (2020). Alternative performance targets for integrating cover crops as a proactive herbicide-resistance management tool. *Weed Science*, 68 (5.), 534-544. <https://doi.org/10.1017/wsc.2020.49>
- Butler, T.J., Celen, A.E., Webb, S.L., Krstic, D., & Interrante, S.M. (2014). Temperature affects the germination of forage legume seeds. *Crop Science*, 54 (6.), 2846-2853. <https://doi.org/10.2135/cropsci2014.01.0063>
- Bybee-Finley, K.A. & Ryan, M.R. (2018). Advancing intercropping research and practices in industrialized agricultural landscapes. *Agriculture*, 8 (6.). <https://doi.org/10.3390/agriculture8060080>
- Campanelli, G., Iocola, I., Leteo, F., Montemurro, F., Platani, C., Testani, E., & Canali, S. (2023). Strip cropping in organically managed vegetable systems: agronomic and environmental effects. *Renewable Agriculture and Food Systems*, 38. <https://doi.org/10.1017/S1742170523000248>
- Canadian Environmental Review Agency. (n.d.). *Environmental Review of Prairie Grain Road Projects*. Government of Canada. <https://ceaa-acee.gc.ca/050/documents/2215/2215E.pdf>

- Canadian Grains Commission. (2023). *Quality of Canada western red spring wheat in 2023*. Government of Canada. <https://www.grainscanada.gc.ca/en/grain-research/grain-harvest-export-quality/wheat/2023/Canada-western-red-spring/>
- Canadian Weed Science Society. (2018). *Description of 0-100 rating scale for herbicide efficacy and crop phytotoxicity*. https://weedscience.ca/cwss_scm-rating-scale/
- Canevari, M., Vargas, R.N., & Orloff, S.B. (2007). Weed management in alfalfa. In C.G. Summers & D.H. Putnam (Eds.), *Irrigated alfalfa management for mediterranean and desert zones*. Chapter 8. University of California Agriculture and Natural Resources.
- Canola Council of Canada (n.d.). *Canadian canola production statistics*. Canola Council of Canada. <https://www.canolacouncil.org/biotech/about-canola/herbicide-tolerant-canola>
- Canola Council of Canada (2016). *Herbicide tolerant canola*. Canola Council of Canada. <https://www.canolacouncil.org/biotech/about-canola/herbicide-tolerant-canola>
- Canola Council of Canada (2019). *What to do with uneven fields*. Canola Council of Canada. <https://www.canolacouncil.org/canola-watch/2019/07/31/what-to-do-with-uneven-fields/>
- Carlyle, W.J. (1997). The decline of summerfallow on the Canadian Prairies. *Canadian Geographies*, 41 (3.), 267-280. <https://doi.org/10.1111/j.1541-0064.1997.tb01313.x>
- Carr, P. M., Gardner, B. G., Schatz, S. W., Zwinger, S. F, & Guldan, S. J. (1995). Grain yield and weed biomass of a wheat-lentil intercrop. *Agronomy Journal*, 87, 574-579.
- Caswell, K., Wallace, J.M., Curran, W.S., Mirsky, S.B., & Ryan, M.R. (2019). Cover crop species and cultivars for drill-interseeding in mid-atlantic corn and soybean. *Agronomy Journal*, 111 (3.), 1060-1067. <https://doi.org/10.2134/agronj2018.08.0511>
- Ceballos, R., Palma, G., Brevis, H., Ortega, F., & Quiroz, A. (2004). Effect of five postemergence herbicides on red clover shoot and root growth in greenhouse studies. *Phytoprotection*, 85 (3.), 153-160. <https://doi.org/10.7202/010907ar>

- Ceballos, R., Cofre, X., Quiroz, A., Espinoza, N., & Palma, G. (2009). Bentazon-MCPA effect on fusarium oxysporum root rot on trifolium pratense in greenhouse conditions. *Revista de la Ciencia del Suelo y Nutrición Vegetal*, 9 (2.), 142-154. <https://dx.doi.org/10.4067/S0718-27912009000200006>
- Chahal, I., Vyn, R.J., Mayers, D., & Van Erd, L.L. (2020). Cumulative impact of cover crops on soil carbon sequestration and profitability in a temperate humid climate. *Scientific Reports*, 10, 13381. <https://doi.org/10.1038/s41598-020-70224-6>
- Chatterjee, A., & Clay, D.E. (2016). Cover crop impacts on nitrogen scavenging, nitrous oxide emissions, nitrogen fertilizer replacement, erosion, and soil health. In A. Chatterjee & D. E. Clay (Eds.), *Soil Fertility Management in Agroecosystems* (pp. 76-88). ASA, CSSA, and SSSA. <https://doi.org/10.2134/soilfertility>
- Chen, G. & Weil, R.R. (2010). Penetration of cover crop roots through compacted soil. *Plant and Soil*, 331, 31-43. <https://doi.org/10.1007/s11104-009-0223-7>
- Chu, L., Gao, Y., Chen, L., McCullough, P.E., Jespersen, D., Sapkota, S., Bagavathiannan, M., & Yu, J. (2022). Impact of environmental factors on seed germination and seed emergence of white clover (*Trifolium repens* L.). *Agronomy Journal*, 12 (1.), 190. <https://doi.org/10.3390/agronomy12010190>
- Clark, A. (2007). *Managing Cover Crops Profitably (3rd ed.)*. Sustainable Agriculture Research and Education.
- Clark, J.C. (2018). *Opportunities for the inclusion of cover crops in the corn-soybean rotation in Ontario*. [Master's thesis, University of Guelph]. The Atrium. <https://atrium.lib.uoguelph.ca/items/b508da3a-107d-4f5f-bb87-75a04b20307e>
- Clark, J. (2024). *Mixing up grains: variety blends, diverse populations & maslins*. Ecological Farmers Association of Ontario. <https://efao.ca/mixed-up-grains-variety-blends-diverse-populations-maslins/>
- Coetzer, E., Al-Khatib, K., & Loughin, T.M. (2001). Glufosinate efficacy, absorption, and translocation in amaranth as affected by relative humidity and temperature. *Weed Science*, 49, 8-13. [https://doi.org/10.1614/0043-1745\(2001\)049\[0008:GEAATI\]2.0.CO;2](https://doi.org/10.1614/0043-1745(2001)049[0008:GEAATI]2.0.CO;2)

- Colquhoun, J., Mallory-Smith, C., & Ball, D. (2003). *Weed management in Clearfield™ wheat with imazamox*. Oregon State University Extension Service. <https://agsci.oregonstate.edu/sites/agscid7/files/cbarc/attachments/em8833.pdf>
- Corteva Agriscience. (n.d.)a. *Ares™ SN Herbicide*. Corteva Agriscience Canada Company. <https://www.corteva.ca/content/dam/dpagco/corteva/na/ca/en/files/products/label/DF-Ares-SN-Herbicide-Label-English.pdf>
- Corteva Agriscience. (n.d.)b. *Liquid Achieve™ SC Herbicide*. Corteva Agriscience Canada Company. <https://www.corteva.ca/content/dam/dpagco/corteva/na/ca/en/files/products/label/DF-Liquid-Achieve-SC-Herbicide-Label-English.pdf>
- Corteva Agriscience. (n.d.)c. *Simplicity™ SN Herbicide*. Corteva Agriscience Canada Company. <https://www.corteva.ca/content/dam/dpagco/corteva/na/ca/en/files/products/label/DF-Simplicity-Herbicide-Label-English.pdf>
- Cotrufo, M.F., Wallenstein, M.D., Boot, C.M., Deneff, K., & Paul, E. (2013). The microbial efficiency-matrix stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: do labile plant inputs form stable soil organic matter? *Global Change Biology*, *19*, 988-995. <https://doi.org/10.1111/gcb.12113>
- Crop Protection Network. (n.d.). Herbicide injury in alfalfa. Crop Protection Network. <https://cropprotectionnetwork.org/encyclopedia/herbicide-injury-in-alfalfa>
- Cruse, R.M. & Gilley, J.E. (2008). *Strip intercropping: a CRP conversion option*. Leopold Center. <https://www.leopold.iastate.edu/files/pubs-and-papers/2008-06-strip-intercropping-crp-conversion-option.pdf>
- Dear, B.S., Sandral, G.A., Wilson, B.C.D. (2006). Tolerance of perennial pasture grass seedlings to pre- and post-emergent grass herbicides. *Animal Production Science*, *46* (5.), 637-644. <https://doi.org/10.1071/EA04173>
- De Bruin, J.L., Porter, P.M., & Jordan, N.R. (2005). Use of a rye cover crop following corn in rotation with soybean in the upper Midwest. *Agronomy Journal*, *97* (2.), 587-598. <https://doi.org/10.2134/agronj2005.0587>

- De Notaris, C., Rasmussen, J., Sorensen, P., Melander, B., & Eivind, J.E. (2019). Manipulating cover crop growth by adjusting sowing time and cereal inter-row spacing to enhance residual nitrogen effects. *Field Crops Research*, 234, 15-25. <https://doi.org/10.1016/j.fcr.2019.02.008>
- Deines, J.M., Guan, K., Lopez, B., Zhou, Q., White, C.S., Wang, S., & Lobell, D.B. (2022). Recent cover crop adoption is associated with small maize and soybean yield losses in the United States. *Global Change Biology*, 29 (3.), 794-807. <https://doi.org/10.1111/gcb.16489>
- Dickson, T.J. (2014). *Growing season weather impacts on canola phenological development and quality*. [Master's thesis, university of Manitoba]. Mspace. <https://mspace.lib.umanitoba.ca/server/api/core/bitstreams/55c7ef30-9f83-4de0-8893-4a060c649db/content>
- Dong, F. & Zeng, W. (2024). Effects of fall and winter cover crops on weed suppression in the United States: a meta-analysis. *Sustainability*, 16 (8.), 3192. <https://doi.org/10.3390/su16083192>
- Doran, J. W. (2002). Soil health and global sustainability: translating science into practice. *Agriculture, Ecosystems, and Environment*, 88 (2.), 119-127. [https://doi.org/10.1016/S0167-8809\(01\)00246-8](https://doi.org/10.1016/S0167-8809(01)00246-8)
- Drost, S.M., Rutgers, M., Wouterse, M., de Boer, W., Bodelier, P.L.E. (2020). Decomposition of mixtures of cover crop residues increases microbial functional diversity. *Geoderma*, 361. <https://doi.org/10.1016/j.geoderma.2019.114060>
- Duan, J.K. (2006). Quality of canola (*Brassica napus* L.) varieties in western Canada: evaluation of variability due to genetic, year, and environmental conditions using data from Canadian grain commission harvest surveys and from environmental Canada meteorological stations. In T. Fu & C. Guan (Eds.), *Proceedings of the 12 International Rapeseed Congress, Wuhan, China: Sustainable Development in Cruciferous Oilseed Crops Production* (pp 10-15).
- Ehrmann, J., & Ritz, K. (2014). Plant soil interactions in temperate multi-cropping production systems. *Plant and Soil*, 376, 1-29. <https://doi.org/10.1007/s11104-013-1921-8>

