The Effect of Integrated Crop Management (ICM) on Crop-Weed Competition, Weed Phenology and Weed Seed Dormancy

by

Uthpala Indeewari Ekanayake Ekanayake Mudiyanselage

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Department of Plant Science
University of Manitoba
Winnipeg, Manitoba, Canada

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LIST OF ABBREVIATIONS

AAFC – Agriculture and Agri-Food Canada

ABA – Abscisic Acid

ACCase – Acetyl-CoA Carboxylase

ALS – Acetolactate Synthase

A.I. – Active Ingredient

AIC – Akaike Information Criterion

ANOVA – Analysis of Variance

BD – Broadcasting

BIC – Bayesian Information Criterion

CAD – Canadian Dollar

CB – Crop Biomass

CD – Crop Density

CWRS – Canada Western Red Spring (wheat class)

CWSS – Canadian Weed Science Society

DAP – Days After Planting

DF – Degrees of Freedom

EEFs – Enhanced efficiency fertilizers

EMMEANS – Estimated Marginal Means (R package)

FA – Fall Application

FR – Full Rate

GDD - Growing Degree Days

GDP – Gross Domestic Product

GHG – Greenhouse Gas

GLMM – Generalized Linear Mixed-effects Models

HR – Half Rate

HWSC – Harvest Weed Seed Control

IISD – International Institute for Sustainable Development

ICM – Integrated Crop Management

IWM – Integrated Weed Management

LMM – Linear Mixed-effects Models

LSD – Least Significant Difference

MB – Manitoba

MCPA – 2-methyl-4-chlorophenoxyacetic acid

MOA – Mode of Action

N – Nitrogen

NTSR – non-target-site resistance

NUE – Nitrogen Use Efficiency

N_2O – Nitrous Oxide

PGR - Plant Growth Regulator

SA – Spring Application

SB – Side banding

SEM- Standard Error of the Mean

SK - Saskatoon

ST – Standard Weed Management

TSR – Target-site resistance

TWSW – Total Weed Seed Weight

UAN – Urea–Ammonium Nitrate

WB – Weed Biomass

WD – Weed Density

4R – Right Source, Right Rate, Right Time, Right Place

ABSTRACT

Integrated Crop Management (ICM) is a holistic framework that integrates soil, nutrient, pest, and weed management to improve agricultural sustainability and productivity. However, limited information exists on how combining nitrogen fertilization strategies with cultural weed control influences crop–weed competition, weed phenology, and weed seed dormancy in Western Canadian wheat systems. Field experiments were conducted in 2023 and 2024 at Carman, Manitoba, and Kernen, Saskatchewan, using a split-plot RCB design with four replicates. Treatments consisted of a four-factor factorial combination of nitrogen fertilizer timing (fall vs. spring application), fertilizer placement (broadcast vs. side-banding), fertilizer rate (full vs. half rate), and weed management strategy (integrated weed management, (IWM) vs. standard management). IWM included narrow row spacing (15 cm), high crop density (400 plants m^{-2}), and early seeding, whereas standard management used wider row spacing (30 cm), lower crop density (200 plants m^{-2}), and late seeding. The study evaluated ICM effects on crop–weed competition, weed phenology, and weed seed dormancy of wild oats (*Avena fatua* L.), volunteer canola (*Brassica napus* L.), and redroot pigweed (*Amaranthus retroflexus* L.). Across site-years, weed density and biomass were reduced by up to 66% and 73%, respectively, under side-banded, half-rate nitrogen combined with IWM compared with broadcast, full-rate nitrogen under standard management during favorable growing conditions at Carman in 2024. Weed height was reduced under IWM during dry conditions in 2023; however, under favorable moisture conditions in 2024, weed height increased in IWM plots, particularly under full-rate nitrogen. Flowering duration was shortened for wild oats and volunteer canola under IWM, resulting in reduced reproductive windows. Total weed seed production declined by up to 93% under full-rate nitrogen, side-banding with IWM relative to broadcasting, full-rate nitrogen with standard management. In large seeds category of wild oats, IWM exhibited lower dormancy, particularly under full-rate N. These reductions in weed pressure translated into substantial wheat yield gains, with IWM increasing grain yield by up to 140% compared with standard management across experiments. Overall, integrating weed management with nitrogen management strengthens crop competitiveness, alters weed phenology and seed dormancy, and improves wheat productivity.

CHAPTER 1

1.0 INTRODUCTION

Wheat (*Triticum aestivum* L.) is the most widely cultivated cereal worldwide and serves as a staple food for over one-fifth of the global population (McFall and Fowler, 2009). Among all wheat types, spring wheat is the key crop in Canadian agriculture, accounting for 72% of the total 34.3 million tonnes of wheat produced in 2024 (Statistics Canada, 2024), generating $22.6 billion CAD in revenue that year (IBISWorld, 2025). Wheat production faces various biotic stresses, including weeds, seedborne pathogens, fungal diseases like leaf rust (*Puccinia triticina* L.) and Fusarium head blight (*Fusarium graminearum* L.), as well as viral infections (Afzal et al., 2015). Additionally, abiotic stresses like drought, heat, cold, nutrient deficiencies, and waterlogging further threaten yields. Of these stresses, weed competition remains one of the most critical and persistent challenges for wheat production, significantly reducing crop productivity and sustainability. Weeds compete directly with wheat for vital resources such as soil nutrients, sunlight, moisture, and physical space, which hampers crop growth and yield potential (Nakka et al., 2019). In Canada, the economic toll of weed interference is considerable. From 2007 to 2017, weed-related yield losses in spring wheat ranged from 7.9% to 47.0%, translating to about 1.6 billion kilograms of wheat lost (Flessner et al., 2021). This decline resulted in an approximate financial loss of $512 million CAD to the Canadian wheat industry over that decade (Flessner et al., 2021).

For decades, herbicides have been the main method of weed control in Western Canadian agriculture. According to CropLife Canada (2003), over three-quarters of all herbicides sold in Canada were applied to field crops like cereals, pulses, and oilseeds, with about 44% specifically used in grain cereals such as wheat, rye, barley, and oats. In Canadian wheat-based cropping systems, reliance on a few herbicide modes of action has led to the spread of competitive, herbicide-resistant weeds like wild oat (*Avena fatua*), green foxtail (*Setaria viridis*), kochia (*Bassia* *scoparia*), and volunteer canola (*Brassica napus*). The number of unique herbicide-resistant weeds and the infested area have increased significantly since the first resistant weed was found in Canada in 1988 (Heap 2025). Recent estimates from 2014 to 2017 show that about 59% of agricultural fields across the Canadian Prairie region were infested with at least one herbicide-resistant weed biotype, causing an estimated annual economic loss of around $530 million CAD (Beckie et al., 2020). Also, climate variability continues to influence weed–crop competition, with changing temperatures and rainfall patterns shifting the balance among weed species. In Western Canada, unpredictable early-season rainfall further reduces the reliability of herbicides. These factors highlight the importance of integrated weed management strategies rather than relying solely on chemical control.

Integrated Weed Management (IWM) has become a key strategy to address weed-related problems in crop production (Harker and O'Donovan, 2013). This approach focuses on different stages of the weed's life cycle and uses various tactics to reduce weed reproduction, limit emergence, deplete seedbanks, and decrease competition with crops (Ferron and Deguine, 2005). IWM emphasizes combining multiple pillars: biological, mechanical, chemical, and cultural methods to lessen reliance on herbicides while still providing effective weed control (Hussain et al., 2021). Among these, cultural weed management strategies show promise because they promote crop competitiveness and suppress weed growth through simple agronomic practices like using competitive cultivars, increasing sowing rates, reducing row spacing, and planting early (Mohler 1996; Chauhan & Johnson, 2010; Harker & O'Donovan, 2013). The main goal of most cultural weed control is to increase crop competitive ability through rapid emergence, quick canopy closure, and space occupation through high plant density or narrow row spacing. Well-established crop canopies cut down the cues for weed seed germination and seedling development (Anderson, 2008). Multiple studies support these effects; Blackshaw et al. (2000) demonstrated that increasing wheat seeding rates from 50 to 300 kg ha^{-1} decreased the biomass and seed production of *Erodium citritarium* L. Similarly, Mahajan and Chauhan (2023) emphasized that early seeding dates combined with higher seeding rates and herbicide use reduced weed biomass and seed production while improving wheat productivity. Collectively, these strategies disrupt weed life cycles, hinder growth and development, and prolong the effectiveness of herbicides (Swanton and Murphy, 1996).

Nitrogen fertilizer management strongly influences crop–weed competition, and the competitive outcome depends on whether nitrogen availability is managed to favor crop uptake over weeds (DiTomaso, 1995; Kaur et al., 2018). Moreover, nutrient strategies influence not only immediate weed suppression but also interact with broader agroecosystem goals such as soil health, carbon cycling, and system resilience. Future cropping systems in Western Canada could be shaped by crops and their management practices to curtail greenhouse gas emissions related to agriculture, as these gases contribute to shifting climatic conditions that intensify both biotic and abiotic stresses (Zhang et al., 2022). Although agriculture contributes about 10% of Canada's greenhouse gas emissions, the sector plays a growing role in climate mitigation through practices like afforestation, improved nitrogen use efficiency, and soil carbon sequestration. Effective use of N fertilizer management with 4R strategies has been identified as a major path to reduce agriculture-related GHG emissions. The concept of 4R nitrogen management stewardship emphasizes applying fertilizer at the right time, in the right place, at the right rate, and from the right source, serving as a foundation for optimizing crop productivity and nutrient use efficiency while reducing GHG emissions (Johnston & Bruulsema, 2014). While N is essential for crop growth, weeds also demand this nutrient, and increased availability can disproportionately boost their competitiveness unless carefully managed (Hans & Johnson, 2002; Blackshaw et al., 2002). Guided by the 4R framework (right time, right place, right rate, and right source of fertilizer), fertilizer management goes beyond nutrient supply to directly influence ecological interactions in the field. Among these principles, the timing and placement of fertilizer applications are especially influential, as they determine whether nitrogen is accessed by crops or exploited by weeds. For example, Blackshaw et al. (2002) demonstrated that side-banding N in spring wheat reduced wild oat (*Avena fatua* L.) emergence and biomass by 25–40% compared with broadcasting, as the concentrated subsurface band was more accessible to crop roots. Similarly, Rasmussen (2002) reported 30–50% reductions in weed biomass when N was placed below the seed row rather than broadcast on the surface. In Barley cultivation, O'Donovan et al. (2008) demonstrated that side-banded nitrogen reduced green foxtail (*Setaria viridis* L.) density by 35% and reduced wild oat fecundity (up to 35%) compared to broadcast N, emphasizing that proper N placement can enhance crop competitiveness and suppress weed reproduction.

Despite these benefits of IWM and fertilizer management on weed control, current weed management strategies still focus on short-term goals like reducing aboveground weed biomass and minimizing immediate yield losses, while longer-term sustained suppression of weeds is often overlooked (Benaragama et al., 2023; Rana and Rana, 2016). Additionally, crop and weed management tactics that directly suppress weeds can create strong selective pressures, encouraging adaptive responses through phenotypic plasticity, genetic shifts, or epigenetic mechanisms (Matzrafi et al., 2025). The extent to which these selective pressures drive the evolutionary development of weed life cycle traits that promote weed persistence in agroecosystems remains unclear. To develop sustainable weed management, an eco-evolutionary framework for IWM is necessary (Menalled, 2016; Neve et al., 2009). Therefore, IWM should evolve from solely managing weed abundance to addressing the evolutionary processes that drive adaptation under both chemical and non-chemical control methods (MacLaren et al., 2020). As weed communities adapt through changes in species composition, traits, and growth patterns, weed control strategies must move beyond focusing solely on weed abundance and yield loss (Storkey, 2022). Consequently, understanding how crop production practices affect weed phenology and seed persistence, such as the timing of life cycle events and seed longevity in the soil, becomes increasingly important in sustainable weed management.

Of the adaptive traits that make weeds successful, phenology and seed persistence are paramount: they determine the timing of crop–weed competition and the capacity to persist through the soil seedbank. Weed phenology includes life cycle events such as emergence, flowering, seed maturation, and seed shattering (Otto et al., 2007). These traits significantly shape population dynamics and competitive ability (Clements and Jones, 2021). Understanding when weeds emerge, flower, set seed, and shatter is crucial for identifying the most effective times for intervention (Colbach et al., 2020). Weed persistence refers to the long-term survival capacity of weed species within agroecosystems, primarily driven by soil seedbank dynamics and influenced by weed seed dormancy, burial depth, and maternal environment (Baskin and Baskin, 2004; Finch-Savage and Leubner-Metzger, 2006). Traditionally, weed adaptation has been primarily explained through Darwinian, genetic-evolutionary perspectives (Maxwell and Mortimer, 1994). However, recent studies highlight maternal effects; non-genetic influences of the mother plant on offspring traits and environmentally induced epigenetic changes, as crucial drivers of adaptation (Bezodis and Penfield, 2025). Maternal effects encompass the influence of a mother plant's environment, physiology, or genetics on its offspring’s traits and characteristics (Donohue and Schmitt, 1998). These effects can significantly shape offspring phenotype and fitness, especially regarding seed dormancy, germination, flowering time, and seed shattering (Weiss et al., 2013). The nutrient status and stress exposure of maternal plants can alter dormancy, germination timing, and seed viability (Donohue and Schmitt, 1998; Penfield and MacGregor, 2017). Most cultural weed management practices aimed to increase crop competitiveness, such as high planting density, narrow row spacing, and early planting time, can shift flowering and pod initiation windows for weeds (Swanton et al., 2015; Yvoz et al., 2020), thereby influencing the weed seed production and their characteristics. Gunton et al. (2011) further demonstrated that sowing date and tillage modify post-germination traits such as flowering duration in weeds. A key area of research focuses on how nitrogen availability shapes weed phenological traits such as emergence, flowering time, and seed production, as well as progeny seed characteristics like germination and dormancy. Despite its recognized importance, this relationship remains underexplored, offering a promising avenue for understanding how nitrogen influences weed phenology and weed seed persistence under varying management systems. For instance, Luzuriaga et al. (2006) found that seeds produced under nitrogen-rich maternal conditions showed reduced germination rates, likely due to increased dormancy induction.

Moving beyond weed abundance, future cropping systems must consider how IWM and N fertilizer strategies act as ecological filters that select for weed adaptations by altered maternal environments, ultimately shaping weed population dynamics (Booth and Swanton, 2002; Storkey, 2022). IWM must focus on both current weed emergence and the traits that influence the persistence of future generations. Fertilizer application timing, source, rate, and placement (4R stewardship) may interact with cultural IWM practices to affect weed abundance, weed phenology, and some weed seed persistence traits. Although both fertilizer management and weed control are essential components of crop production, they are often considered separately rather than as interacting drivers of crop–weed competition, phenology, and seed dormancy. In practice, farmers must make these decisions simultaneously, while their potential additive or interactive effects on crop–weed competition, weed seed germination, dormancy traits, and yield remain poorly understood. Therefore, this research explores the combined effects of cultural weed management and nitrogen fertilizer management (right time, right rate, and right place) on crop–weed competition, identifies shifts in weed phenology, and examines weed seed dormancy in some common weed species in Western Canada.

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 An Overview of Canadian Agriculture

Agriculture is a fundamental part of the Canadian economy, rural livelihood, and global food supply. Spanning over 65 million hectares of farmland, the Canadian agricultural sector makes a significant contribution to national Gross Domestic Product (GDP), employment, and trade, accounting for nearly $135 billion in GDP and 1 in 9 jobs as of 2022 (AAFC, 2023). The Prairie provinces account for approximately 85% of Canada's 30 million hectares of arable land. Canada ranks among the top five global exporters of wheat, canola, pulses, and other cereals, supplying both domestic markets and over 190 countries worldwide (Statistics Canada, 2022). Beyond its economic importance, agriculture is vital for food security and plays a pivotal role in environmental stewardship, particularly through land use and biodiversity management (Bremer et al., 2023). The Prairie provinces: Alberta, Saskatchewan, and Manitoba, form the agricultural core of the country, producing approximately 80% of Canada’s field crops (IISD, 2021). These regions are primarily characterized by cereal-legume rotations, particularly wheat, canola, barley, and pulses like peas and lentils (Cutforth et al., 2009).

2.2 Emerging Challenges in Canadian Agriculture

Canadian agriculture faces multiple growing challenges. Climate change, including prolonged droughts, unpredictable rainfall, and warming trends is threatening crop productivity and altering planting windows and pest pressures (Bonsal et al., 2019). Soil degradation, including erosion, compaction, and loss of organic matter, remains a persistent problem, especially under continuous cropping and minimal residue cover (McKenzie et al., 2004). Besides these major ecological problems, the rising cost of agricultural inputs, including fertilizers, pesticides, and fuel, along with labour shortages and fluctuating commodity price, add financial strain to Canadian farmers

(CFA, 2022). These economic pressures hinder farmers' ability to adopt more diverse or sustainable farming practices. Furthermore, policy shifts, such as carbon pricing, environmental regulations, and trade uncertainties, pose both risks and opportunities for Canadian farmers, necessitating innovation in cropping system management (AAFC, 2018). Additionally, widespread reliance on herbicide-dependent systems has accelerated the development of herbicide-resistant weeds, with multiple resistance cases now recorded in significant weed species in Canada, including wild oat (*Avena fatua* L.), kochia (*Bassia scoparia* L.), and waterhemp (*Amaranthus tuberculatus* L.) (Beckie et al., 2020; Heap, 2024). The global rise in herbicide-resistant weeds, driven largely by intensive and repeated herbicide use, poses an increasing challenge to chemical weed control and threatens the long-term sustainability of current weed management strategies (Brunharo et al., 2022). The rapid development of cross-resistance and multiple resistance has made weed management more complex and challenging (Riechers et al. 2024). Target-site resistance (TSR), involving specific mutations at the herbicide-binding site that reduce herbicide efficacy, is among the most documented mechanisms. TSR has been well documented for ACCase- and ALS-inhibiting herbicides in several key weed species in Western Canada, including wild oats and kochia (Beckie et al. 2019; Riechers et al. 2024). However, recent research highlights the growing importance of non-target-site resistance (NTSR) mechanisms, which can confer resistance to herbicides with multiple modes of action through enhanced metabolism, reduced uptake/translocation, or sequestration (Busi and Powles, 2016). For example, wild oats, a prevalent weed in Western Canada, exhibits metabolic resistance mediated by cytochrome P450 monooxygenases and glutathione S-transferases, providing resistance to both ALS and ACCase inhibitors despite their differing targets (Délye et al. 2013; Beckie et al. 2019). Similarly, kochia in Western Canada, is increasingly exhibiting multiple herbicide resistance, including resistance to ALS inhibitors, glyphosate, and auxinic herbicides, greatly complicating its management in cropping systems (Beckie & Harker, 2017).

2.3 Agronomic and Economic Impact of Weeds

Weeds are among the most persistent and costly biological constraints in modern Canadian agriculture, significantly impacting both crop productivity and farm profitability. From an agronomic perspective, weeds compete with crops for essential resources such as light, water, nutrients, and space, often reducing yield and quality through direct competition and allelopathic effects (Liebman and Zimdahal, 2018, Swanton et al., 2015). Economically, weeds lead to yield losses, lower crop quality, and higher costs for herbicides, tillage, scouting, and labor (Liebman et al., 2001). According to Oerke (2006), global crop yield losses caused by weeds, even with conventional control measures are estimated at 10–20%, amounting to billions of dollars in annual economic losses. The extent of yield loss varies depending on crop types, weed community composition, management practices, and environmental factors, and can range from 10% to over 80% without control (Oerke, 2006). Weeds cause significant yield and revenue reductions every year in Canada. The rising occurrence of herbicide-resistant weed populations presents serious challenges to weed management, farm profitability, and ecological resilience. Herbicide-resistant weeds are estimated to decrease wheat profitability by \$20 to \$50 CAD per acre annually in Western Canada, depending on the weed spectrum and resistance profile (Beckie et al., 2020). Additional herbicide costs and tank mixes used to control herbicide-resistant weeds can raise weed control expenses by 30% to 80%, especially when layered pre- and post-emergent applications are needed (Norsworthy et al., 2012). A national survey by the Canadian Weed Science Society (CWSS) identified wild oat (*Avena fatua* L.), green foxtail (*Setaria viridis* L.), cleavers (*Galium aparine* L.), and kochia (*Bassia scoparia* L.) among the most economically damaging weeds in western Canadian cropping systems (Leeson et al., 2005). In Western Canada, management of weeds such as wild oat and kochia relies heavily on herbicides, and both target-site and non-target-site resistance have been documented across multiple herbicide classes, complicating control efforts and increasing costs (Geddes et al., 2024). The failure of herbicide-only weed control methods highlights the need to better understand weed biology and ecology, especially traits related to seed persistence, dormancy, germination, and reproductive flexibility, all of which contribute to long-term survival and reinfestation cycles in agroecosystems (Liebman et al., 2001; Neve et al., 2018).