- Eley, R. (2006). Effects of GF-1674 on the Vegetative Vigour of Non-Target Terrestrial Plants (Tier I) - 2005, Dow AgroSciences, unpublished report No. ACE-05-214, 27 June 2006 https://www3.epa.gov/pesticides/chem_search/cleared_reviews/csr_PC-108702_3-May-08_y.pdf
- Elferjani, R. & Soolanayakanahally, R. (2018). Canola Responses to Drought, Heat, and Combined Stress: Shared and Specific Effects on Carbon Assimilation, Seed Yield, and Oil Composition. *Frontiers in Plant Science*, 9, 1224. <https://doi.org/10.3389/fpls.2018.01224>
- Elferjani, R., Pahari, S., Soolanayakanahally, R., Ballantyne, K., Nambara, E. (2024). Drought induced metabolic shifts and water loss mechanisms in canola: role of cysteine, phenylalanine and aspartic acid. *Frontiers in Plant Science*, 15. <https://doi.org/10.3389/fpls.2024.1385414>
- Enache, A.J. & Ilnicki, R.D. (1990). Weed control by subterranean clover (*Trifolium subterraneum*) used as a living mulch. *Weed Technology*, 4 (3.), 534-538. <https://doi.org/10.1017/S0890037X00025926>
- Enloe, S.F., Johnson, J., Renz, M., Dorough, H., & Tucker, K. (2014). Hairy buttercup control and white clover tolerance to pasture herbicides. *Forage and Grazinglands*, 12 (1). <https://doi.org/10.2134/FG-2013-0013-RS>
- Entz, M.H. & Fowler, D.B. (1991). Agronomic performance of winter versus spring wheat. *Agronomy Journal*, 83 (3.), 527-532. <https://doi.org/10.2134/agronj1991.00021962008300030002x>
- Environment and Climate Change Canada. (n.d.). *Canadian climate normals*. Government of Canada. https://climate.weather.gc.ca/climate_normals/index_e.html
- Everman, W., & Anderson, M. (2025). *Herbicides and variable weather*. Iowa State University Extension and Outreach. <https://crops.extension.iastate.edu/post/herbicides-and-variable-weather>
- Evers, G.W., Grichar, W.J., Pohler, C.L., Schuber, A.M. (1993). Tolerance of Three Annual Forage Legumes to Selected Postemergence Herbicides. *Weed Technology*, 7 (3.), 735-739. <https://doi.org/10.1017/S0890037X00037623>

- Feng, X., Alletto, L., Cong, W., Labreuche, J., & Lamichhane, J.R. (2024). Strategies to improve field establishment of cover crops. A review. *Agronomy for Sustainable Development*, 44 (47.). <https://doi.org/10.1007/s13593-024-00986-0>
- Feike, T., Doluschitz, R., Cehn, Q., Graeff-Hönninger, S., & Claupein, W. (2012). How to overcome the slow death of intercropping in the north China plain. *Sustainability*, 4 (10.), 2550-2565. <https://doi.org/10.2290/su4102550>
- Fernando, M. & Shrestha, A. (2023). The potential of cover crops for weed management: a sole tool or component of an integrated management system? *Plants (Basel)*, 12 (4.), 752. <https://doi.org/10.3390/plants12040752>
- Fisher, K.A., Momen, B., & Kratochvil, R.J. (2011). Is broadcasting seed and effective winter cover crop planting method? *Agronomy Journal*, 103 (2.), 472-478. <https://doi.org/10.2134/agronj2010.0318>
- Fletcher, A. L., Kirkegaard, J. A., Peoples, M. B., Robertson, M. J., Whish, J., & Swan, A. D. (2016). Prospects to utilise intercrops and crop variety mixtures in mechanised, rain-fed, temperate cropping systems. *Crop & Pasture Science*, 67, 1252-1267. <http://dx.doi.org/10.1071/CP16211>
- Flood, H.E., & Entz, M.H. (2009). Effects of wheat, triticale and rye plant extracts on germination of navy bean (*Phaseolus vulgaris*) and selected weed species. *Canadian Journal of Plant Science*, 89 (5.), 999-1002. <https://doi.org/10.4141/CJPS09014>
- Food and Water Wellness Foundation. (2024). *Producer perspectives on barriers to the adoption of regenerative agriculture on the Canadian Prairies*. Nature United. <https://www.natureunited.ca/content/dam/tnc/nature/en/documents/Barriers-to-Adoption-Report.pdf>
- Frank, K., Gelderman, R., & Beegle, D. (2011). Phosphorus. In M.V. Nathan & R.H. Gelderman (Eds.), *Recommended Chemical Soil Test Procedures for the North Central Region* (pp 17-21). North Central Regional Research. https://www.canr.msu.edu/uploads/234/68557/rec_chem_soil_test_proce55c.pdf
- Fraser, J., Moyer, J.R., Topinka, A.K., & McCartney, D. (2003). Tolerance of annual forage legumes to herbicides in Alberta. *Canadian Journal of Plant Science*, 83, 649-652. <https://doi.org/10.4141/P02-108>

- Frey, J. & Thiessen Martens, J. (2024). *Establishment of annual crop-living mulch system* [Poster presentation]. 2024 Manitoba Agronomist Conference. Winnipeg, MB, Canada. <https://umanitoba.ca/agricultural-food-sciences/sites/agricultural-food-sciences/files/2023-12/FREY%2C%20JESSICA%20-%20POSTER%20PDF.pdf>
- Frye, W.W. Blevins, R.L., Smith, M.S., Corak, S.J., & Varco, J.J. (1988). Role of annual legume cover crops in efficient use of water and nitrogen. In W.L. Hargrove (Ed.), *Cropping Strategies for Efficient Use of Water and Nitrogen* (pp. 129-154). American Society of Agronomy. <https://doi.org/10.2134/asaspecpub51.c8>
- Garand, M.J., Simard, R.R., MacKenzie, A.F., & Hamel, C. (2001). Underseeded clover as a nitrogen source for spring wheat on a gleysol. *Canadian Journal of Soil Science*, 81 (1.), 93-102. <https://doi.org/10.4141/S99-060>
- Garnett, E.R., & Khandekar, M.L. (2017). Weather and climate extremes on the Canadian Prairies: an assessment with a focus on grain production. *Environment and Ecology Research*, 5 (4.), 255-268. <https://doi.org/10.13189/eer.2017.050402>
- Gaudin, A.M.C., Westra, S., Loucks, C.E.S., Janovicek, K., Martin, R.C., & Deen, W. (2013). Improving resilience of northern field crop systems using inter-seeded red clover: a review. *Agronomy*, 3 (1.), 148-180. <https://doi.org/10.3390/agronomy3010148>
- Gbur, E.E., Stroup, W.W., McCarter, K.S., Durham, S., Young, L.J., Christman, M., West, M., & Kramer, M. (2012). More complex examples. In W. Dick et al. (Eds.), *Analysis of generalized linear mixed models in the agricultural and natural resources sciences* (pp. 199-237). ASA, CSSA, and SSSA. <https://doi.org/10.2134/2012.generalized-linear-mixed-models.c6>
- Geddes, C.M., & Gulden, R.H. (2021). Wheat and cereal rye inter-row living mulches interfere with early season weeds in soybeans. *Plants*, 10 (11.), 2276. <https://doi.org/10.3390/plants10112276>
- Gelderman, R., & Beegle, D. (2011). Nitrate-nitrogen. In M.V. Nathan & R.H. Gelderman (Eds.), *Recommended Chemical Soil Test Procedures for the North Central Region* (pp. 17-21). North Central Regional Research. https://www.canr.msu.edu/uploads/234/68557/rec_chem_soil_test_proce55c.pdf

- Glaze-Corcoran, S., Hashemi, M., Sadeghpour, A., Afshar, R.K., Liu, X., & Herbert, S.J. (2020). Chapter five- understanding intercropping to improve agricultural resiliency and environmental sustainability. In D.L. Sparks (Ed.), *Advances in Agronomy*, 162 (pp.199-256). Academic Press. <https://doi.org/10.1016/bs.agron.2020.02.004>
- Government of Manitoba. (n.d.)a. *Tips for improving forage establishment success*. Agriculture. <https://www.gov.mb.ca/agriculture/crops/crop-management/forages/print,tips-for-improving-forage-establishment-success.html>
- Government of Manitoba. (n.d.)b. *What is the extent of crop damage from the heavy rains?* Agriculture. <https://www.gov.mb.ca/agriculture/crops/crop-management/print,extent-of-crop-damage-from-heavy-rains.html>
- Government of Ontario. (2022). *Red clover haylage*. Rural and North. <https://www.ontario.ca/page/red-clover-haylage>
- Government of Saskatchewan. (n.d.). *Soil improvements with legumes*. Government of Saskatchewan. <https://www.saskatchewan.ca/business/agriculture-natural-resources-and-industry/agribusiness-farmers-and-ranchers/crops-and-irrigation/soils-fertility-and-nutrients/soil-improvements-with-legumes>
- Greenland, R.G. (2004). *Herbicide screening for vegetables and living mulches*. North Dakota State University. <https://www.ag.ndsu.edu/oakes/2004Report/hrbscreen04rpt.htm#HERBICIDE>
- Groff, S. (2015). The past, present, and future of the cover crop industry. *Journal of Soil and Water Conservation*, 70 (6.), 130A-133A. <https://doi.org/10.2489/jwsc.70.6.130a>
- Gu, C., Bastiaans, L., Anten, N.P.R., Makowski, D., & van der Werf, W. (2021). Annual intercropping suppresses weeds: a meta-analysis. *Agriculture, Ecosystems, & Environment*, 322, 107658. <https://doi.org/10.1016/j.agee.2021.107658>
- Guardia, G., Abalos, D., García-Marco, S.m Quemada, N., Alonso-Ayuso, M., Cárdenas, L.M., Dixon, E.R., & Vallejo, A. (2016). Effect of cover crops on greenhouse gas emissions in an irrigated field under integrated soil fertility management. *Biogeosciences*, 13 (18.), 5245-5257. <https://doi.org/10.5194/bg-13-5245-2016>

- Guenther, L. (2018). *Ins and outs of intercropping*. Grainnews. <https://www.grainnews.ca/features/ins-and-outs-of-intercropping/>
- Gunasekera, C.P., Martin, L.D., Siddique, K.H.M., & Walton, G.H. (2006). Genotype by environment interactions of Indian mustard (*Brassica juncea* L.) and canola (*Brassica napus* L.) in Mediterranean-type environments: II. Oil and protein concentrations in seed. *European Journal of Agronomy*, 25 (1.), 13-21. <https://doi.org/10.1016/j.eja.2006.02.001>
- Gunsolus, J.L. & Curran, W.S. (1999). Herbicide mode of action and injury symptoms. North Central Regional Extension. [https://appliedweeds.cfans.umn.edu/sites/appliedweeds.cfans.umn.edu/files/202204/herbicide mode of action and injury symptoms.pdf](https://appliedweeds.cfans.umn.edu/sites/appliedweeds.cfans.umn.edu/files/202204/herbicide%20mode%20of%20action%20and%20injury%20symptoms.pdf)
- Haramoto, E.R. & Gallandt, E.R. (2004). Brassica cover cropping for weed management: a review. *Renewable Agriculture and Food Systems*, 19 (4.), 187-198. <https://doi.org/10.1079/RAFS200490>
- Haramoto, E.R. & Gallandt, E.R. (2005). Brassica cover cropping: I. effects on weed and crop establishment. *Weed Science*, 53 (5.), 695-701. <https://doi.org/10.1614/WS-04-162R.1>
- Harker, K.N., Blackshaw, R.E., Kirkland, K.J., Derksen, D.A., & Wall, D. (2000). Herbicide-tolerant canola: weed control and yield comparisons in western Canada. *Canadian Journal of Plant Science*, 80 (3.), 647-654. <https://doi.org/10.4141/P99-149>
- Harker, K.N., Clayton, G.W., O'Donovan, J.T., Blackshaw, R.E., & Stevenson, F.C. (2004). Herbicide timing and rate effects on weed management in three herbicide-resistant canola systems. *Weed Technology*, 18 (4.), 1006-1012. <https://doi.org/10.1614/WT-03-188R1>
- Haruna, S.I., Anderson, S.H., Udawatta, R.P., Gantzer, C.J., Phillips, N.C., Cui, S., & Gao, Y. (2020). Improving soil physical properties through the use of cover crops: a review. *Agrosystems, Geosciences & Environment*, 3 (1.), 20105. <https://doi.org/10.1002/agg2.20105>
- Hashemi, M., Farsad, A., Sadeghpour, A., Weis, S. A., & Herbert, S. J. (2013). Cover-crop seeding-date influence on fall nitrogen recovery. *Journal of Plant Nutrition and Soil Science*, 176 (1.), 69-75. <https://doi-org.umid.oclc.org/10.1002/jpln.201200062>