2.4 Weed Seed Persistence and Seedbank Dynamics

Weed persistence is the ability to continually evolve, survive, thrive, and reproduce under a variety of natural and anthropogenic selection pressures (Shrestha et al., 2022). The persistence of seeds in the soil seedbank is a key driver of weed population dynamics and presents a major challenge for long-term weed management (Liebman et al., 2001). Weed seedbanks are generally classified into two categories: transient, where seeds germinate or die within a year, and persistent, where viable seeds remain in the soil for multiple years (Schwartz-Lazaro & Copes, 2019). These seedbanks serve as a buffer against unfavorable conditions and management interventions, contributing to weed resilience and long-term persistence in agroecosystems. The dynamics of weed seedbanks are governed by a set of interconnected biological processes, including seed rain (input), dormancy (delayed germination), germination, the duration viable weed seeds remain in the soil, and seed loss through predation or decay (Tozer et al., 2011). The balance among these processes determines whether a weed species will persist or decline over time. Understanding the factors that regulate these mechanisms is critical for developing effective and sustainable weed control strategies.

2.4.1 Influence of Seed-Related Factors on Weed Seed Persistence

Several inherent seed traits directly influence persistence in the seedbank. These include seed dormancy, seed size, physiological maturity, and innate longevity (Liebman et al., 2001). Dormancy plays a crucial role by delaying germination until environmental conditions are right, increasing the chances of survival and persistence (Baskin & Baskin, 2014). Small-seeded species, such as *Amaranthus tuberculatus* and *A. palmeri*, tend to have shorter viability periods but depend on high fecundity and dispersal to persist (Conn et al., 2006). In contrast, some species produce seeds capable of remaining viable for decades. For example, *Ipomoea* spp. (morning glories) can survive in the soil for at least 39 years (Toole & Brown, 1949), and *Chenopodium album* has shown multi-decade persistence under burial (Telewski & Zeevaart, 2002).

Seed input, or seed rain, is another essential factor influencing seedbank dynamics. Williams and Harvey (2002) showed that even minimal seed return (as low as 3–6% of the total yearly seed rain) could be enough to restore weed seedbanks, highlighting the need to reduce seed return in the field. Without ongoing replenishment, seed banks can decrease quickly. Burnside et al. (1986) documented a 95% decrease in the seedbank over five years in maize fields kept weed-free.

2.4.2 Influence of Biotic Factors on Weed Seed Persistence

Seed predation and microbial decay are key natural mechanisms for depleting seedbanks (Kremer & Spencer 1989). Predators such as insects, rodents, and soil fauna can consume a large portion of seeds before they germinate, especially when seeds are left near the surface (Davis et al., 2006). Soil microbial communities also play a role in seed decay, particularly under moist, warm, and biologically active conditions (Chee-Sanford et al., 2006). However, these biological processes vary greatly and are influenced by local soil properties, residue cover, and farming systems. Weed seedbank modeling studies show that natural losses from predation and decay rarely exceed 20–

30% annually without active management (Neve & Caicedo, 2022). In Canadian prairie cropping systems, seed predation rates tend to be higher in no-till systems with more surface residue, which creates favorable microhabitats for granivorous beetles and other predators (Gallandt et al., 2005; Liebman et al., 2022). Increased crop competition, like higher seeding rates, narrow row spacing, or using competitive cultivars, can affect predator activity by changing microclimate and litter dynamics. For example, dense canopies retain more moisture and provide a stable habitat for seed predators. Additionally, rapid canopy closure can shade emerging weeds, reducing seedling success and increasing the time seeds stay vulnerable on the soil surface (Walters et al., 2023). Predator activity is also affected by factors such as crop residue cover, tillage intensity, timing of seed shedding, and landscape heterogeneity (Frank et al., 2011). For instance, in diversified crop rotations or fields near natural vegetation, predator diversity and seed removal rates are often higher, indicating a link between agroecological complexity and weed control. Microbial activity is another critical factor influencing weed seed persistence. Soil fungi and bacteria can infect and break down weed seeds, especially under warm, moist, and biologically active conditions (Chee-Sanford et al., 2006). However, decay rates depend heavily on soil type, oxygen levels, microbial community structure, and carbon-nitrogen balance (Kremer & Spencer, 1989). Gardarin et al. (2010) found that decay rates weed seeds were notably higher in organically managed soils, likely due to greater microbial diversity and activity. Conversely, dry or compacted soils can restrict microbial colonization of seeds, allowing them to survive longer. Cultural practices that promote early canopy closure or root-zone competition can indirectly suppress weed seedling emergence, increasing seed exposure to biotic decay agents. Moreover, cover crops with dense root systems can influence microbial activity and moisture retention at the surface, indirectly boosting decay. Certain cover crops or companion plants, such as rye and buckwheat, produce allelopathic compounds that inhibit weed germination or seed viability. Dense root systems also alter microbial dynamics and moisture, indirectly affecting seed survival (Teasdale & Mohler, 2000).

2.4.3 Influence of Environmental and Crop Management Factors on Weed Seed Persistence

Environmental variables such as temperature, moisture, and light availability significantly influence seed persistence and germination. For instance, changing temperatures and soil moisture levels affect the rate of dormancy release and germination, thereby determining how long seeds remain in the seedbank (Korres et al., 2018). Soil disturbance from tillage impacts seed burial depth and oxygen availability, which in turn affect dormancy status and seed survival (Mohler, 2001). Crop management practices, including crop rotation, herbicide use, and canopy structure, can alter seed input and losses. Reducing seed production by controlling weed escapes promptly or improving crop competitiveness helps limit seed rain. However, herbicide failure or absence for even a single year can quickly reverse reductions in the seed bank (Burnside et al., 1986).

Seed prevalence longevity in soil results from the combined effects of the factors above and is a key indicator of the risk posed by a particular weed species. Wild oat seeds can stay viable in the soil for up to 7 years, with a small percentage surviving even longer under dry, cool, and undisturbed conditions (Beckie et al., 2020). Kochia, despite its low inherent dormancy, usually has short-lived seed banks lasting 1–2 years, but its rapid and abundant seed production combined with wind dispersal allows it to quickly re-establish populations, especially under reduced tillage (Friesen et al., 2009). While some other species like *Xanthium strumarium*, *Sida spinosa*, *Euphorbia* spp. can persist 3–4 years without seed return (Bararpour & Oliver, 1998), others may survive for decades. Even with intensive management, seedbanks can recover swiftly; for example, a single year of seed return after herbicide failure can cancel out several years of seedbank decline

(Burnside et al., 1986). Therefore, persistence depends not only on seed traits but also on the ecological and agronomic conditions in which those seeds are found. Long-term seedbank management requires a multi-year, integrated approach that simultaneously targets seed input and seed survival processes.

2.5 Introduction to Maternal Environmental Effects

Maternal plant effects refer to the influence of a mother plant's environment and physiology on the traits and characteristics of its offspring (Adji et al., 2022). These effects mainly relate to the conditions and experiences of the mother plant during seed development and early seedling growth stages. Environmental maternal effects describe how mother plants might modify their offspring's phenotype to enhance their performance in expected environments, especially if local conditions are predictable over generations (Lukić et al., 2023). The offspring's phenotype can be directly affected by the maternal environment through seed provisioning, hormonal priming, and epigenetic modifications (Herman & Sultan, 2011). Mousseau and Fox (1998) explained that for maternal effects to be considered as evolving over time, three conditions must be met: the progeny's environment should be predictable from the maternal environment, the maternal influence should improve the survival and reproductive success of both mother and offspring, and there must be genetic differences in how mothers respond to their environment, allowing natural selection to act on those traits. Several studies support this. For example, offspring of *Polygonum persicaria* L. from parent plants grown under low-light conditions allocate more resources to shoot growth than those from parents exposed to higher light. Similarly, offspring of nutrient-limited parents allocate more resources to root growth than do genetically similar offspring of nutrient-rich parents (Sultan, 1996). Puy et al. (2021) found that younger offspring of mother plants facing more intense competition exhibited better competitive performance, quicker germination, and faster growth. Larson et al. (2021) discovered that offspring of parents experiencing high levels of competition showed a more conservative resource-use phenotype. These offspring, facing stronger competition, displayed resource-conservation traits and faster development, even when they were not in highly competitive environments themselves. This maternal influence can improve a plant's ability to withstand stress and promote coexistence by reducing trait hierarchies and competition intensity (Carmona et al., 2019).

These maternal environmental effects are increasingly recognized as a form of stress memory, in which the parent plant's experiences are encoded in the physiology, hormonal balance, or gene regulation of the next generation (Crisp et al., 2016). Stress memory refers to a plant's ability to remember previous exposure to stress conditions and respond more effectively during future encounters with similar stress. This memory can be short-term (within the same generation) or long-term (passed to subsequent generations). It enables plants, including weeds, to better survive fluctuating or recurring environmental challenges such as drought, heat, nutrient deprivation, or herbicide exposure. This process exemplifies intergenerational or transgenerational stress memory, which environmental cues experienced by the parent are biologically encoded and transmitted to the next generation, influencing traits such as dormancy, germination, growth timing, and stress tolerance (Crisp et al., 2016; Lamke & Bäurle, 2017). The transfer of maternal resources, such as proteins, lipids, hormones, and RNA, into the developing seed is known as seed provisioning (Herman and Sultan, 2011). Weed competitiveness and persistence can be affected by differences in maternal provisioning strategies, especially under abiotic stressors (Herman & Sultan, 2011). As extreme adaptive and opportunistic plants, weeds may rely on these strategies to withstand repeated stresses in agroecosystems (Walkup, 2000).

2.6 Seed Dormancy

2.6.1 Types, Regulation, and Environmental Controls

Seed dormancy is the inability of a viable seed to germinate even under the most favorable germination conditions (Baskin and Baskin, 1998). During dormancy, seeds remain alive but stay in a state of suspended development until certain internal or external factors break dormancy (Bewley et al., 2013). Dormancy can be categorized into two main types: primary dormancy, which is established during seed development on the mother plant, and secondary dormancy, which occurs after seed dispersal in response to unfavorable environmental cues (Mahajan et al., 2018). While primary dormancy prevents immediate germination after seed maturation, secondary dormancy allows seeds to re-enter dormancy when conditions become suboptimal, thereby improving survival in changing environments (Soltani et al., 2019). Further seed dormancy can happen through multiple mechanisms, broadly classified as physical dormancy (caused by hard or impermeable seed coats that prevent water and gas exchange), physiological dormancy (due to internal physiological conditions that inhibit embryo growth, such as high abscisic acid (ABA) and low gibberellin (GA) levels), morphological dormancy (caused by underdeveloped embryos at seed dispersal), and others.

Weed seed dormancy can greatly influence weed control efforts in agriculture and is essential for developing effective management strategies for weed populations (Finch-Savage and Leubner-Metzger, 2006). Dormancy expression is affected by both genetic and environmental factors. Soil temperature, in particular, has been identified as a key factor in breaking seed dormancy (Bouwmeester and Karssen, 1992). The combined effects of temperature and moisture potential largely influence seed germination dynamics (Gardarin et al., 2010), affecting both seed dormancy and the rate of germination in non-dormant seeds. Additionally, factors such as daylight and soil pH are critical in altering weed seed dormancy (Baskin and Baskin, 1998). Soil pH can either increase or decrease weed seed dormancy depending on species, with both acidic and alkaline conditions known to modify dormancy release and persistence. Light has been shown to enhance the germination of *Bidens tripartita* (L.), *Carex flacca* (Schreb.), *Juncus conglomeratus* (L.), and *Scirpus sylvaticus* (L.) (Grime et al., 1981). Conversely, *Chenopodium bonus-henricus* (L.) seeds did not germinate in darkness (Khan and Karssen, 1980). Evidence also suggests that other environmental factors, such as gases and nitrates, can regulate dormancy (Benech-Arnold et al., 2000). For instance, breaking dormancy in *Sysimbrium officinale* (L.) Scop. requires both light and nitrates simultaneously (Hilhorst, 1990) During winter, seeds of the summer annual species *S. officinale* lose their dormancy and become more sensitive to nitrates (Hilhorst, 1990). Studies have also highlighted burial depth as an important factor affecting dormancy (Benech-Arnold & Batlla, 2022), indicating that agronomic practices such as tillage are significant in altering weed seed dormancy.

2.6.2 Influence of Maternal Environment on Dormancy

The conditions under which seeds develop are crucial in determining their dormancy status and germination behavior. Important factors such as nutrient availability, water stress, and temperature during seed development on the parent plant can greatly influence seed quality, hormonal balance, and physiological readiness for germination. This is mainly because the tissues surrounding the embryo, along with most of the endosperm, form during seed development and depend on nutrient and hormonal inputs from the parent plant (Donohue, 2009). For example, Gutterman (2000) reported that applying nitrogen fertilizer during seed formation can reduce primary dormancy in weed seeds, underscoring the role of nutrient availability during development. Supporting this, Alboresi et al. (2005) suggested that nitrogen may serve as a signaling molecule in the abscisic acid (ABA) and gibberellin (GA) pathways that regulate seed dormancy and germination. Consistent with these findings, Iwasaki et al. (2022) showed that the dormancy of *Brassica* seeds is affected by various environmental conditions during development, with temperature being the most influential factor. Exposure to low temperatures and dry conditions during seed maturation is associated with increased ABA accumulation, which, in turn, enhances dormancy. Conversely, higher nitrate levels in the parent plant have been shown to decrease ABA content, resulting in lower dormancy in the offspring. Springthorpe and Penfield (2015) also noted that even small changes in temperature, such as a 1°C difference experienced during the parent plant's growth, can significantly affect the dormancy characteristics of its seeds.

Light availability during seed development also plays a crucial role in dormancy regulation. Chen et al. (2020) observed that changes in plant density affect shading conditions, which in turn influence seed dormancy. Seeds produced in shaded environments tend to exhibit increased dormancy, reducing the likelihood of germination under less favorable, competitive conditions. In a related study, Kigel et al. (1977) found that when redroot pigweed (*Amaranthus retroflexus*) was grown under 73% shade, seed dormancy levels varied depending on photoperiod. Dormancy decreased under short-day conditions (8 hours of light) but increased under long-day conditions (16 hours of light), indicating a complex interaction between light duration and parental shading in controlling seed dormancy.

Although maternal environments are known to influence seed dormancy traits, their relative impact across different dormancy stages remains unclear. The maternal effect on seed primary dormancy has been extensively studied in Arabidopsis but less is known about their influence on secondary dormancy (Alboresi et al., 2005; Matakiadis et al., 2009). For example, Brown et al. (2022) demonstrated that in crop species such as volunteer canola, secondary dormancy can be triggered by adverse environmental conditions such as low temperature or insufficient light. These responses, often affected by maternal environments during seed development, help maintain the seedbank of volunteer canola. In addition to genetic and physiological factors, agricultural practices such as harvest timing and tillage also influence secondary dormancy induction in buried canola seeds, emphasizing the complex interaction between maternal effects and field management in determining weed persistence.

2.7 Germination

Weed seed germination is a critical phase in the life cycle of weeds and a primary factor determining their establishment, and survival. Germination is the process by which a viable, non-dormant seed resumes metabolic activity after water uptake (imbibition) and completes embryo growth, resulting in the emergence of the radicle from the seed coat (Baskin and Baskin, 2014). Germination is regulated by a complex interplay of environmental cues, edaphic, internal physiological and genetic conditions (Baskin and Baskin, 2014). Understanding the biological and ecological factors that influence germination is essential for designing effective weed management strategies. At the most fundamental level, seed germination depends on external physical and chemical cues, including temperature, moisture availability, oxygen, and light. According to Baskin and Baskin (2014), non-dormant seeds require specific temperature ranges to initiate germination, and some respond best to alternating day/night temperatures, which mimic natural fluctuations in the field. Water availability is critical for imbibition, the first step in germination. However, over-saturation can create anoxic conditions that inhibit germination (Baskin and Baskin, 2014). Adequate oxygen is required for aerobic metabolism during germination, and oxygen limitations due to waterlogging can delay or prevent the process. Seeds require exposure to light (positive photoblastic), while others are inhibited by it. Light sensitivity is often associated with shallow burial in the seedbank and plays a major role in germination (Baskin and Baskin., 2014). Beyond these external signals, internal genetic and physiological factors influence how seeds interpret and respond to environmental stimuli. Hormonal balance plays a central role, particularly the ratio between abscisic acid (ABA), which enforces dormancy, and gibberellins (GA), which promote germination by stimulating enzymatic degradation of endosperm reserves (Tuan et al., 2018). These hormonal interactions are further modulated by the conditions under which seeds develop, especially within the parental plant.

2.7.1 Influence of Maternal Environment on Germination

The temperature during maternal seed maturation influences which phytochromes are activated during germination, thereby modifying the light sensitivity settings of the resulting seeds (Donohue et al., 2008). Red and far-red photoreceptors called phytochromes control how plants react to light during germination (Casal and Sanchez, 1998). In the Brassicaceae family, particularly in *Arabidopsis thaliana*, it has been shown that certain knockout mutants retain the ability to germinate even when seeds mature under elevated temperature conditions, provided that the maternal plants are exposed to a sequential regime of warm followed by cold imbibition in darkness (Tamura et al., 2006). Seeds matured under high temperature and short photoperiods while on their maternal plants generally exhibit reduced dormancy and increased germination rates, potentially due to altered hormonal signaling or developmental programming (Baskin & Baskin, 2014; Karssen, 1982). For example, Matzrafi et al. (2020) reported that maternal heat stress in *Amaranthus palmeri* significantly reduced seed dormancy and increased germination, facilitating rapid emergence under favorable conditions. Water stress faced by mother plants during seed development can also influence progeny seed behavior. Drought-stressed maternal plants often produce seeds with traits that enhance drought tolerance during germination (Chen et al., 2021). Drought stress experienced by the parent plant during seed development can lead to physiological and biochemical changes in the developing seeds, resulting in altered dormancy, hormonal balances, and germination responses (Benech-Arnold et al., 1991). Drought-stressed plants often produce seeds with increased abscisic acid (ABA) levels, reduced sensitivity to gibberellins (GA), or altered seed coat properties, all of which contribute to improved drought tolerance during germination (Chen et al., 2021). Other maternal environmental factors, such as seed position in the plant, nutrient availability, and resource allocation, also influence germination dynamics. Boyd et al. (2007) demonstrated that the architectural position of *Arabidopsis thaliana* seeds on the maternal plant affected their likelihood to germinate. Nutrient availability, especially nitrogen and phosphorus, influences seed mass and vigor, which are associated with germination success. Seeds produced under nutrient-deficient conditions tend to be smaller and may show delayed or reduced germination, although some weed species adaptively modify seed composition to improve early survival (Benech-Arnold et al., 2000; Fenner, 1991). These effects are particularly significant in agroecosystems where soil fertility fluctuates due to management practices. Additionally, the maternal environment shapes seed coat structure, influencing permeability, mechanical strength, and responsiveness to germination cues (Radchuk and Borisjuk, 2014). Seeds developing under stress conditions often have altered seed coat characteristics that can delay water uptake or protect the embryo under suboptimal conditions (Mohler, 2001). These structural modifications further contribute to maternal control over germination behavior. Maternal environmental effects create variability in weed seed germination, complicating the prediction of weed emergence and reducing the effectiveness of management strategies that assume uniform seed behavior (Merfield, 2013).

Integrating maternal effect knowledge into integrated weed management (IWM) programs such as modifying crop canopy characteristics, crop architecture like row spacing and densities, as well as using cover crops and intercrops, could influence not only crop-weed competition but also alter weed seed persistence, as discussed above. The overlap between the weed's emergence window and the crop canopy's development, caused by changes in environmental cues like light and fluctuating temperatures that affect seed germination, will determine how effectively a crop canopy controls weed emergence (Kruk et al., 2006). Understanding how seed sensitivity to light varies over time enables better planning of sowing dates. By planting at times when weed seeds on the soil surface are most responsive to light cues, and when the canopy exposes more far-red wavelengths, it is possible to reduce weed germination. This strategy exploits natural light conditions to suppress weeds without additional inputs.