- Harvey, R.G. (1991). Bentazon for annual weed control in newly seeded alfalfa (*Medicago sativa* L.). *Weed Technology*, 5 (1.), 154-158. <https://doi.org/10.1017/S0890037X00033431>
- Hendrickson, J.R., Liebig, M.A., Archer, D.W., Schmer, M.R., Nichols, K.A., & Tanaka, D.L. (2021). Late-seeded cover crops in a semiarid environment: overyielding, dominance and subsequent crop yield. *Renewable Agriculture and Food Systems*, 36 (6.), 587-598. <https://doi.org/10.1017/S174217052100020X>
- Hijano, N., Monquero, P.A., Munhoz, W.S., & Gusmão, M.R. (2013). Herbicide selectivity in alfalfa crops. *Planta Daninha*, 31 (4.), 903-918. <https://doi.org/10.1590/S0100-83582013000400017>
- Hill, R. & Moretti, M. (2024). *Weed control during pollinator habitat establishment*. University of California. <https://ucanr.edu/blogs/blogcore/postdetail.cfm?postnum=59799>.
- Hossain, Z., Johnson, E.N., Wang, L., Blackshaw, R.E., & Gan, Y. (2019). Comparative analysis of oil and protein content and seed yield of five Brassicaceae oilseeds on the Canadian Prairies. *Industrial Crops and Products*, 136, 77-86. <https://doi.org/10.1016/j.indcrop.2019.05.001>
- Hudson, D., Mutch, D.R., Martin, T.E., Everman, W., Knorek, J., & Staton, M. (2011). *Using red clover as a cover crop in wheat*. Midwest Cover Crops. https://www.midwestcovercrops.org/wpcontent/uploads/2016/09/MI_2011_Red_clover_in_wheat_HudsonEtAl_MSU.pdf
- Hummel, J. D., Dosdall, L. M., Clayton, G. W., Turkington, C. T., Lupwayi, N. Z., Harker, K. N., & O'Donovan, J. T. (2009). Canola-wheat intercrops for improved agronomic performance and integrated pest management. *Agronomy Journal*, 101 (5.), 1190- 1197. <https://doi-org.uml.idm.oclc.org/10.2134/agronj2009.0032>
- Idowu, J., & Grover, K. (2014). *Principles of cover cropping for arid and semi-arid farming systems*. New Mexico State University. https://pubs.nmsu.edu/_a/A150.pdf
- Janzen, V.F. (2024). *Evaluation of species selection and management decisions for fall seeded cover crops in Manitoba*. [Master's thesis, University of Manitoba]. Mspace. <https://mspace.lib.umanitoba.ca/server/api/core/bitstreams/e040c2e6-5f2c-4318-a641-30161833f8a3/content>

- Janzen, V., & Lawley, Y. (2022). *Cover crops 101*. Seine Rat Roseau Watershed District. <https://srrwd.ca/wp-content/uploads/2022/05/Cover-Crops-March-2022.pdf>
- Jenks, B., Willoughby, g., Lukach, J., Menalled, F., & Davis, E. (2010). *Comparison of Desiccant Timing and Harvest Method in Canola* [Paper presentation]. 2010 ASA, CSSA, and SSSA International Annual Meeting, Long Beach, CA.
- Johnson, N., & Hansen, N. (2014). *Observation from interseeding red clover as a cover crop with barley*. [Poster presentation]. 2014 ASA, CSSA, SSSA Annual Meeting, Long Beach, CA, USA. <https://a-c-s.confex.com/crops/2014am/webprogram/Handout/Paper88024/NatalieJohnsonRedClover.pdf&ved=2ahUKEwiUnI61s6KRAxUdl4kEHZiaIrUQFnoECAIQAw&usg=AOvVaw3oeqHETThjFX3YVAecVLiA>
- Johnson, E., Ulrich, D., Blackshaw, R., & Boswell, L. (2007). *Herbicide screening in red clover and perennial ryegrass*. Saskatchewan forage seed development commission. <https://static1.squarespace.com/static/604144090e5c1277769e4535/t/60a8fe258c2e2e1f8da801a5/1621687845529/Herbicide-Screening-in-Red-Clover-and-Perennial-Ryegrass.pdf>
- Johnson II, F.E., Roth, R.T., Ruffatti, M.D., & Armstrong, S.D. (2024). Cover crop impacts on nitrogen losses and environmental damage cost. *Agriculture, Ecosystems & Environment*, 363, 108859. <https://doi.org/10.1016/j.agee.2023.108859>
- Johnston, J. & Bowman, M. (2000). *Yield of barley and canola when grown as a companion crop*. Farm North. <https://farmnorth.com/websites/farmnorth.com/images/research/Yield%20of%20Barley%20and%20Canola%20when%20Grown%20as%20a%20Companion%20Crop.pdf>
- Justes, E., Beaudoin, N., Bertuzzi, P., Charles, R., Constantin, J., Dürr, C., Joannon, A., Le Bas, C., Mary, B., Montfort, F., Ruiz, L., Sarthou, J.P., Souchère, V., & Tournebize, J. (2017). Main lessons drawn from the analysis of the literature. In E. Justes (Ed.), *Cover Crops for Sustainable Farming* (pp. 13-40). Springer. <https://doi.org/10.1007/978-94-024-0986-4>
- Kahimba, F.C., Sri Ranhan, R., Froese, J., Entz, M.H., & Nason, R. (2008). Cover crop effects on infiltration, soil temperature, and soil moisture distribution in the Canadian Prairies. *Applied Engineering in Agriculture*, 24 (3.), 321-333. <https://doi.org/10.13031/2013/24502>

- Kalil, A., Keene, C., Ostlie, M., Jacobs, J., & Shaw, L. (2023). *Intercropping for grain production in the Northern Great Plains*. North Dakota State University Extension. <https://www.ndsu.edu/agriculture/sites/default/files/2023-04/a2048.pdf>
- Kamo, T., Sato, M., Kato, K., Hiradate, S., Nakajima, E., Fujii, Y., & Hirota, M. (2006). Quantification of cyanamide contents in herbaceous plants. *Bioscience, Biotechnology, and Biochemistry*, 70 (9.), 2310-2312. <https://doi.org/10.1271/bbb.60171>
- Kandel, H.J., Samarappuli, D.P., Johnson, K.L., & Berti, M.T. (2021). Soybean relative maturity, not row spacing, affected interseeded cover crops biomass. *Agriculture*, 11 (5.). <https://doi.org/10.3390/agriculture11050441>
- Kaye, J.P. & Quemada, M. (2017). Using cover crops to mitigate and adapt to climate change. A review. *Agronomy for Sustainable Development*, 37 (4.). <https://doi.org/10.1007/s13593-016-0410-x>
- Kaye, J.P., Finney, D., White, C., Bradley, B., Schipanski, M., Alonso-Ayuso, M., Hunter, M., Burgess, M., & Mejia, C. (2019). Managing nitrogen through cover crop species selection in the U.S. mid-atlantic. *Public Library of Science ONE*, 14 (4.). <https://doi.org/10.1371/journal.pone.0215448>
- Kelton, J., Price, A.J., Mosjidis, J. (2012). Allelopathic weed suppression through the use of cover crops. In A.J. Price (Ed.), *Weed Control* (pp. 115-132). InTech. <https://doi.org/10.5772/1988>
- Khakbazan, M., Liu, K., Biswas, D., Choo-Foo, K., Entz, M., Peng, G., & Chau, H.W. (2025). Economic analysis of legume-absed intercropping across Canadian Prairies. *Canadian Journal of Plant Science*, 105, 1-13. <https://doi.org/10.1139/cjps-2025-0029>
- Kherif, O., Seghouani, M., Zemmouri, B., Bouhenache, A., Keskes, M.I., Yacer-Nazih, R., Ouaret, W., & Latati, M. (2021). Understanding the response of wheat-chickpea intercropping to nitrogen fertilization using agro-ecological competitive indices under contrasting pedoclimatic conditions. *Agronomy*, 11 (6.) 1225. <https://doi.org/10.3390/agronomy11061225>
- Kientzy, D., Milhollin, R., Ellis, C., & Massey, R. (2023). Understanding equipment management for planting cover crops. *Journal of Soil and Water Conservation*, 78 (6.), 113A-117A. <https://doi.org/10.2489/jswc.2023.0818A>

- Kilcher, M.R., & Heinrichs, D.H. (1960). The use of cereal grains as companion crops in dryland forage crop establishment. *Canadian Journal of Plant Science*, 40 (1.), 81-93. <https://doi.org/10.4141/cjps60-009>
- King, C. (1999). *Could green manuring fit into growers' cropping systems?*. Top Crop Manager. <https://www.topcropmanager.com/could-green-manuring-fit-into-growers-cropping-systems-10460/>
- King, C. (2023). *Teaming up two high value oilseed crops*. Top Crop Manager. <https://www.topcropmanager.com/teaming-up-two-high-value-oilseed-crops/#:~:text=Both%20winter%20canola%20and%20soybeans,is%20planted%20into%20tilled%20strips>
- Kirk, S., Yoder, C., & Gauthier, T. (2017a). *A three year comparative study of desiccant use on red clover seed crops in the Peace River region*. Peace Region Forage Seed Association. http://www.peaceforageseed.ca/pdf/SeedHeads/SH_14_Red_Clover&_Dessicants.pdf
- Kirk, S., Yoder, C., & Gauthier, T. (2017b). *A three year comparative study of desiccant use on alsike clover seed crops in the Peace River region*. Peace Region Forage Seed Association. http://www.peaceforageseed.ca/pdf/SeedHeads/SH_15_Alsike_&_Dessicants.pdf
- Kirkegaard, J.A., Lilley, J.M., Brill, R.D., Ware, A.H., & Walela, C.K. (2018). The critical period for yield and quality determination in canola (*Brassica napus*L.). *Field Crops Research*, 222 (1.), 180-188. <https://doi.org/10.1016/j.fcr.2018.03.018>
- Kladivko, E.J. (2020). Cover crops: progress and outlook. In J.A. Delgado et al., (Eds.), *Soil and water conservation: a celebration of 75 years* (pp. 293-302). Soil and Water Conservation Society.
- Klopp, H.W. (2024). Effects of interseeding cover crops into corn and soybean on biomass production, grain yields and ecosystem services: a review. *Agronomy*, 14 (6.), 1229. <https://doi.org/10.3390/agronomy14061229>
- Kocira, A., Staniak, M., Tomaszewska, M., Kornas, R., Cymerman, J., Panasiewicz, K., & Lipińska, H., (2020). Legume cover crops as one of the elements of strategic weed management and soil quality improvement: a review. *Agriculture*, 10 (9.), 394. <https://doi.org/10.3390/agriculture10090394>

- Koehler-Cole, K., Brandle, J.R., Francis, C.A., Shapiro, C.A., Blankenship, E.E., & Baenziger, P.S. (2016). Clover green manure productivity and weed suppression in an organic grain rotation. *Renewable Agriculture and Food Systems*, 32 (5.), 474-483. <https://doi.org/10.1017/S1742170516000430>
- Koehler-Cole, K. & Elmore, R.W. (2020). Seeding rates and productivity of broadcast interseeded cover crops. *Agronomy*, 10 (11.). <https://doi.org/10.3390/agronomy10111723>
- Koudahe, K., Allen, S.C., & Djaman, K. (2022). Critical review of the impact of cover crops on soil properties. *International Soil and Water Conservation Research*, 10 (3.), 343-354. <https://doi.org/10.1016/j.iswcr.2022.03.003>
- Kumar, V., Singh, M., Thapa, R., Yadav, A., Blanco-Canqui, H., Wortman, S.E., Taghvaeian, S., & Jhala, A.J. (2024). Implications of cover crop management decisions on *Amarathus* species density and biomass in temperate cropping systems: a meta-analysis. *Weed Science*, 73. <https://doi.org/10.1017/wsc.2024.99>
- Kumari, A., Price, A.J., Gamble, A., Li, S., & Jacobson, A. (2024). Integrating cover crops and herbicides for weed control in soybeans. *Weed technology*, 38, 1-25. <https://doi.org/10.1017/wet.2024.24>
- Lakeland Agricultural Research Association. (2013). *Lakeland agricultural research association 2013 annual report*. Lakeland Agricultural Research Association. <https://docplayer.net/170948061-Lakeland-agricultural-research-association.html>
- Lal, R. (2015). Soil carbon sequestration and aggregation by cover cropping. *Journal of Soil and Water Conservation*, 70 (6.), 329-339. <https://doi.org/10.2489/jswc.70.6.329>
- Law, E.P., Wayman, S., Pelzer, C.J., DiTommaso, A., & Ryan, M.R. (2021). Intercropping red clover with intermediate wheatgrass suppresses weeds without reducing grain yield. *Agronomy Journal*, 114 (1.), 700-716. <https://doi.org/10.1002/agj2.20914>
- Lawley, Y. (2013). Cover crop strategies for annual and perennial forages. In S. Bittman & D. Hunt (Eds.), *Cool Forages: Advanced Management of Temperate Forages* (pp. 12-16). Farmwest.