2.8 Flowering

Flowering is a vital life-cycle event that directly impacts reproductive success and, consequently, population dynamics. Understanding weed flowering patterns and how they respond to various crop and weed management practices can improve the timing of control measures, reduce seed production, and decrease persistence. Weeds that flower early in the season may avoid control measures such as mowing, herbicide application, or tillage. At the same time, late-flowering species may produce viable seeds after crop harvest, replenishing the seedbank (Gaba et al., 2012). Weeds that synchronize their flowering with crops can compete more effectively for pollinators and resources, whereas asynchronous flowering may lessen overlap in resource demand but also extend periods of competition (Ghersa & Holt, 1995). Flowering is also affected by numerous physical, chemical, and environmental factors. High temperatures usually accelerate flowering onset by shortening the vegetative phase (Wilczek et al., 2009). This may lead to earlier but often shorter flowering periods. Shorter photoperiods can delay flowering in long-day species but speed it up in short-day plants (Fenner, 1998). Water availability also directly influences flowering duration; for example, under drought stress, many annual weeds exhibit early and rapid flowering as a drought escape strategy (Franks, 2011). Besides these primary environmental factors, various agronomic practices also affect flowering. High crop density and dense canopy cover cause shading and resource competition, which can delay flowering onset in weeds (Mohler, 2001). Reduced light quality (low red:far-red ratio) under dense canopies slows floral initiation and might shorten flowering periods in shade-sensitive weeds (Brainard et al., 2005). Practices like tillage, mowing, or herbicide application can promote early flowering or favor fast-regenerating individuals (Gaba et al., 2011). High soil nitrogen levels generally accelerate flowering and can extend it's duration by supporting greater biomass and sustained reproductive effort (Blackshaw et al., 2003).

2.8.1 Influence of Maternal Environment on Flowering

Mother plant's management practices also significantly influence flowering phenology. Recent literature highlights the roles of light, temperature, and planting time of mother plants on the flowering traits of their offspring. Findings suggest that photoperiod and temperature experienced by the mother plants are key environmental factors affecting flowering timing in the next generation. Burgess et al. (2007) showed that the timing of maternal flowering not only determines the germination period of progeny seeds but also influences whether the next generation develops as an annual or biennial. For instance, in *Campanulastrum americana* L., seeds from early-flowering plants tend to germinate in fall, resulting in annuals, while seeds from later-flowering plants are more likely to germinate in the following spring, producing biennials. Gunton et al. (2011) found that the timing of management practices such as seed sowing and tillage applied to the mother plant affects the flowering onset of their offspring. Franklin and Whitelam (2005) discussed how plants perceive and respond to changes in light quality, especially the red to far-red light ratio, which serves as a key indicator of vegetation density and competition. They explain that a low red to far-red ratio, common under dense canopies like those of cereal crops, accelerates flowering and leads to shorter weed flowering periods under cereal crops. Senseman and Oliver (1993) investigated flowering behavior and somatic polymorphism in three major weed species: pitted morning glory (*Ipomoea lacunosa*), common cocklebur (*Xanthium strumarium*), and sickle pod (*Senna obtusifolia*), under both interspecific interference with soybean and non-interference conditions. They demonstrated that interspecific competition with soybean caused a significant reduction (85–99%) in flower number across all weed species.

2.9 Seed Production

Weed seed production is a key aspect of weed population dynamics and long-term survival. Various factors, including environmental conditions, crop management practices, and interactions with neighboring plants, influence it. Among these, abiotic factors such as light availability, soil moisture, nutrient levels, and temperature directly affect weed growth, reproductive efforts, and ultimately seed production (Radosevich et al., 2007). Light availability plays a crucial role in photosynthesis and seed development. Shaded environments, especially under dense crop canopies, generally decrease weed biomass and seed output (Brainard et al., 2005; Mohler, 2001). Soil fertility notably impacts weed growth and reproduction. Excessive nitrogen levels often lead to increased weed biomass and seed production (Blackshaw et al., 2003). For example, *Amaranthus retroflexus* and Setaria spp. produce significantly more seeds in nitrogen-rich soils compared to nutrient-poor soils (Blackshaw et al., 2003).

Beyond environmental factors, crop management practices, especially those that enhance crop competitiveness play a crucial role in reducing weed seed production. High seeding densities, narrow row spacing, optimal fertilization, and the use of fast-growing, early canopy-closing cultivars can suppress weed growth and seed production by limiting light, space, and resources (Liebman & Davis, 2009). Kegode et al. (1999) demonstrated that crop rotations incorporating conservation tillage and increased crop diversity significantly decrease grass and broad-leaved weed seed production, regardless of management input levels. Weed seed production in *Viola arvensis* L. and *Papaver rhoeas* L. rises significantly under lower wheat crop densities due to increased weed biomass, with *P. rhoeas* especially producing abundant seeds without crop competition (Wilson et al., 1995). Edwards (1980) found that *Sinapis arvensis* L. produced 1.5 to 15 times more seeds under low-competition conditions, and Chancellor and Peters (1970) showed an approximately linear decline in wild oats seed production with increasing wheat density. The timing of weed emergence relative to the crop is another key factor. Weeds that emerge before or alongside the crop often face less competition and can allocate more resources to seed production. Conversely, late-emerging weeds are usually suppressed by the crop canopy and produce far fewer seeds. Research indicates that delaying weed emergence by just a few weeks can reduce seed production by over 90% in some species (Knezevic et al., 2003). Similarly, flowering time and the length of the flowering period influence reproductive success under competitive conditions. Weeds that flower early may avoid peak competition and environmental stresses, completing their life cycle before conditions become unfavorable. However, early flowering often results in smaller plants and fewer flowers, which can limit seed yield (Franks, 2011; Gaba et al., 2012).

2.10 Seed Shattering

Seed shattering is common in weeds and happens when seeds mature and drop naturally. Although seed shattering is largely under genetic control, environmental conditions, agronomic practices, and maternal effects can modify its expression and influence the degree of shattering observed in the field (Burton et al., 2016). Weed seed shattering is a key factor in seed bank dynamics and persistence (Delouche et al., 2007; Burton et al., 2016). Because seed shattering makes it easier for seeds to disperse from the mother plant and establish in specific ecological niches, it is crucial for the survival and spread of many wild weed species (Delouche et al., 2007). Various interventions such as agronomic, physiological, hormonal, and pharmacological can be used to manipulate the timing of weed seed development, helping weeds retain their seeds longer. Delaying or preventing seed shattering allows for more seeds to be collected and destroyed during harvest (Ashworth et al., 2016). The seed-shattering phenology in arable weeds can vary greatly and is heavily influenced by the agronomic practices applied for the mother plants (Walsh and Powles, 2014). Environmental factors throughout growth, especially during blooming and anthesis, can impact both the timing and extent of seed shattering (Konishi et al., 2006). Malamasuri et al. (2005) found that the nutrition level of the mother plant and soil fertility influence seed initiation, shattering time, and seed quality and quantity in sunflowers. Higher nitrogen levels resulted in larger seed heads, more seeds, and better seed quality, with earlier seed shedding observed under high nitrogen conditions. By exploiting variations in seed shattering timing, strategies like harvest weed seed control (HWSC) and other crop management practices aim to limit weed reproduction and reduce weed seed persistence in the soil (Maity et al., 2021). Levels of seed shattering vary significantly between weed species, cropping systems, and climates; adjusting sowing times and choosing early-maturing cultivars can help improve control efforts, especially against species like green foxtail (*Setaria viridis*) or wild oat (*Avena fatua*) that shatter early (Walsh et al., 2018). The current literature does not fully understand how anthropogenic, environmental, and genetic factors combine to influence seed shattering behaviors in weeds. To enhance integrated weed management (IWM) tactics, a more thorough examination of the adaptive processes controlling seed shattering is necessary. Understanding the selective pressures from different control strategies such as mechanical, cultural, and chemical, can offer valuable insights into managing seed-shattering traits in weeds.

2.11 Phenotypic Plasticity

Phenotypic plasticity offers a flexible response system that allows plants to survive in unpredictable or rapidly changing environments during the growing season (Alpert & Simms, 2002). As plants progress through their life cycle, they must react to conditions that may differ from those experienced by the parent plant. This is when phenotypic plasticity becomes crucial. Environmental heterogeneity is widespread across many spatial scales. Through pollen and seed transfer or changes in the local environment, plants can be exposed to different habitats across generations (Herman & Sultan, 2011). Both the neo-Darwinian evolutionary model and Mendelian genetics agree that a plant's environment and genotype interact to shape its phenotype (Davila-Velderrain and Alvarez-Buylla, 2014). Traditionally, adaptation was seen as a gradual process driven by genetic mutation and natural selection over long periods. However, a single genotype can express multiple phenotypes under different environmental conditions thanks to adaptive phenotypic plasticity (Schmalhausen, 1949). Phenotypic plasticity is a common way for plants to adapt to environmental changes (West-Eberhard 1989). Changes in trait expression in response to the environment can be passive reactions to resource limitations, like reduced biomass under poor lighting and nutrients (Whitman and Agrawal, 2009). More often, though, plasticity is a functional modification of the phenotype that enhances fitness in the current environment (Van Kleunen & Fischer, 2003). This plasticity also helps weeds adapt to environmental shifts, enabling them to withstand disturbances in agroecosystems such as herbicide use, tillage, and competition with crops—often making them harder to control. Adaptive plasticity can drive evolutionary change over both short and long timescales, from single-generation responses to longer-term genetic shifts shaped by selection (Hendry, 2016; Reznick & Ghalambor, 2001). In Canada, species like *A. retroflexus, A. powellii*, and *A. hybridus* are noted for their remarkable plasticity and adaptability, allowing them to thrive in a wide variety of environments, including both agricultural (agrestal) and disturbed (ruderal) habitats. Their seeds exhibit variable dormancy and polymorphic germination, influenced by maternal environment, highlighting a trans-generational plastic strategy (Costea et al., 2004).

The interplay of maternal environmental effects and phenotypic plasticity provides weeds with a powerful combination of inherited traits and environment-driven responses, forming a crucial basis for weed adaptation (Galloway, 2005). Weeds are plants that thrive under both natural and human-made selection pressures. Their ability to survive and succeed in various and often tough conditions results from multiple reinforcing traits and strategies, including maternal effects, stress memory, and phenotypic plasticity. Stress memory is the biological ability of a plant to "remember" previous exposure to stress, such as drought, heat, salinity, or herbicides, and respond more effectively when faced with the same or similar stress again (Thellier, 2017). The success of weeds is largely due to a collection of biological and ecological traits that improve survival, competitiveness, and persistence across a wide range of environmental conditions and management practices (Ghersa et al., 2000; Radosevich et al., 2007). These adaptive mechanisms give weeds an advantages in traits like germination, growth, stress tolerance, reproductive success, and competitive ability, allowing them to survive and flourish under diverse environmental and management conditions (Gaba et al., 2017).

2.12 Integrated Weed Management (IWM)

Integrated weed management (IWM) is a comprehensive approach to weed control that combines various weed-control techniques to provide the crop an advantage over weeds (Harker and O'Donovan, 2013). By combining diverse management strategies, IWM helps maintain weed populations at manageable levels, enhances the sustainability of cropping systems, and reduces the selection pressure that drives the evolution of herbicide-resistant weeds (Scavo and Mauromicale, 2020). The goal of integrated weed management is to keep weed populations below an economic threshold, focusing less on eradication and more on containment and increasing weed diversity (Cardina et al., 1999). This is achieved by targeting different stages of the weed's lifecycle and implementing strategies to prevent weed reproduction, reduce weed emergence, deplete seed banks, and limit competition with the crop (Ferron and Deguine, 2005). IWM involves a variety of tools and timely actions to lessen the impact of weeds on crops (Liebman et al., 2001). It is built on four main pillars: cultural, mechanical, chemical, and biological control methods. By combining these methods, integrated weed management (IWM) is widely recognized as a sustainable alternative to depending solely on herbicides (Lewis et al., 1997). Unlike exclusive reliance on chemicals, advocates of IWM emphasize the importance of using a diverse range of weed control techniques (Swanton & Weise, 1991). The concept of "many little hammers," first introduced by Liebmann and Gallandt (1997), highlights the value of employing multiple small-scale tactics to reduce selection pressure for herbicide resistance. According to Soltani et al. (2023), using diverse crop and weed management techniques effectively controls water hemp in maize, soybeans, and wheat while decreasing the number of viable water hemp seeds in the seedbank.

Farmers should proactively diversify their crop and weed management strategies by implementing practices such as rotating crops, increasing seeding rates, narrowing crop rows, using tillage at key rotation points, adding cover crops after winter wheat, and gradually integrating various herbicide modes of action.

2.12.1 Cultural Weed Management

Cultural weed control is a fundamental aspect of integrated weed management (IWM). Over time, cultural weed control methods have developed around enhancing crop competitive ability. Three key factors affecting crop-weed competition have been identified: First, the timing of weed emergence relative to the crop (Kropff and Spitters 1991). Weeds that emerge at the same time or earlier than the crop tend to be more competitive and cause greater yield losses than those that emerge later (Fahad et al., 2015). For instance, early-emerged redroot pigweed (*Amaranthus retroflexus* L.) in soybean (*Glycine max* L.) and corn (*Zea mays* L.) can reach threshold levels 8–10 times higher than weeds that emerge after the crop (Dieleman et al., 1996; Knezevic et al., 1994). Although weeds that emerge later are less competitive in terms of yield loss, they can still impact both yield quality and quantity (Dieleman et al. 1996). The second factor is weed seedling density, where higher density correlates with earlier interference. As a result, the length of the critical period for weed control heavily depends on weed seedling density (Dunan et al., 1996). The third factor involves weed species identity, as different species vary significantly in their competitive ability due to traits such as dense root systems, rapid leaf development, plant height, and specific morphological, reproductive, and life-cycle characteristics (Swanton et al., 2015).

Narrow row spacing, high crop density, and early crop seeding are the most common cultural practices in IWM to enhance crop competitiveness (Knezevic et al., 2003). Numerous studies have shown that narrow row spacing effectively suppresses weed growth by promoting early canopy closure and reducing light availability to weeds. Fahad et al. (2015) demonstrated that wheat grown in narrow rows (11 cm) significantly suppressed the growth and seed production of *Galium aparine* and *Lepidium sativum* compared to wider row spacings (15 cm and 23 cm). Narrow row spacing generally inhibits weed growth in wheat, even when wider crop rows make intercultural activities easier. Mohler (1996) also showed that increased crop density decreases weed emergence and growth of many annual weeds. Not only in wheat, but several other crops, like soybean, planted in narrow spacings (15-19 cm), significantly reduce total weed biomass and increase crop yield, often achieving similar or even higher net returns compared to soybean planted in 57-95 cm rows (Johnson et al., 1998; Young et al., 1994). A meta-analysis by Spokas and Forcella (2009) revealed that narrow rows suppressed weed density by 42%, reduced weed biomass by 71%, and increased soybean yield by 12% compared to the standard 76 cm row spacing. Narrow row spacing, combined with crop shading, can improve weed management without raising costs or harming the environment (Barberi, 2002). Narrow rows give the crop a competitive advantage over weeds by capturing resources more effectively (Chauhan and Johnson, 2010; Kristensen et al., 2008; Mashingaidze et al., 2009;).

Alongside row spacing, increasing crop density or seeding rate is an effective IWM strategy. Kolb et al. (2012) reported that increasing spring wheat seeding rate from 400 to 600 plants per square meter reduced weed density by 64%. Similarly, Van der Meulen and Chauhan (2017) identified high crop density as a critical component of integrated crop management, reducing weed pressure and promoting wheat growth, while Chauhan and Gill (2014) noted that higher seeding rates improve both crop density and performance. Numerous Canadian and international studies support the claim that rates higher than recommended enhance weed suppression in wheat (Blackshaw et al., 2000; Carlson and Hill, 1985;), barley (O’Donovan et al., 1999), and canola (Harker et al., 2003; O'Donovan, 2001). The importance of seeding density as a cultural IWM strategy has also been demonstrated in on-farm studies across Alberta (O'Donovan et al., 2001).

Besides row spacing and seeding rate, planting time is crucial for weed suppression and crop competitiveness. Early planting can give crops a vital advantage by allowing them to establish before weeds appear. Bullied et al. (2006) noted that canola's competitiveness and yield both increased with early seeding, likely due to better resource use and earlier canopy coverage in Manitoba. Likewise, early-planted soybeans have been shown to intercept more light, close their canopy sooner, suppress weed growth, and achieve higher photosynthetic efficiency and seed yields (Yelverton & Coble, 1991).

These cultural weed management strategies that reduce reliance on herbicides, such as early planting and increased crop competitiveness, not only cut herbicide costs but also reduce the selection pressure for herbicide-resistant weed biotypes and lower the environmental impact of chemical use. Traditionally, wheat is planted later in the growing season, requiring reliance on pre-seeding weed control followed by in-crop herbicide applications to manage subsequent weed competition. In contrast, ultra-early wheat planting systems, as outlined by Collier et al. (2020, 2021), involve seeding before most weeds emerge, when soil temperatures stay below 6 °C. This approach encourages early crop emergence, increasing the crop's ability to compete against weeds that appear later in the season. To address this limitation, fall-applied residual soil herbicides—which have proven effective in other crop systems in western Canada—can be used to control early emerging weeds and maintain weed suppression during critical early growth periods (Jha & Kumar, 2017; Johnson et al., 2018).

2.12.2 Biological Weed Management

Biological control of weeds involves using natural enemies such as insects, pathogens, and competitive plants to suppress weeds (Zimdahl, 1993). The main benefit of this approach is its potential to offer long-term and environmentally friendly control with minimal input after establishment. Biological control is defined as an ecologically sound, selective method that employs host-specific control agents to target specific weeds without harming native plants or non-target crops (Pleban & Strobel 1998; Rosenthal et al. 1985). Biological weed management is often carried out using either the classical or augmentative methods. According to Zimdahl (1993), the classical ecological technique involves inoculating weed populations with a self-sustaining biological agent that feeds on the targeted weed species. Similar to herbicide applications, the augmentative or inundative strategy involves applying bioherbicidal annual sprays of endemic or foreign agents (Goeden, 1999). According to McFadyen, (1998), the success of biological weed management typically occurs in distinct phases. However, for financial reasons, the effectiveness of biocontrol agents using the classical method has been limited to situations where the weeds are invasive in aquatic, forest, or range land (Abbas & Barrentine 1995; Randall 1998). Due to many challenges, the biological pillar of IWW is not widely practiced on large-scale farms in the prairies.

2.12.3 Mechanical Weed Management

Mechanical methods physically disrupt weed growth and include tillage, mowing, hoeing, and flaming. These approaches are often used alongside cultural practices in both conventional and organic systems. Tillage is effective at uprooting established weeds and burying weed seeds. However, it can cause soil erosion and disturb soil structure, making it less suitable for conservation agriculture (Derpsch et al., 2010). Although primary and secondary tillage, along with mowing and cutting, significantly affect weeds, mechanical weed management is mostly associated with tertiary tillage. Inter-row cultivation has been revitalized with the advent of precision technologies, allowing selective removal of weeds between crop rows while minimizing crop injury (Christiansen et al., 2020). It is quite costly and labor-intensive, making it impractical as a primary or stand-alone weed control method (Pannacci et al., 2017). The effectiveness may also depend on the weed species present; for example, hand weeding is probably less effective against species that can re-establish from plant fragments (Peerzada, 2019).

2.14.4 Chemical Weed Management

Chemical weed control involves using herbicides to manage weed populations. It is currently the most widely adopted method due to its efficiency and scalability. Herbicides are classified by their mode of action (e.g., photosystem II inhibitors, ALS inhibitors) and application timing (pre-emergence vs. post-emergence). Common examples include glyphosate, atrazine, and 2,4-D. Extensive use of chemical herbicides has led to the emergence of herbicide-resistant weeds, as explained above. In the Canadian Prairies, resistance mainly involves Group 1 (ACCase inhibitors) and Group 2 (ALS inhibitors), with frequent cases in wild oat (*Avena fatua*) and kochia (*Bassia scoparia*) (Sutherland et al., 2025). Therefore, combining all components together is always recommended to minimize the drawbacks of each. Several studies highlight the importance of combining different weed control tools in Integrated Weed Management (Anderson 2000, 2005; Blackshaw et al., 2005, 2008; Holm et al., 2006; Kolbe et al., 2012; Melander et al., 2005; Wang et al., 2012).