- Leiva, S.C. (2025). *Significant reduction of available soil nitrate through fall-planted cereal and brassica cover crops in North Dakota*. North Dakota State University. <https://www.ndsu.edu/agriculture/ag-hub/impact-stories/significant-reduction-available-soil-nitrate-through-fall-planted-cereal-and>
- Li, L., Sun, J., Zhang, F., Li, X., Yang, S., & Rengel, Z. (2001). Wheat/maize or wheat/soybean strip intercropping: I. yield advantage and interspecific interactions of nutrients. *Field Crops Research*, 71 (2.), 123-137. [https://doi.org/10.1016/S0378-4290\(01\)00156-3](https://doi.org/10.1016/S0378-4290(01)00156-3)
- Li, Y., Allen, V.G., Chen, J., Hou, F., Brown, P., & Green, P. (2013). Allelopathic influence of a wheat or rye cover crop on growth and yield of no-till cotton. *Agronomy Journal*, 105 (6.), 1581-1587. <https://doi-org.uml.idm.oclc.org/10.2134/agronj2013.0065>
- Liebman, M. (1988). Ecological suppression of weeds in an intercropping system: a review. In M.A. Altieri & M. Liebman (Eds.), *Weed management in agroecosystems* (pp 197-211). CRC Press.
- Liebman, M., & Dyck, E. (1993). Crop rotation and intercropping strategies for weed management. *Ecological Applications*, 3 (1.), 92-122. <https://doi.org/10.2307/1941795>
- Liebig, M.A., Hendrickson, J.R., Archer, D.W., Schmer, M.A., Nichols, K.A., & Tanaka, D.L. (2015). Short-term soil responses to late-seeded cover crops in a semi-arid environment. *Agronomy Journal*, 107 (6.), 2011-2019. <https://doi.org/10.2134/agronj15.0146>
- Lins, R.D., Colquhoun, J.B., Cole, C.M., & Mallory-Smith, C.A. (2005). Postemergence Small Broomrape (*Orobanche minor*) Control in Red Clover. *Weed Technology*, 19 (2.), 411-415. <https://doi.org/10.1614/WT-04-175R1>
- Lithourgidis, A., Damalas, C. A., Vlachostergios, D. N., & Dordas, C. (2011). Annual intercrops: an alternative pathway for sustainable agriculture. *Australian Journal of Crop Science*, 5 (4.), 396-410.
- Liu, C., Gan, Y., & Poppy, L. (2014). Evaluation of on-farm crop management decisions on canola productivity. *Canadian Journal of Plant Science*, 94, 131-139. <https://doi.org/10.4141/cjps2013-121>

- Liu, K., Choo-Foo, K., Wen, G., Schoenau, J., & Knight, J.D. (2025). Assessing crop productivity, grain quality, and soil liable carbon and nitrogen in pea-based intercrops under low nitrogen input. *Canadian Journal of Plant Science*, 105, 1-12. <https://doi.org/10.1139/cjps-2024-0136>
- Lockley, P. & Wu, H. (2008, May). *Herbicide tolerance in pasture legumes and herbs*. [Paper presentation]. Sixteenth Australian Weeds Conference, Cairns, Queensland. <https://caws.org.nz/old-site/awc/2008/awc200813191.pdf>
- Lucas, M., Nguyen, L.T.T., Guber, A., & Kravchenko, A.N. (2022). Cover crop influence on pore size distribution and biopore dynamics: enumerating root and soil faunal effects. *Frontiers in Plant Science*, 13. <https://doi.org/10.3389/fpls.2022.928569>
- Ma, Q., Wu, Y., Liu, Y., Shen, Y., Wang, Z. (2024). Interspecific interaction and productivity in a dryland wheat/alfalfa strip intercropping. *Field Crop Research*, 309 (1.). <https://doi.org/10.1016/j.fcr.2024.109335>
- MacLaren, C., Waswa, W., Aliyu, K. T., Claessens, L., Mead, A., Schöb, Vanlauwe, B., & Storkey, J. (2023). Predicting intercrop competition, facilitation, and productivity from simple functional traits. *Field Crops Research*, 297, 108926. <https://doi.org/10.1016/j.fcr.2023.108926>.
- Maitra, S., Hossain, A., Brestic, M., Skalicky, M., Ondrisik, P., Gitari, H., Brahmachari, K., Shankar, T., Bhadra, P., Palai, J.B., Jena, J., Bhattacharya, U., Duvvada, S. K., Lalichetti, S., & Sairam, M. (2021). Intercropping-A low input agricultural strategy for food and environmental security. *Agronomy*, 11 (2.). <https://doi.org/10.3390/agronomy11020343>
- Malalgoda, M., Ohm, J.B., Ransom, J.K., Howatt, K., & Simsek, S. (2020). Effects of pre-harvest glyphosate application on spring wheat quality characteristics. *Agriculture*, 10 (4.), 111. <https://doi.org/10.3390/agriculture10040111>
- Malik, N. & Waddington, J. (1990). Alfalfa (*Medicago sativa*) seed yield response to herbicides. *Weed Technology*, 4 (1.),63-67. <https://doi.org/10.1017/S0890037X00024994>
- Manitoba Agriculture. (2010). *Soil series descriptions*. <https://agrimaps.gov.mb.ca/agrimaps/extras/info/SoilSeriesDescriptions.pdf>

- Manitoba Agriculture (2025). Weed control. In Manitoba Agriculture (Ed.), Guide to field crop protection 2025 (pp. 51-522). <https://www.gov.mb.ca/agriculture/crops/guides-and-publications/pubs/guide-crop-protection-weeds-2025.pdf>
- Manitoba Pulse and Soybean Growers. (2018). *On-farm evaluation of peaola intercropping*. Manitoba Pulse and Soybean Growers. <https://manitobapulse.ca/wpcontent/uploads/2018/02/On-Farm-Evaluation-of-Peola-2016.pdf>
- Mapfumo, E., Chanasyk, D.S., Puurveen, D., Elton, S., & Acharya, S. (2023). Historic climate change trends and impacts on crop yields in key agricultural areas of the prairie provinces in Canada: a literature review. *Canadian Journal of Plant Science*, 103, 243-258. <https://doi.org/10.1139/CJPS-2022-0215>
- Marchiori, O., Inoue, M.H., Braccini, A.L., Oliveira Jr., R.S., Avila, M.R., Lawder, M., & Constantin, J. (2002). Quality and yield of canola (*Brassica napus*) seeds after pre-harvest desiccant application. *Advances in Weed Science*, 20 (2.), 253-261. <https://doi.org/10.1590/S0100-835820020020012>
- Mbanyele, V., Enesi, R.O., Shaw, L., & Gorim, L.Y. (2024). A review of intercropping systems in western Canada. *Agronomy Journal*, 116 (5.), 2089-2108. <https://doi.org/10.1002/agj2.21622>
- McAuley, W.P. (2023). *Effect of intercropping with faba bean on land equivalency ratio and soil health in Saskatchewan* [Master's thesis, University of Saskatchewan]. HARVEST. <https://harvest.usask.ca/server/api/core/bitstreams/6472d525-ea65-4d55-8584-175689b033/content>
- McConnell, C.A., Rozum, R.K.N., Shi, Y., & Kemanian, A.R. (2023). Tradeoffs when interseeding cover crops into corn across the Chesapeake Bay watershed. *Agricultural Systems*, 209. <https://doi.org/10.1016/j.agsy.2023.103684>
- McCurdy, J.D., McElroy, J.T., & Flessner, M.L. (2013). Differential response of four trifolium species to common broadleaf herbicides: implications for mixed grass-legume swards. *Weed Technology*, 27 (1.), 123-128. <https://doi.org/10.1614/WT-D-12-00093.1>
- McCurdy, J.D., McElroy, J.S., Flessner, M.L., Hoyle, J.A., & Parker, E.T. (2016). Tolerance of three clovers (*Trifolium* spp.) to common herbicides. *Weed Technology*, 30 (2.), 478-485. <https://doi.org/10.1614/WT-D-15-00062.1>

- McGinn, S.M. (2010). Weather and climate patterns in Canadas prairie grasslands. In J.D. Shorthouse & K.D. Floate (Eds.), *Arthropods of Canadian Grasslands (Volume 1): Ecology and Interactions in Grassland Habitats*. Biological Survey of Canada. <https://doi.org/10.3752/9780968932148.ch5>
- McGuire, A. (2025). *Cover crop benefits depend on biomass: how much do you need?* Center for Sustaining Agriculture and Natural Resources. <https://csanr.wsu.edu/cover-crop-benefits-depend-on-biomass-how-much-do-you-need/>
- McInnes, B., & Slowski, J. (2020). *Demonstrating the effects of red and alsike clover seed crops in rotation*. Northeast Agriculture Research Foundation. <https://neag.ca/wpcontent/uploads/2021/04/Red-and-Alsike-Clover-in-Rotation-with-Canola-as-a-cover-crop-1.pdf>
- McKenzie-Gopsill, A., Mills, A., MacDonald, A.N., & Wyand, S. (2022). The importance of species selection in cover crop mixture design. *Weed Science*, 70 (4.), 436-447. <https://doi.org/10.1017/wsc.2022.28>
- Menendez, A.I., Gundel, P.E., Lores, L.M., & Martinez-Ghersa, M.A. (2017). Assessing the impacts of intra- and interspecific competition between *Triticum aestivum* and *Trifolium repens* on the species' responses to ozone. *Botany*, 95 (9). <https://doi.org/10.1139/cjb-2016-0275>
- Michigan State University. (2019). *Table 3A- weed response to herbicides in small grains*. Michigan State University. <https://www.canr.msu.edu/weeds/extension/weed-control-guide/2019WG-smallgrains.pdf>
- Michigan State University. (2024). Weed control in forages. In 2024 weed control guide (pp. 113-122). Michigan State University.
- Miller, P., Jones, C., Zabinski, C., & Holmes, J. (2018). *Mixed cover crop and nitrogen rate effects on wheat yield and protein after 6 years*. Montana State University. <https://landresources.montana.edu/fertilizerfacts/html/FF76.html>
- Mirdoraghi, M., Farahani, S.M., & Rezazadeh, A. (2024). Oilseeds in intercropping systems: strategies to increase oil quality and fatty acid profile, a review. *Journal of Agriculture and Food Research*, 17, 101229. <https://doi.org/10.1016/j.jafr.2024.101229>

- Mohammed, Y. A., Matthees, H. L., Gesch, R. W., Patel, S., Forcella, F., Aasand, K., Steffl, N., Johnson, B. L., Wells, M. S., & Lenssen, A. W. (2020). Establishing winter annual cover crops by interseeding into Maize and Soybean. *Agronomy Journal*, *112* (2.), 719-732. <https://doi-org.uml.idm.oclc.org/10.1002/agj2.20062>
- Moller, K., Stinner, W., & Leithold, G. (2008). Growth, composition, biological N₂ fixation and nutrient uptake of a leguminous cover crop mixture and the effect of their removal on field nitrogen balances and nitrate leaching risk. *Nutrient Cycling in Agroecosystems*, *82*, 233-249. <https://doi.org/10.1007/s10705-008-9182-2>
- Moore, E.B., Wiedenhoef, M.H., Kaspar, T., & Cambardella, C.A. (2014). Rye cover crop effects on soil quality in no-till corn silage-soybean cropping systems. *Soil Science Society of America Journal*, *78* (3.), 968. <https://doi.org/10.2136/sssaj2013.09.0401>
- Morrison, C.L. (2021). *Cover cropping on the Prairies*. The Canadian Agri-Food Policy Institute. <https://capi-icpa.ca/wp-content/uploads/2021/06/2021-06-10-Callum-Morrison-Individual-Report-1-2.pdf>
- Morrison, C.L., & Lawley, Y. (2021). *2020 Prairie cover crop survey report*. Department of Plant Science University of Manitoba. <https://umanitoba.ca/agricultural-food-sciences/sites/agricultural-food-sciences/files/2021-10/2020-prairie-cover-crop-survey-report.pdf>
- Moyer, J.R., Acharya, S.N., Fraser, J., Richards, K.W., & Foroud, N. (1996). Desiccation of alfalfa for seed production with diquat and glufosinate. *Canadian Journal of Plant Science*, *76* (3.), 435-439. <https://doi.org/10.4141/cjps96-077>
- Muhammad, I., Wang, J., Sainju, U.M., Zhang, S., Zhao, F., & Khan, A. (2021). Cover cropping enhances soil microbial biomass and affects microbial community structure: a meta-analysis. *Geoderma*, *381*, 114696. <https://doi.org/10.1016/j.geoderma.2020.114696>
- Mutch, D.R., Martin, T.E., & Kosola, K.R. (2003). Red clover (*Trifolium pratense*) suppression of Common ragweed (*Ambrosia artemisiifolia*) in winter wheat (*Triticum aestivum*). *Weed Technology*, *17* (1.), 181-185. [https://doi.org/10.1614/0890-037X\(2003\)017\[0181:RCTPSO\]2.0.CO;2](https://doi.org/10.1614/0890-037X(2003)017[0181:RCTPSO]2.0.CO;2)
- Myers, R. A., Weber, A., & Tellatin, S. (2019). *Cover crop economics*. SARE Outreach. <https://www.sare.org/publications/cover-crop-economics/how-to-get-a-faster-return-from-cover-crops/creating-a-baseline-for-cover-crop-costs-and-returns/>

- Natural Resources Conservation Service. 2022. *Carbon: nitrogen ratio (C:N)*. United States Department of Agriculture. https://www.nrcs.usda.gov/sites/default/files/2022-09/Soil_TechNote23A.pdf
- Nelson, A.G., Pswarayi, P., Quideau, S., Frick, B., & Spaner, D. (2012). Yield and weed suppression of crop mixtures in organic and conventional systems of the western Canadian prairie. *Agronomy Journal*, 104 (3.), 756-762. <https://doi.org/10.2134/agronj2011.0374>
- Nelson, W.A., Khan, B.A., & Roberts, B.W. (1991). Screening cover crops for use in conservation tillage systems for vegetables following spring plowing. *HortScience*, 26 (7.), 860-862. <https://doi.org/10.21273/HORTSCI.26.7.860>
- Newlands, N.K., Zamar, D.S., Kouadio, L.A., Zhang, Y., Chipanshi, A., Potgieter, A., Toure, S., & Hill, H.S. (2014). An integrated, probabilistic model for improved seasonal forecasting of agricultural crop yield under environmental uncertainty. *Frontiers in Environmental Science*, 2. <https://doi.org/10.3389/fenvs.2014.00017>
- Nichols, V., Martinez-Feria, R., Weisberger, D., Carlson, S., Basso, B., & Basche, A. (2020). Cover crops and weed suppression in the U.S. Midwest: a meta-analysis and modeling study. *Agricultural and Environmental Letters*, 5 (1.). <https://doi.org/10.1002/ael2.20022>
- Nielsen, D.C., Lyon, D.J., Hergert, G.W., Higgins, R.K., & Holman, J.D. (2015). Cover crop biomass production and water use in the central great plains. *Agronomy Journal*, 107 (6.), 2047-2058. <https://doi.org/10.2134/agronj15.0186>
- Nielsen, D.C., Lyon, D.J., Higgins, R.K., Hergert, G.W., Holman, J.D., & Vigil, M.F. (2016). Cover crop effect on subsequent wheat yield in the central great plains. *Agronomy Journal*, 108 (1.), 243-256. <https://doi.org/10.2134/agronj2015.0372>
- Noland, R.L., Wells, S.M., Sheaffer, C.C., Baker, J.M., Martinson, K.L., & Coulter, J.A. (2018). Establishment and function of cover crops interseeded into corn. *Crop Science*, 58 (2.), 863-873. <https://doi.org/10.2135/cropsci2017.06.0375>
- North Peace Applied Research Association. (2020). *Intercrop trial results 2020*. North Peace Applied Research Association. <https://npara.ca/wp-content/uploads/2021/11/Intercrop-Trial-Results-2020.pdf>

- North Peace Applied Research Association. (2023). *Companion cropping clovers with main rotational crops in the peace region*. North Peace Applied Research Association. <https://npara.ca/wp-content/uploads/2024/01/PRL-Annual-Clovers-2023.pdf>
- Nurk, L., Grab, R., Pekrun, C., & Wachendorf, M. (2017). Effect of sowing method and weed control on the performance of maize (*Zea mays* L.) intercropped with climbing beans (*Phaseolus vulgaris* L.). *Agriculture*, 7 (7), 51. <https://doi.org/10.3390/agriculture7070051>
- Obour, A.K., Simon, L.M., Holman, J.D., Carr, P.M., Schipanski, M., Fonte, S., Ghimire, R., Nleya, T., Blanco-Canqui, H. (2021). Cover crops to improve soil health in the North American Great Plains. *Agronomy Journal*, 113 (6.), 4590-4604. <https://doi.org/10.1002/agj2.20855>
- Ogilvie, C.M., Loucks, C., Beach, H., Johnson, P., & Martin, R.C. (2020). Survey of interseeded red clover management and perceived challenges by Ontario wheat growers. *Canadian Journal of Plant Science*, 100 (5.). <https://doi.org/10.1139/cjps-2020-0039>
- Oliveira, M.C., Butts, L., & Werle, R. (2019). Assessment of cover crop management strategies in Nebraska, US. *Agriculture*, 9 (6.). <https://doi.org/10.3390/agriculture9060124>
- Opoku, A., Ogunleye, A.M., Solomon, J.K.Q., & Payne, W.A. (2024). Cover crop systems impact on biomass production, carbon-to-nitrogen ratio, forage quality, and soil health in a semi-arid environment. *Heliyon*, 10 (20.). <https://doi.org/10.1016/j.heliyon.2024.e39600>
- Osipitan, O. A., Dille, J. A., Assefa, Y., Radicetti, E., Ayeni, A., & Knezevic, S. Z. (2019). Impact of cover crop management on level of weed suppression: a meta-analysis. *Crop Science*, 59 (3.), 833-842. <https://doi.org/10.2135/cropsci2018.09.0589>
- Otchere, O., Lawley, Y., & Congreves, K.A. (2023). Do cover crops on the Canadian Prairies affect soil nitrogen cycling? *Canadian Journal of Soil Science*, 103 (2.), 318-331. <https://doi.org/10.1139/cjss-2022-0079>
- Padilla, M.A., Min, Y., & Zhang, G. (2008). Type I error rates of the Kenward-roger f-test for a split-plot design with missing values and non-normal data. *Journal of Modern Applied Statistical Methods*, 7 (2.), 385-397. <https://doi.org/10.22237/jmasm/1225512180>

- Parkland Crop Diversification Foundation. (2020). *Intercropping: canola-cover crop (year 1)*. Parkland Crop Diversification Foundation Annual Report 2020. <https://mbdiversificationcentres.ca/wp-content/uploads/2021/03/2020-PCDF-Canola-CoverCrop-Intercrop-Year-1.pdf>
- Parkland Crop Diversification Foundation. (2021). Parkland Crop Diversification Foundation Annual Report 2021. <https://mbdiversificationcentres.ca/wpcontent/uploads/2022/03/2021-PCDF-Annual-Report.pdf>
- Peace Region Living Lab. (2024). *Companion cropping annual clovers with the main rotational crops in the peace region*. North Peace Applied Research Association. <https://npara.ca/ca/wp-content/uploads/2025/03/PRL-Annual-Clovers-2024.pdf>
- Pellegrini, F., Carlesi, S., Nardi, G., & Bàrberi, P. (2021). Wheat-clover temporary intercropping under mediterranean conditions affects wheat biomass, plant nitrogen dynamics and grain quality. *European Journal of Agronomy*, 130, 126347. <https://doi.org/10.1016/j.eja.2021.126347>
- Penner, D.E. (2024). *Agronomic and economic evaluation of fall cover crops and the natural fall plant community in on-farm experiments in Manitoba*. [Master's thesis, University of Manitoba]. Mspace. <https://mspace.lib.umanitoba.ca/server/api/core/bitstreams/44ebc60d0-4555-464c-a0d3-35ae0a973b2e/content>
- Pest Management Regulatory Agency. (2011). *Tralkoxydim*. Health Canada. https://publications.gc.ca/collections/collection_2011/sc-hc/H113-28-2011-1-eng.pdf
- Peterson, A.T., Berti, M.T., & Samarappuli, D. (2019). Intersowing cover crops into standing soybean in the US upper Midwest. *Agronomy*, 9 (5.), 264. <https://doi.org/10.3390/agronomy9050264>
- Petrie, C.A., & Bates, J. (2017). 'Multi-cropping', intercropping and adaptation to variable environments in Indus south Asia. *Journal of World Prehistory*, 30, 81-130. <https://doi.org/10.1007/s10963-017-9101-z>
- Pieters, A.J. (1927). History of green manuring. In J.G. Lipman (Eds.) *Green Manuring: Principles and Practices* (pp. 10-16). JWS.

- Phillips, D. (2023). *Canada's top 10 weather stories of 2022*. Government of Canada. <https://www.canada.ca/en/environment-climate-change/services/top-ten-weather-stories/2022.html>
- Phillips, D. (2024). *Canada's top 10 weather stories of 2023*. Government of Canada. <https://www.canada.ca/en/environment-climate-change/services/top-ten-weather-stories/2023.html>.
- Plastina, A., Liu, F., Miguez, F., Carlson, S., & Marcillo, G. (2018). Annual net returns to cover crops in Iowa. *Journal of Applied Farm Economics*, 2 (2.). <https://doi.org/10.7771/2331-9151.1030>
- Powell, G.E. & Sprague, C.L. (2016). *Fall herbicide applications allow for frost-seeding of red clover in winter wheat*. [Poster presentation]. 2016 Weed Science Society of America Annual Meeting, San Juan, Puerto Rico. https://www.canr.msu.edu/uploads/234/89012/weeds/Weed_control_for_red_clover_frost_seeding.pdf
- Pridham, J. C. & Entz, M. H. (2008). Intercropping spring wheat with cereal grains, legumes, and oilseeds fails to improve productivity under organic management. *Agronomy Journal*, 100 (5.), 1436-1442. <https://doi.org/10.2134/agronj2007.0227>
- Queen, A., Earl, H., & Deen, W. (2009). Light and moisture competition effects on biomass of red clover underseeded to winter wheat. *Agronomy Journal*, 101 (6.), 1511-1521. <https://doi.org/10.2134/agronj2008.0163>
- Quinn, D., Poffenbarger, H., & Lee, C. (2019). *Cover crop benefits and challenges in Kentucky*. University of Kentucky Cooperative Extension. <http://www2.ca.uky.edu/agcomm/pubs/AGR/AGR240/AGR240.pdf>
- Rabin, K.C., Johnson, G.A., Strock, J.S., Jordan, N.R., & Garcia y Garcia, A.X. (2023). Tillage and cover crop mixtures interseeded in maize-soybean in the upper Midwest. *Agronomy Journal*, 115 (3.), 1188-1201. <https://doi.org/10.1002/agj.2.21322>
- Rajalahti, R.M. Bellinder, R.R., and Hoffman, M.P. (1999). Time of hilling and interseeding affects weed control and potato yield. *Weed Science*, 47 (2.), 215-225. <https://doi.org/10.1017/S0043174500091645>.