2.15 Integrated Nutrient Management (INM)

Integrated Nutrient Management (INM) has become a vital strategy for achieving sustainable agricultural productivity while preserving soil and environmental quality through optimized fertilizer use. INM involves the careful and combined application of inorganic fertilizers, organic manures, crop residues, green manures, and biofertilizers to supply essential nutrients for crop growth and to maintain or improve soil fertility (Meena & Reddy, 2021). This comprehensive approach aims to enhance nutrient use efficiency, decrease dependence on chemical fertilizers, and support long-term agricultural sustainability (Costa et al., 2020).

Soil fertility management is essential not only for crop growth, development, and achieving optimal yields but also for weed control. Fertilizer application can sometimes benefit weeds more than crops because weeds tend to absorb nutrients faster and more efficiently than crop plants (Balasubramanian and Palaniappan, 2004). The source, amount, timing, and method of fertilizer application can affect herbicide effectiveness (Mithila et al., 2011), as well as weed emergence, persistence, distribution, dormancy, dynamics, and growth characteristics (Bajwa et al., 2022). Blackshaw & Brandt (2008) found that at lower nitrogen levels (60 mg N kg^{-1} soil), *Amaranthus retroflexus* was less competitive than spring wheat. However, as nitrogen availability increased to 240 mg N kg^{-1} soil, the weed became more dominant, shifting the competitive balance in its favor. In another study, applying 50–150 kg N ha^{-1} resulted in an 82–160% increase in weed biomass, while rice biomass grew even more significantly, by 92–229% under flooded conditions, suggesting that nitrogen fertilization benefits the crop more than the weeds in such environments (Awan et al., 2016). Soil nutrients, especially NO3-N and organic matter, are linked to weed seed survival and development (Davis et al., 2005).

Seed persistence is also strongly influenced by soil nutrient conditions, with fertility levels affecting seed longevity and germination dynamics. Weed seeds performed better in soils with higher pH values and lower C:N ratios (Pakeman et al., 2012). Fawcett & Slife (1978) showed that lamb's quarters exhibited strong seed-level responses to nitrogen, where seeds from nitrate-treated plots were less dormant and germinated at much higher rates (34% vs. 3% in controls). Seeds also accumulated more nitrate internally (126.3 μg/g at 280 kg/ha N vs. 18.7 μg/g in unfertilized controls). Karimmojeni et al. (2014) also demonstrated that maternal N affected *Amaranthus retroflexus* seed persistence traits; higher fertilizer rates (100 kg/ha) increased germinability, while 200 kg/ha promoted greater dormancy. Potential impacts on microbial communities and their subsequent effects on weed seed degradation in soil may be caused by soil organic carbon and moisture (Chee-Sanford et al., 2006). Volunteer canola seed survival over winter was significantly correlated with soil texture, bulk density, organic matter, cation exchange capacity, and soluble salt content (Geddes, 2013). Nitrogen fertilization also contributes to microbial seed deterioration (Davis et al., 2006). However, strategic control of soil nutrient levels is essential for sustainable weed management in conjunction with optimizing crop nutrient availability.

2.15.1 4R Nitrogen Management Stewardship

The 4R nutrient management stewardship is a global framework for sustainable fertilizer use. It provides guidelines for applying the right source, at the right rate, right time, and right quantity (Reetz et al., 2015). 4R practices align with farm management goals, including profitability, productivity, durability, and environmental health. According to the United Nations Sustainable Development Goals, the 2015 Paris Climate Conference (COP21), and the 2017 Pan-Canadian Framework on Clean Growth and Climate Change, Canada can meet its environmental sustainability targets while ensuring food security by adopting the 4Rs, which boost agriculture's resilience, productivity, and sustainability. Canadian 4R Research Network (2019) showed that the 4R strategy can reduce greenhouse gas emissions by up to 75%, increase yields by over 20%, and cut phosphorus runoff by 60% in Ontario's maize farming. In Manitoba, GHG emissions from wheat can be lowered by up to 55%. Nitrate leaching into the soil can be reduced by up to 32% in Prince Edward Island through the use of the 4Rs in potato farming.

The 4R Nutrient Stewardship framework was developed as a practical guide to ensure that fertilizer application is managed responsibly, aligning agricultural practices with environmental protection, social responsibility, and economic sustainability. On the Canadian Prairies, fertilizer management strategies are highly diverse and dictated by many interacting factors such as weather, farm size, farm equipment, crops, and cropping systems. Nitrogen fertilizer was traditionally applied by broadcasting (McKenzie et al., 2004). Due to the size of farms, many growers are practicing urea broadcasting to increase operational efficiencies, which includes speeding up the seeding process. Farmers are more concerned about the start date of their cultivation because it has been found that delaying crop seeding beyond May 1st in southern Alberta can lead to significant yield reductions, with studies showing daily yield losses ranging from 0.6% to 1.7%, depending on the crop (Alberta Agriculture, 2023). In addition, recent research indicates that applying urea or urea ammonium nitrate (UAN) at shallow depths (less than 2 inches below the soil surface) results in nitrogen losses similar to surface broadcasting, making these methods less efficient for nitrogen retention and crop uptake (Grant et al., 2016). Therefore, identifying appropriate fertilizer application timing, placement, and rate for farmers through agricultural research is an immense need.

2.15.2 Timing of Fertilizer Application (Right Time)

Fertilizer application timing is a key factor in 4R nitrogen management. The best timing depends on the crop's growth stage and peak nutrient needs. Proper timing involves considering weather conditions, other time-sensitive tasks, the logistical and physical constraints of applying fertilizer, and crop height (Reetz et al., 2015). In western Canada, fall and spring are the two main fertilizer application periods. For mobile nutrients like N, timing is more critical than for P and K, which are more stable in the soil. N is prone to multiple loss processes, especially under wet conditions that increase leaching and denitrification. To meet crop growth needs while reducing potential N losses to the environment, N application should be as close as possible to the required time. of rapid crop absorption. This will help to limit losses and enhance N use efficiency.

The Canadian 4R Research Network (2019) showed that in Manitoba, applying urea in spring at planting reduces more GHG emissions than fall application. Comparing fall-applied versus spring-applied nitrogen in spring wheat, Blackshaw et al. (2004) found that spring application decreased the density and biomass of key weeds such as wild oat, green foxtail, wild mustard, and lamb's quarters. Evans et al. (2003) provided additional evidence, noting that the timing of fertilizer application plays a crucial role in shaping crop–weed competition. They observed that applying fertilizer early in the crop's growth cycle can give the crop a competitive advantage, thereby suppressing weed growth, while delayed applications may instead increase weed competitiveness. Consistent with Sweeney et al. (2008), early-season (early-spring) nitrogen applications in maize stimulated weed germination that would otherwise remain dormant, leading to greater late-season (late-spring) competition with the crop. Applying nitrogen at planting in April (spring) can accelerate weed emergence timing and increase abundance. Furthermore, the same study identified that when nitrogen sources such as urea or UAN are broadcast at planting, weed germination speeds up, likely because the added fertilizer increases available soil nitrogen during a critical germination window. Blackshaw et al. (2005) found that spring-applied fertilizers reduced weed biomass and increased field pea yield, indicating that proper nutrient management can enhance crop performance. Applying fertilizers in the fall on the northern Great Plains is generally effective because, by then, soil temperatures have dropped, and microbial activity has slowed. As a result, the active ingredients in most fertilizers remain stable in the soil and are still effective when weeds begin to emerge the following spring (Cessna et al., 2017). Fall-applied nitrogen fertilizers face a higher risk of loss, especially in cold weather, through processes such as denitrification, which can lead to nitrogen losses of up to 35%, particularly in wet conditions on Saskatchewan soils (Aulakh & Rennie, 1986). Additionally, 7–20% of the nitrogen may become immobilized in the soil, making it unavailable to crops in the spring.

2.15.3 Source of Fertilizer (Right Source)

Selecting the right nitrogen source involves providing nitrogen in a chemical form that matches crop uptake needs and minimizes nutrient loss pathways such as volatilization, leaching, and denitrification. Enhanced efficiency fertilizers (EEFs) are widely recognized as effective options within the 4R Nutrient Stewardship framework to improve nitrogen use efficiency (NUE) and reduce environmental impacts (Nigon, 2024). Among these, urease inhibitors slow the hydrolysis of urea, thus decreasing NH_3 volatilization from surface-applied fertilizers like broadcast urea or UAN. Multiple reviews report consistent reductions in NH_3 losses, with field evidence indicating that combining UAN with urease inhibitors enhances prairie winter wheat performance and NUE (Owens et al, 2023). Similarly, nitrification inhibitors delay the microbial conversion of NH_4^+ to NO_3^-, reducing nitrate leaching and nitrous oxide (N_2O) emissions. Meta-analyses show that nitrification inhibitors increase crop yields by about 6–9% and significantly lower emissions, with several syntheses confirming yield increases of 4–9% and notable reductions in N_2O losses (Qiao et al., 2015; Yang et al., 2016). Controlled- or polymer-coated urea acts as a physical barrier to slow nitrogen release, aligning nutrient supply more closely with crop demand. Prairie multi-site studies in Alberta and Saskatchewan have demonstrated that polymer-coated urea moderates soil nitrate dynamics, reduces N_2O emissions, and maintains optimal crop nitrogen supply. Supporting data from Canada's 4R Chair program also show an average 27% decrease in N_2O emissions across 21 site-years, with minimal impact on yields (Graham et al., 2014). In Ontario, combining urea-ammonium nitrate (UAN) with nitrification and urease inhibitors at the eighth-leaf stage of corn growth allows producers to reduce greenhouse gas emissions by up to 75% (Canadian 4R Research Network, 2019). When used in the fall, this fertilizer type helps prevent nitrogen losses and has been shown to produce canola yields comparable to those from spring deep banding (Grant et al., 2016; Canola Council of Canada, 2022). Overall, EEFs offer significant agronomic and environmental benefits, especially when applied in high-risk scenarios such as surface applications, high-pH soils, or heat conditions.

2.15.3 Placement of Fertilizer (Right Place)

Proper nutrient placement ensures that crop roots have consistent access to essential nutrients throughout the growing season. Fertilizer placement strategies are designed to position nutrients optimally in relation to root growth, thereby enhancing nutrient uptake efficiency and supporting healthy crop development (Reetz et al., 2015). Traditionally, nitrogen fertilizer was applied on the Canadian Prairies by broadcasting, a method that involves spreading urea or other nitrogen sources evenly across the soil surface. In recent years, many growers have revisited this approach, particularly the broadcasting of urea, as an easy means to improve operational efficiency, save time, and cost, especially on large-scale farms (Alberta Grains, n.d).