- Ramsey, R.J.L., Stephenson, G.R., & Hall, J.C. (2002). Effect of relative humidity of the uptake, translocation, and efficacy of glufosinate ammonium in wild oat (*Avena fatua*). *Pesticide Biochemistry and Physiology*, 73 (1.), 1-8. [https://doi.org/10.1016/S0048-3575\(02\)00017-2](https://doi.org/10.1016/S0048-3575(02)00017-2)
- Ransom, C.V., Rice, C.A., & Ishida, J.K. (2001). *Herbicides for alfalfa setback and preharvest desiccation in alfalfa seed production*. Oregon State University. <https://agsci.oregonstate.edu/sites/agscid7/files/malheur/attachments/ar/2001-05AlfalfaSetbackHerbicides.pdf>
- Raza, M. A., Din, A. M. U., Zhiqi, W., Gul, H., Rehman, S. U., Bukhari, B., Haider, I., Rahman, M. H. U., Liang, X., Luo, S., El Sabagh, A., Qin, R., & Zhongming, M. (2023). Spatial differences influence nitrogen uptake, grain yield, and land-use advantage of wheat/soybean relay intercropping systems. *Scientific Reports*, 13. <https://doi.org/10.1038/s41598-023-43288-3>.
- Rees, J., Proctor, C., & Melvin, S. (2021). *Interseeding cover crops into corn and soybean: what we've learned*. University of Nebraska-Lincoln Institute of Agriculture and Natural Resources. <https://cropwatch.unl.edu/2021/interseeding-cover-crops-corn-and-soybean>
- Rees, J., Elmore, R., Proctor, C., Melvin, S., & Sindelar, M. (2019). *Interseeding cover crops into corn or soybean*. University of Nebraska-Lincoln Institute of Agriculture and Natural Resources. <https://cropwatch.unl.edu/2019/interseeding-cover-crops-corn-or-soybean>
- Robinson, M.A., Letarte, J., Cowbrough, M.j., Sikkema, P.H., & Tardif, F.J. (2014). Response of underseeded red clover (*Trifolium pratense* L.) to winter wheat (*Triticum aestivum* L.) herbicides as affected by application timing. *Agricultural Sciences*, 5 (13.), 1351-1360. <https://doi.org/10.4236/as.2014.513145>
- Ross, S.M., King, J.R., Izaurralde, R.C., & O'Donovan, J.T. (2001). Weed suppression by seven clover species. *Agronomy Journal*, 93 (4.), 820-827. <https://doi.org/10.2134/agronj2001.934820x>
- Ross, S.M., King, J.R., O'Donovan, J.T., & Izaurralde, R.C. (2003). Seeding rate effects in oat-berseem clover intercrops. *Canadian Journal of Plant Science*, 83 (4.), 769-778. <https://doi.org/10.4141/P02-130>

- Ruffo, M.L., & Bollero, G.A. (2003). Modeling rye and hairy vetch residue decomposition as a function of degree-days and decomposition-days. *Agronomy Journal*, 95 (4.), 900-907. <https://doi.org/10.2134/agronj2003.9000>
- Rusch, H.L., Coulter, J.A., Grossman, J.M., Johnson, G.A., Porter, P.M., Garcia y Garcia, A.X., & Snapp, S.S. (2020). Towards sustainable maize production in the U.S. upper Midwest with interseeded cover crops. *Public Library of Science ONE*, 15 (4.). <https://doi.org/10.1371/journal.pone.0231032>
- Saadat, D., Hashemi, M., Herbert, S., & Siller, A. (2025). Contribution of roots and shoots of three summer cover crops to soil C and N cycling post-termination. *Agronomy*, 15 (6.), 1467. <https://doi.org/10.3390/agronomy15061467>
- Sabbahi, R., Azzaoui, K., Rhazi, L., Ayerdi-Gotor, A., Aussenac, T., Depeint, F., Taleb, M., & Hammouti, B. (2023). Factors affecting the quality of canola grains and their implications for grain-based foods. *Foods*, 12 (11.), 2219. <https://doi.org/10.3390/foods12112219>
- Sanderson, M., Johnson, H., & Hendrickson, J. (2018). Cover crop mixtures grown for annual forage in a semi-arid environment. *Agronomy Journal*, 110 (2.), 525-534. <https://doi.org/10.2134/agronj2017.04.0228>
- Saskatchewan Soil Survey. (1993). *The soils of St. Andrews rural municipality No. 287 Saskatchewan*. Saskatchewan Institute of Pedology. https://sis.agr.gc.ca/cansis/publications/surveys/sk/sk287/sk287_report.pdf
- Satchivi, N.M., DeBoer, G.J., & Bell, J.L. (2017). Understanding the differential response of *Setaria viridis* (green foxtail) and *Setaria pumila* (yellow foxtail) to pyroxsulam. *Journal of Agricultural and Food Chemistry*, 65 (34.), 7328-7336. <https://doi.org/10.1021/acs.jafc.7b01453>
- Sauchyn, D., Barrow, E.M., Hopkinson, R.F., & Leavitt, P.R. (2002). Aridity on the Canadian Prairies. *Géographie Physique et Quaternaire*, 56 (2), 247. <https://doi.org/10.7202/009109ar>
- Scavo, A., Fontanazza, S., Restuccia, A., Pesce, G.R., Abbate, C., & Mauromicale, G. (2022). The role of cover crops in improving soil fertility and plant nutritional status in temperate climates. A review. *Agronomy for Sustainable Development*, 42 (93.). <https://doi.org/10.1007/s13593-022-00825-0>

- Scavo, A., Restuccia, A., & Mauromicale, G. (2018). Allelopathy: principles and basic aspects for agroecosystem control. In S. Gaba, B. Smith, & E. Lichtfouse (Eds.), *Sustainable Agriculture Reviews 28* (pp. 47-103). Springer. https://doi.org/10.1007/978-3-319-90309-5_2
- Schmid, B., Hector, A., Saha, P., & Loreau, M. (2008). Biodiversity effects and transgressive overyielding. *Journal of Plant Ecology*, *1* (2.), 95-102. <https://doi.org/10.1093/jpe/rtn011>
- Schmitt, M.B., Berti, M., Samarappuli, D., & Ransom, J.K. (2021). Factors affecting the establishment and growth of cover crops intersown into maize (*Zea mays* L.). *Agronomy*, *11* (4.), 712. <https://doi.org/10.3390/agronomy11040712>
- Schuster, M.Z., Pelissari, A., Szymczak, L.S., Luatosa, S.B.C., & Moraes, A. (2015). Chemical control of white clover in soybean crops. *Planta Daninha*, *33* (3.), 561-565. <https://doi.org/10.1590/S0100-83582015000300018>
- Secchi, M.A., Fernandez, J.A., Stamm, M.J., Durrett, T., Prasad, P.V.V., Messina, C.D., & Ciampitti, I.A. (2023). Effects of heat and drought on canola (*Brassica napus* L.) yield, oil, and protein: A meta-analysis. *Field Crop Research*, *293*, 108848. <https://doi.org/10.1016/j.fcr.2023.108848>
- Shahzad, B., Rehman, S.U., Bajwa, A., Hussain, S., Rehman, A., Alam, S., Abbas, T., Ali, A., Shah, L., Adkins, S., & Li, P. (2019). Utilizing the allelopathic potential of brassica species for sustainable crop production: a review. *Journal of Plant Growth Regulation*, *38* (1.). [10.1007/s00344-018-9798-7](https://doi.org/10.1007/s00344-018-9798-7)
- Sharma, S.D., & Singh, M. (2001). Environmental factors affecting absorption and bio-efficacy of glyphosate in Florida beggarweed (*Desmodium tortuosum*). *Crop Protection*, *20* (6.), 511-516. [https://doi.org/10.1016/S0261-2194\(01\)00065-5](https://doi.org/10.1016/S0261-2194(01)00065-5)
- Sheaffer, C.C., Gunsolus, J.L., Grimsbo Jewett, J. & Lee, S.H. (2002). Annual *Medicago* as a smother crop in soybean. *Journal of Agronomy and Crop Science* *188*, 408–416. <https://doi.org/10.1046/j.1439-037X.2002.00590.x>
- Sheaffer, C.C, Goplen, J., Wiersma, J., & Kaiser, D. (2022). *Alfalfa and red clover can supply n for following crops when grown for one year*. University of Minnesota extension. <https://blog-crop-news.extension.umn.edu/2022/04/alfalfa-and-red-clover-can-supply-n-for.html>

- Sheldon, K., Purdom, S., Shekoofa, A., Steckel, L., & Sykes, V. (2021). Allelopathic impact of cover crop species on soybean and goosegrass seedling germination and early growth. *Agriculture*, 11 (10.), 965. <https://doi.org/10.3390/agriculture11100965>
- Shirriff, K., Krishna Bahadur, K. C., & Berg, A. (2022). Evaluation of agrobiodiversity and cover crop adoption in southern Ontario field crops. *Agronomy*, 12 (2.), 415. <https://doi.org/10.3390/agronomy12020415>
- Si, P. & Walton, G.H. (2004). Determinants of oil concentration and seed yield in canola and Indian mustard in the lower rainfall areas of western Australia. *Australian Journal of Agricultural Research*, 55 (3.), 367-377. <https://doi.org/10.1071/AR03151>
- Šimansky, V., Horváthová, J., & Jonczak, J. (2021). Suitability of carbon and nitrogen management indices for the evaluation of soil organic matter under different soil management practices in a productive vineyard. *Journal of Ecological Engineering*, 22 (7.), 150-162. <https://doi.org/10.12911/22998993/139027>
- Six, J., Conant, R.T., Paul, E.A., & Paustian, K. (2002). Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. *Plant and Soil*, 241, 155-176. <https://doi.org/10.1023/A:1016125726789>
- Smith, D. H., & Ruark, M. (2022). *Interseeding cover crops*. University of Wisconsin-Madison Integrated Pest and Crop Management. <https://ipcm.wisc.edu/blog/2022/06/interseeding-cover-crops/>
- Smith, R., Cudney, D.W., & Elmore, C.L. (2007). *Clovers*. Pest Notes University of California Agriculture and Natural Resources. [https://ipm.ucanr.edu/legacy_assets/PDF/PEST NOTES/pnclovers.pdf](https://ipm.ucanr.edu/legacy_assets/PDF/PEST_NOTES/pnclovers.pdf)
- Smith, R.G., Atwood, L.W., & Warren, N.D. (2014). Increased productivity of a cover crop mixture is not associated with enhanced agroecosystem services. *Public Library of Science ONE*, 9 (5.). <https://doi.org/10.1371/journal.pone.0097351>
- Soltani, N., Shropshire, C., & Sikkema, P.H. (2020). Control of annual ryegrass with spring-applied herbicides prior to seeding corn. *Canadian Journal of Plant Science*, 100 (4.), 372-379. <https://doi.org/10.1139/cjps-2019-0189>

- Stahl, L., & Ley, E. (2022). *Can I plant a cover crop if I used a PRE herbicide?* University of Minnesota Extension. <https://blog-crop-news.extension.umn.edu/2022/05/can-i-plant-cover-crop-if-i-used-pre.html>
- Statistics Canada. (2015). *Proportion of farms reporting field crops that used over winter cover crops by census division (CD), 2015*. Statistics Canada. <https://www150.statcan.gc.ca/n1/pub/95-634-x/2017001/article/54903/catm-ctra-245-eng.htm>
- Statistics Canada. (2023). *Cover, companion or green manure crops used as field crop management practice*. Farm Management Survey. <https://doi.org/10.25318/3210038701-eng>
- Stute, J.K. & Posner, J.L. (1993). Legume Cover Crop options for grain rotations in Wisconsin. *Agronomy Journal*, 85 (6.), 1128-1132. <https://doi.org/10.2134/agronj1993.00021962008500060006x>
- Sullivan, D.M., Andrews, N., & Brewer, L.J. (2020). *Estimating plant available nitrogen release from cover crops*. Oregon State University. <https://extension.oregonstate.edu/sites/default/files/documents/pnw636.pdf>
- Sumiahadi, A., Acar, R., Koyun, N. K., Özel, A. (2019). The potential use of cover crops for controlling soil erosion caused by water. In A. Namli et al., (Eds.), *Proceedings of the 10th International Soil Congress 2019, Ankara, Turkey: Successful transformation toward land degradation neutrality: future perspective* (pp.160-164). Biomulch and Phytoremediation projects.
- Swanton, C.J., Chandler, K., & Shrestha, A. (1998). Control of established alfalfa (*Medicago sativa* L.) and red clover (*Trifolium pratense* L.) in a no-till corn (*Zea mays* L.) cropping sequence. *Canadian Journal of Plant Science*, 78, 175-177. <https://doi.org/10.4141/P97-058>
- Syngenta Crop Protection Canada Inc. (2014). Reglone® desiccant. Syngenta Crop Protection Canada Inc. https://assets.syngenta.ca/pdf/labels/REGLONE_Desiccant_26396_en_pamphlet.pdf
- Szumigalski, A. & Van Acker, R. (2005). Weed suppression and crop production in annual intercrops. *Weed Science*, 53 (6.), 813-825. <https://doi.org/10.1614/WS-05-014R.1>

- Takano, H.K. & Dayan, F.E. (2020). Glufosinate-ammonium: a review of the current state of knowledge. *Pest Management Science*, 76 (2.), 3911-3925. <https://doi.org/10.1002/ps.5965>
- Takano, H.K., Beffa, R., Preston, C., Westra, P., & Daya, F.E. (2019). Reactive oxygen species trigger the fast action of glufosinate. *Planta*, 249, 1837-1849. <https://doi.org/10.1007/s00425-019-03124-3>
- Teasdale, J.R. (2017). The use of rotations and cover crops to manage weeds. In R. Zimdahl (Ed.), *Integrated Weed Management for Sustainable Agriculture* (pp. 227-260). Burleigh Dodds Science Publishing Limited.
- Teasdale, J.R. & Daughtry, C.S.T. (1993). Weed suppression by live and desiccated hairy vetch (*Vicia villosa*). *Weed Science*, 41 (2.), 207-212. <https://doi.org/10.1017/S0043174500076074>
- Teasdale, J.R., Brandsaeter, L.O., Calegari, A., & Skora Neto, F. (2007). Cover crops and weed management. In M.K. Upadhyaya & R.E. Blackshaw (Eds.), *Non-Chemical Weed Management: Principles, Concepts and Technology* (pp. 49-64). CABI.
- Thapa, V.R., Mirsky, S.B., & Tully, K.L. (2018). Cover crops reduce nitrate leaching in agroecosystems: a global meta-analysis. *Journal of Environmental Quality*, 47 (6.), 1400-1411. <https://doi-org.uml.idm.oclc.org/10.2134/jeq2018.03.0107>
- Thiessen Martens, J. R., Hoepfner, J.W., & Entz, M. H. (2001). Legume cover crops with winter cereals in southern Manitoba: establishment, productivity, and microclimate effects. *Agronomy Journal*, 93 (5.), 1086-1096. <https://doi.org/10.2134/agronj2001.9351086x>
- Thiessen Martens, J. R., Entz, M. H., & Hoepfner, J.W. (2005). Legume cover crops with winter cereals in southern Manitoba: fertilizer replacement values for oat. *Canadian Journal of Plant Science*, 85 (3.), 645-648. <https://doi.org/10.4141/P04-114>
- Thiessen Martens, J. R., Entz, M. H., & Wonneck, M. D. (2015). Review: redesigning Canadian prairie cropping systems for profitability, sustainability, and resilience. *Canadian Journal of Plant Science*, 95 (6.), 1049-1072. <https://doi.org/10.4141/CJPS-2014-173>

- Thomas, B.W., Larney, F.J., Chantigny, M.H., Goyer C., & Hao, X. (2017). Fall rye reduced residual soil nitrate and dryland spring wheat grain yield. *Agronomy Journal*, 109 (2.), 718-728. <https://doi.org/10.2134/agronj2016.10.0616>
- Thorne, M. & Lyon, D. (2024). *Herbicide options for Italian ryegrass control in glyphosate-tolerant spring canola* [Conference presentation]. 2024 Pacific Northwest Canola Association Workshop, Moscow, ID, United States. <https://pnwcanola.org/wp-content/uploads/2024/02/Thorne-Italian-ryegrass-control-in-spring-canola- PNWCA-012524.pdf>
- Thorsted, M.D., Weiner, J., & Olesen, J.E. (2006). Above- and below-ground competition between intercropped winter wheat *Triticum aestivum* and white clover *Trifolium repens*. *Journal of Applied Ecology*, 43 (2.), 237-245. <https://doi.org/10.1111/j.1365-2664-2006.01131.x>
- Tonks, D., Jeffery, L.S., & Webb, B.L. (1991). Response of Seedling Alfalfa (*Medicago sativa*) to Four Postemergence Herbicides. *Weed Technology*, 5 (4.), 736-738. <https://doi.org/10.1017/S0890037X00033777>
- University of Minnesota Extension. (2021). *Seedling diseases-alfalfa*. University of Minnesota. <https://extension.umn.edu/forage-pest-management/seedling-diseases>
- Van Oort, P.A.J., Gou, F., Stomph, T.J., & van der Werf, W. (2020). Effect of strip width on yields in relay-strip intercropping: a simulation study. *European Journal of Agronomy*, 112, 125936. <https://doi.org/10.1016/j.eja.2019.125936>
- Vandermeer, J. (1984). The interpretation and design of intercrop systems involving environmental modification by one of the components: a theoretical framework. *Biological Agriculture & Horticulture*, 2 (2.), 135-156. <https://doi.org/10.1080/01448765.1984.9754424>
- Vanhie, T.R., Tardif, F.J., Smith, P., Vazan, S., Cowbrough, M., & Swanton, C.J. (2020). An integrated weed management strategy for the control of horseweed (*conyza canadensis*). *Weed Science*, 69 (1.), 119-127. <https://doi.org/10.1017/wsc.2020.92>
- VanKoughnet, B. (2015). *On-farm evaluation of Peaola intercropping*. Manitoba Pulse and Soybean Growers. <https://www.manitobapulse.ca/wp-content/uploads/2018/02/On-Farm-Evaluation-of-Peaola-Intercropping-2015.pdf>

- Villamil, M.B., Bollero, G.A., Darmody, R.G., Simmons, F.W., & Bullock, D.G. (2006). No-till corn/soybean systems including winter cover crops. *Soil Science Society of America Journal*, 70 (6.), 1936-1944. <https://doi.org/10.2136/sssaj2005.0350>
- Voisin, R., Horwitz, P., Godrich, S., Sambell, R., Cullerton, K., & Devine, A. (2024). What goes in and what comes out: a scoping review of regenerative agricultural practices. *Agroecology and Sustainable Food Systems*, 48 (1.), 124-158. <https://doi.org/10.1080/21683565.2023.2270441>
- Volkman, M., Carr, P., Dahlhausen, S. (2022). *Manure Legacy: Compost Carryover and Intercropping*. Montana State University. <https://agresearch.montana.edu/carc/researchresults/2022researchpages/manurelegacycompostcarryover.html>
- Wagg, C., van Erk, A., Fava, E., Comeau, L. P., Mitterboeck, T. F., Goyer, C., Li, S., McKenzie-Gopsill, A., & Mills, A. (2021). Full-season cover crops and their traits that promote agroecosystem services. *Agriculture*, 11 (9.). <https://doi.org/10.3390/agriculture11090830>
- Wallace, J.M., Curran, W.S., Mortensen, D.A. (2019). Cover crop effects on horse-weed (*Erigeron canadensis*) density and size inequality at the time of herbicide exposure. *Weed Science*, 67 (3.), 327-338. <https://doi.org/10.1017/wsc.2019.3>
- Wallander, S., Smith, D., Bowman, M., & Claassen, R. (2021). *Cover crop trends, programs, and practices in the United States*. U.S. Department of Agriculture, Economic Research Service. <https://www.ers.usda.gov/publications/pub-details?pubid=100550>
- Wang, R., Sun, S., Zhang, L., Yang, N., Feng, L., Bai, W., Zhang, D., Wang, Q., Evers, J. B., Liu, Y., Ren, J., Zhang, Y., & Van der Werf, W. (2020). Border-row proportion determines strength of interspecific interactions and crop yield in maize/peanut strip intercropping. *Field Crop Research*, 253. <https://doi.org/10.1016/j.fcr.2020.107819>
- Weisberger, D.A., Bastos, L.M., Sykes, V.R., & Basinger, N.T. (2023). Do cover crops suppress weeds in the U.S. southeast? A meta-analysis. *Weed Science*, 71 (3.), 244-254. <https://doi.org/10.1017/wsc.2023.21>
- Wendt, R.C., & Burwell, R.E. (1985). Runoff and soil losses for conventional, reduced, and no-till corn. *Journal of Soil and Water Conservation*, 40 (5.), 450-454. <https://doi.org/10.1080/00224561.1985.12455900>

- Westman Agricultural Diversification Organization. (2017). *2017 annual report*. WADO. <https://mbdiversificationcentres.ca/wp-content/uploads/2018/06/2017-WADO-Annual-Report-web-.pdf>
- Westman Agricultural Diversification Organization. (2021). *2021 annual report*. WADO. <https://mbdiversificationcentres.ca/wp-content/uploads/2022/04/2021-WADO-Annual-Report.pdf>
- Westman Agricultural Diversification Organization. (2024). *2024 annual report*. WADO. <https://mbdiversificationcentres.ca/wp-content/uploads/2025/06/WADO-2024-Annual-Report.pdf>
- Whalen, D.M., Bish, M.D., Young, B.G., Conley, S.P., Reynolds, D.B., Norsworthy, J.K., & Bradley, K.W. (2020). Herbicide programs for the termination of grass and broadleaf cover crop species. *Weed Technology*, 34 (1.), 1-10. <https://doi.org/10.1017/wet.2019.73>
- White, P.A. (2014). *The Growing Business of Cover Crops*. National Wildlife Federation. <https://www.nwf.org/~media/PDFs/Wildlife/A-G/TheGrowingBusinessofCoverCropsWhitePA882014.pdf>
- Wilson, R.G. & Burgener, P.A. (2009). Evaluation of glyphosate-tolerant and conventional alfalfa weed control systems during the first year of establishment. *Weed Technology*, 23 (2.), 257-263. <https://doi.org/10.1614/WT-08-082.1>
- Wiersma, J., Sheaffer, C., Nelson, G., Wyse, D., & Betts, K. (2005). Intercropping legumes in hard red spring wheat under semi-arid conditions. *Crop Management Research*, 4 (1.), 1-5. <https://doi.org/10.1094/CM-2005-0119-01-RS>
- Wong, K.M., Griffiths, M., Moran, A., Johnston, A., Liu, A.E., Sellers, M.A., & Topp, C.N. (2023). Cover crop cultivars and species differ in root traits potentially impacting their selection for ecosystem services. *Plant and Soil*, 1-18. <https://doi.org/10.1007/s11104-0223-06431-7>
- Wortman, S.E., Francis, C.A., & Lindquist, J.L. (2012). Cover crop mixtures for the western corn belt: opportunities for increased productivity and stability. *Agronomy Journal*, 104 (3.), 699-705. <https://doi-org.uml.idm.oclc.org/10.2134/agronj2011.0422>

- Wu, Q, Lawley, Y., & Congreves, K.A. (2023). Soil health indicator responses to three years of cover crop and crop rotation in a northern semi-arid region, the Canadian Prairies. *Agriculture, Ecosystems, & Environment*, 359, 108755. <https://doi.org/10.1016/j.agee.2023.108755>
- Yang, X., Drury, C.F., Reynolds, W.D., & Reeb, M.D. (2023). Legume cover crops as a primary nitrogen source in an organic crop rotation in Ontario, Canada: impacts on corn, soybean, and winter wheat fields. *Organic Agriculture*, 14, 9-31. <https://doi.org/10.1007/s13165-023-00452-3>
- Youngerman, C.Z., DiTommaso, A., Curran, W.S., Mirsky, S.B., & Ryan, M.R. (2018). Corn density effect on interseeded cover crops, weeds, and grain yield. *Agronomy Journal*, 110 (6.), 2478-2487. <https://doi.org/10.2134/agronjj2018.01.0010>
- Zagar, M., Bayat, M., & Astarkhanova, T. Study of postemergence-directed herbicides for redroot pigweed (*Amaranthus retroflexus* L.) control in winter wheat in southern Russia. *Journal of Plant Protection Research*, 60 (1.). <https://doi.org/10.24425/jppr.2019.131272>
- Zandstra, B., Particka, M., & Masabni, J. (2004). *Guide to tolerance of crops and susceptibility of weeds to herbicides*. Michigan State University, <https://www.uky.edu/Ag/Horticulture/masabni/xreflist/E-2833.pdf>

7.0 APPENDICES

A.1 Appendix A: Cover Crop Persistence in Canola

A 1.1 Methods

Cover crop persistence counts were taken at the same time as cover crop biomass in early to mid-October, prior to the first predicted killing frost. Cover crop plant counts were measured from two adjacent one-meter rows at both the front and back of the treatment plot. Mean plant counts were a combination of all species in the mixture. Deviation from emergence values (Section 3.4.2.1) was calculated by subtracting the fall persistence count from the spring emergence count per plot, which was then averaged across treatments. Statistical analysis for cover crop persistence used a reduced model as data was only collected for Carman in 2022 and 2023. Due to a high frequency of 0 counts in Carman22 from low establishment, statistical analysis was only carried out on a reduced model from 2023. Statistical analysis was conducted using ANOVA and the PROC GLIMMIX procedure. The model statement included the herbicide tolerance system and the herbicide frequency as fixed effects. Random effects in the model included replication by herbicide tolerance system interaction (to account for variation at the replication and main plot levels). Since the count data did not follow a normal distribution, the Poisson distribution was applied prior to ANOVA and back transformed for presentation.

A 1.2 Results and Discussion

Similar to biomass performance in Carman22 (Section 3.4.2.3), no trends could be derived from the persistence count data. However, in Carman23, persistence counts in the Liberty and Roundup herbicide tolerance systems followed numerical patterns consistent with biomass results from Kern22, Carman23, and Kern23. Numerically, the highest plant densities were observed in the pre-emergence only treatment, which declined with an in-season application and further decreased after a desiccant application. Statistically, there were no

differences between the densities among the different herbicide tolerance systems or herbicide frequencies for the persistence plant count taken in October.

Although the pre-emergence only treatments did not receive a post-emergence herbicide application, cover crop density numerically decreased for all treatments compared to their emergence counts because of competition with the canola cash crop. Cover crop density within the pre-emergence only treatment ranged from 15 to 20 plants m^{-2} (Table A.1). Intercropped cover crops are often at a disadvantage compared to the dominant crop, in this case, canola, which has a competitive edge due to rapid emergence and greater biomass production (Belfry & Van Eerd, 2016). Canola establishes more rapidly than the cover crops, with a taproot reaching 3 to 5 centimetres at emergence, allowing it to outcompete the cover crops for nutrients and moisture (Bagg et al., 2022). The lack of light intensity following rapid canopy closure further stresses the cover crop seedlings. High stress combined with drought and extreme heat during the 2023 growing season increases plant mortality (Schmitt et al., 2021), which could contribute to the decrease in cover crop density in October.

Unlike pre-emergence treatments, where density decreased due to competition, numerical reductions in in-season application treatments were primarily due to the herbicide application. Following an in-season application, the Liberty herbicide tolerance system resulted in the lowest plant density of 7 plants m^{-2} numerically and aligns with the lowest fall biomass among the herbicide tolerance systems (Section 3.4.2.3). The application of glufosinate resulted in extensive plant mortality, with herbicide damage ratings of 83% in clovers and 73% in alfalfa, leading to a reduction in the stand of 125 plants m^{-2} from emergence (Section 3.4.2.2.1). Numerically, the second greatest density was in the Roundup tolerance system with a density of 15 plants m^{-2} , followed by Clearfield, which resulted in the greatest density of 26 plants m^{-2} . The persistence

stand, however, was numerically greater in the Clearfield system following an in-season herbicide application compared to the pre-emergence only treatment, which may be attributed to human errors in the counts. Though the in-season application of imazamox+ imazethapyr resulted in non-severe injury to cover crops, plant densities numerically declined (-93 plants m⁻² deviation from emergence stand) when compared to emergence counts. This could be a result of competition for nutrients and limited light penetration.

Table A.1. Mean cover crop persistence in October for Carman22 and Carman23 following three herbicide frequencies (pre-emergence only, pre-emergence and in-season, and pre-emergence, in-season, and desiccant) in three herbicide tolerance systems (Liberty Link®, Roundup Ready®, and Clearfield®). All cover crop species counts were combined for the total number of plants remaining. Values in parentheses represent the departure from the June emergence count values.

Site-year	Herbicide tolerance system	Herbicide frequency		
		PRE ^a	PRE,IS ^b	PRE,IS,D ^c
		plants m ⁻²		
Carman22	Liberty (glufosinate)	1 (-13)	2 (-11)	2 (-8)
	Roundup (glyphosate)	1 (-14)	0 (-13)	0 (-18)
	Clearfield (imazamox+imazethapyr)	0 (-12)	3 (-7)	3 (-11)
Carman23	Liberty (glufosinate)	19 (-102)	7 (-125)	3 (-113)
	Roundup (glyphosate)	20 (-87)	15 (-113)	11 (-110)
	Clearfield (imazamox+imazethapyr)	15 (-121)	26 (-93)	14 (-121)

^a Pre-emergence

^b pre-emergence and in-season

^c pre-emergence, in-season, and desiccant

The same trend occurred with the application of a desiccant, where numerically the Liberty herbicide tolerance system had the lowest density of 3 plants m⁻², and Clearfield produced the greatest at 14 plants m⁻². All herbicide tolerance systems saw a numerical decline following the application of a desiccant when compared to their in-season treatments. However, unlike the in-season application, the Clearfield tolerance system saw the greatest numerical decline of 121 plants m⁻² with a desiccant application, whereas Liberty and Roundup systems saw similar reductions in density (Table 3). Diquat ion can result in complete plant death to

broadleaves and grasses 1-3 days after application and thus could have reduced the stand of the cover crop species however, previous studies on established uniform stands of red clover (Kirk et al., 2017 a) or alsike clover (Kirk et al., 2017 b) have found diquat does not reduce clover density.

B.1 Appendix B: Cover Crop Persistence in Wheat

B.1.1 Methods

Cover crop persistence counts were taken at the same time as cover crop biomass in early to mid-October, prior to the first predicted killing frost. Mean plant counts were a combination of all species in the mixture. Deviation from emergence values was calculated by subtracting the fall persistence count from the spring emergence count per plot, which was then averaged across treatments. Statistical analysis for cover crop persistence used a reduced model, as data was only collected for Carman in 2022 and 2023. Due to a high frequency of 0 counts for October persistence in Carman22 from low establishment, statistical analysis was only carried out on a reduced model from 2023. Statistical analysis was conducted using ANOVA and the PROC GLIMMIX procedure. The model statement included treatment as the fixed effect. Since the count data in 2023 did not follow a normal distribution, the negative binomial distribution was applied prior to ANOVA and back-transformed for presentation. To account for the use of the negative binomial statement, the nloptions statement was included to control the number of iterations to 500 when estimating the parameters of the negative binomial model.

B.1.2 Results and Discussion

Persistence counts in Carman23 follow the same trend as Carman23 biomass, where numerically the pre-emergence only application resulted in the greatest density, which numerically declined with an in-season herbicide application (Section 4.4.2.3). The control which had cover crops and no in-season herbicides resulted in the greatest plant stand at 11.3 plants m⁻² (Table B.1) which was nearly double the best performing in-season herbicide, which was bentazon. Although the pre-emergence only treatment did not receive any in-season herbicides, cover crop density numerically declined by 65.7 plants m⁻² and can be attributed to increased plant mortality from resource competition with wheat and cover crop species, drought

conditions, and the shallow wheat rooting system. Previous research on winter wheat intercropped with white clover saw winter wheat and clover compete for nutrients and light (Thorsted et al., 2006). When clover under seeded into wheat, it has a low competitive ability compared to the cereal counterpart, resulting in mortality (Menendez et al., 2017). Though there is competition for light, the moisture depletion from the competitive wheat crop is more detrimental, leading to clover death and non-uniform stands (Queen et al., 2009).

Table B.1. Average cover crop persistence at the end of the growing season for Carman22 and Carman23 following two herbicide frequency treatments (pre-emergence only and pre-emergence and in-season). In-season herbicides were bentazon (group 6), tralkoxydim (group 1), or pyroxsulam (group 2). All cover crop species counts were combined for the total number of plants remaining. Values in parenthesis represents the departure from the June emergence.

Herbicide	Carman22	Carman23
	plants m ⁻²	
	Pre-emergence	
Control	0.5 (-7.3)	11.3 (-65.7)
	Pre-emergence and in-season	
Bentazon	0.3 (-3.2)	6.6 (-73.5)
Tralkoxydim	0.3 (-6.7)	4.9 (-73.7)
Pyroxsulam	0.0 (-4.0)	1.7 (-65.7)

Furthermore, under low rainfall conditions, intercropped wheat has been found to be more competitive than other legumes such as chickpea (*Cicer arietinum* L.) (Kherif et al., 2021) and corresponds with our findings of decreased plant densities as drought was experienced during both years at Carman. The same competitive nature of wheat has been observed with under-seeded alfalfa, where wheat displayed competitive dominance and suppressed alfalfa growth (Ma et al., 2024). Other experiments by Wiersma et al. (2005) have found an increase in legume density when intercropped with wheat. At the time of wheat harvest, alfalfa had an increase of 32 plants m⁻² and red clover had a greater increase of 43 plants m⁻² when compared to their emergence densities.

As seen with a reduction of biomass, the same trend also occurred following the in-season herbicide applications, where the greatest density was observed in the tralkoxydim treatment, followed by bentazon, and then pyroxsulam treatments. Surprisingly, the group 6 herbicide resulted in the greatest density of all in-season herbicide applications at 7 plants m⁻². This treatment, however, resulted in a similar reduction in density as observed within the tralkoxydim treatment, with a reduction of 74 plants m⁻² as compared to the pre-emergence values. Similar to the bentazon treatment, though not producing visible injury to cover crop species, the application of tralkoxydim resulted in a stand reduction of 73.7 plants m⁻². Previous experiments on intercropped red clover have found that following an application of tralkoxydim, plant stand was reduced from 154 plants m⁻² in the untreated control to 131 plants m⁻² following a late herbicide application (Robinson et al., 2014). The lowest density was observed within the pyroxsulam treatment, where the density was 2 plants m⁻² following an in-season herbicide application. The reduction in density aligns with the high herbicide damage ratings (Section 4.2.2.2) observed for clovers, which comprised the majority of the species mixture.