Because most annual weeds recruit from the upper few centimeters of soil, surface-broadcast fertilizer elevates nutrient availability in this germination zone, enabling weeds to access nutrients alongside the crop (Melander et al., 2005). Accordingly, nutrient supply near the soil surface is a key determinant of weed emergence; surface applications can therefore stimulate recruitment (Guza et al., 2008). When nitrogen is broadcast, it is available at the soil surface, giving early germinating weeds like green foxtail and wild mustard immediate access to nutrients. This can increase weed biomass and diminish crop growth (Blackshaw et al., 2002, 2005). Applying nitrogen to the 0–15 cm soil layer has little influence on tap-rooted broadleaf weeds (e.g., *Chenopodium album*, *Brassica kaber*), still it markedly affects small-seeded species (e.g., *Euphorbia supina*) and fibrous-rooted grasses (e.g., *Avena fatua*, *Setaria viridis*), which rely on near-surface nutrient pools during establishment. Losses from urea and urea ammonium nitrate (UAN) positioned less than two inches below the soil surface are higher and comparable to those from broadcast treatments. Broadcast and shallow banding are still inferior to deep banding urea and (UAN) at 2" and lower. When comparing sub-surface banding or point-injection to broadcast N, shoot N concentration and weed biomass were frequently lower in banding and showed better weed control from banding than broadcasting. Boomsma et al. (2007) elaborated fertilizer banding instead of broadcasting has several potential benefits, such as lessening the fixation and stratification of available Nitrogen, Phosphorus and exchangeable potassium in soil, raising P and K soil-test levels in a consistent zone of nutrient enrichment, possibly allowing plants to absorb more N, P and K from deeper soil horizons during dry years, and allowing plants to be planted more promptly when used in conjunction with strip-tillage systems. Borges and Mallarino, (2000) have reported that higher soybean yield was obtained with deep band fertilizer applications compared to broadcast applications. However, some research has revealed that N placement has no effect on crop weed competition, suggesting that the effect of fertilizer placement is crop and weed-specific (Cochran et al., 1990). Broadcasting fertilizer at the surface without incorporation had the highest environmental N loss, which was primarily caused by NH_3 volatilization. When nitrogen fertilizer is injected at planting or with side dress, the NH_3 loss is reduced considerably (Rahman and Zhang, 2018).

2.15.4 Rate of Fertilizer (Right Rate)

Applying nitrogen at the correct rate ensures crops receive adequate nutrition to reach their yield potential while minimizing surplus nitrogen that could be exploited by competing weed species.

Fertilizer rates, especially nitrogen, can significantly influence crop–weed interactions by either promoting or suppressing weed growth (Cathcart & Swanton, 2003). Effective weed management involves avoiding excess nutrient applications and applying fertilizers at rates plants can efficiently utilize, thereby limiting weeds' competitive advantage. Weeds respond differently to various fertilizer rates. Guza et al. (2008) reported that increasing nitrogen application rates led to a corresponding rise in total weed biomass. The application rate should be based on the crop's needs and the environment (Major et al., 2005). *Palmer amaranth* is highly responsive to higher fertilization rates (Ruf-Pachta et al., 2013). A study by Toler et al. (2004) found that weeds generally grow well and respond favorably to initial fertilizer doses. Over-application of nitrogen has been linked to increased weed biomass and enhanced competitiveness of nitrophilous weeds like *Setaria* spp. and *Amaranthus* spp., especially in reduced-tillage systems (Blackshaw et al., 2003; DiTommaso, 1995). Conversely, nitrogen deficiency can stress crops, reducing canopy development and early-season vigor, thereby weakening their ability to compete with weeds for light, space, and nutrients (Liebman & Davis, 2000). Research indicates that site-specific and crop-specific nitrogen rate recommendations based on soil tests and yield goals can significantly improve nitrogen use efficiency while reducing environmental losses (Fixen, 2007; Roberts, 2008). Blackshaw and Brandt (2008) found that at low N levels (60 mg N kg^{-1} soil), *Amaranthus retroflexus* was less competitive than spring wheat. However, at higher N rates (240 mg N kg^{-1}), the weed became more competitive than the crop. Several studies show that higher N rates increase weed competitiveness over crops, and in some cases, crop yields are unaffected or even decrease (Ampong-Nyarko and de Datta, 1993; Andreasen et al., 2006; Dhima and Eleftherohorinos, 2001). Other research suggests that N fertilizer can benefit crops more than weeds (Abouziena et al., 2007; Cathcart and Swanton, 2004; Evans et al., 2003). Moreover, applying optimal N rates adjusted to the crop's growth stage and uptake pattern can align nutrient availability with demand, enhancing economic returns and agronomic efficiency. Incorporating the "right rate" into wider 4R practices is especially important in conservation agriculture systems, where N dynamics are affected by residue cover, moisture retention, and microbial activity.

2.16 Toward Sustainable Weed Management in Canada

Much of the literature evaluates the individual effects of strategic fertilizer management (4R) and specific weed-control tactics on weed suppression and crop yield. However, a growing consensus emphasizes that sustainable weed management results from integrating a wide range of practices rather than relying on any single tactic. For example, studies in western Canada have demonstrated that using appropriate cultural techniques, such as optimal seeding rates and fertilization, crop rotation, and targeted low-dose herbicide applications, can lead to higher weed suppression and reduce weed seed return compared to less diverse farming practices that depend heavily on herbicides. Blackshaw et al. (2000) observed an 85% decrease in pigweed seed production with zero-tillage, different seeding dates and rates, and optimal fertilizer placement. According to Harker et al. (2023), combining weed control methods can effectively manage wild oat populations and provide up to six times more control than using a single strategy. Growing taller cultivars, doubling seeding rates, varying crop rotations, and strategic fertilizer application reduced wild oat seed production in barley by 97% (Harker et al., 2009).

When INM is incorporated into broader weed management systems alongside competitive cultivars, higher seeding rates, and strong, uniform canopies, the combined approach leads to more effective, and consistent weed suppression and reduces seed return to the seedbank, thereby improving yield resilience (Shafi et al., 2018). Chauhan (2014) also found that nutrient management (120 kg N, 60 kg P_2O_5, 40 kg K_2O ha^{-1}) combined with timely post-emergence weed control is most effective for increasing wheat productivity, nutrient uptake, and economic returns while efficiently managing weeds. Additionally, Kristensen et al. (2008) stressed that sustainable wheat production requires integrating weed and nutrient management, where higher crop density, uniform spatial distribution, and well-timed nitrogen fertilization work together to suppress weeds and boost yield, highlighting the complementary roles of cultural practices and fertilizer stewardship in crop–weed competition. Liebman and Gallandt (2002) argued that over-reliance on herbicides risks the development of resistance and replenishment of the seedbank. Conversely, a systems-based approach that combines INM and IWM can keep weed populations below economic thresholds for longer periods. Similarly, Swanton et al. (2015) emphasized that crop competition should be optimized through both cultural and fertility practices to shorten the critical weed interference period and diminish weed persistence across different sites and years. In this context, it is especially important to assess the additive and interactive effects of nitrogen fertilizer strategies alongside cultural weed control on weed phenology, persistence, and fecundity. Such integrated strategies provide a pathway toward sustainable weed management in Canada, balancing productivity goals with long-term ecological stability. Therefore, it is valuable to understand the combined influence of nitrogen fertilizer application strategies and various weed management practices on crop-weed competition and weed traits such as phenology, persistence, and fecundity as part of a long-term, sustainable weed management plan.

The present study investigated the impact of ICM on crop-weed competition, phenology, and persistence traits of common weed species in spring wheat. This thesis hypothesizes that integrated cultural weed management combined with optimized nitrogen (N) rate, timing, and placement will interact positively to reduce weed density and weed biomass and increase grain yield compared with IWM or N management alone. These changed growing conditions may also impact maternal environments, leading to variations in weed seed dormancy.

CHAPTER 3

3.0 MATERIALS AND METHOD

3.1 Experimental Design and Treatments

Field experiments were conducted in 2023 and 2024 in the same field at the Carman Research Farm in southern Manitoba (49°30′04.6″ N, 98°01′42.1″ W; gleyed Black Chernozem, pH 5.5, 6 % organic matter) and at the Kernen Research Farm near Saskatoon, Saskatchewan (52.1529° N, 106.5449° W; Black Chernozemic loam, pH 7.7, 2.9 % organic matter). The goal was to evaluate the effects of integrated crop management on crop performance, crop–weed competition, weed phenology, and weed seed dormancy. A split-plot Randomized Complete Block (RCB) design was used with four replicates per site per year, resulting in 64 plots per location per season. A four-factor factorial treatment structure was tested (16 combinations in total). Nitrogen application timings (fall vs. spring) were allocated as the main-plot factor, fertilizer placements (broadcast vs. banding) were applied as the subplot factor, and nitrogen rates (100 % vs. 50 % of soil-test recommendation) and weed management (standard vs. IWM) were allocated as sub-subplot factors. IWM included narrow row spacing (15 cm), high crop density (400 plants m^2), and early seeding (2nd week of May). Standard weed management used wider row spacing (30 cm), lower crop density (200 plants m^2), and late seeding (4th week of May). Main plots were separated by permanent border strips (50 m × 8 m). Within each main plot, subplots received one of two N placement treatments. These subplots were further divided into sub-subplots for rate and weed management treatments. Individual plots measured 2.5 m × 8 m with alleyways between blocks.

Fall-applied urea was broadcast within one week of the first snowfall, while spring-applied urea was applied immediately prior to seeding. In broadcast treatments, urea was evenly spread across plots and incorporated with light tine-harrowing within 24 hours. Side-banded applications were delivered at seeding, with fertilizer placed approximately 15 cm in IWM plots and 30 cm in standard weed management plots to the side of the seed row. Nitrogen rates corresponded to either

100% or 50% of the soil-test recommendation targeting a spring wheat yield of 3,300 kg ha^{-1}. Two weed-management regimes were imposed: the standard practice featured lower crop density (200 plants m^{-2}), wide row spacing (30 cm), and a delayed seeding date (late-May), whereas the IWM treatment doubled seeding density to 400 plants m^{-2}, narrowed rows to 15 cm, and advanced seeding to mid-May. Spring wheat (AAC Brandon) was sown at 2–5 cm depth, depending on soil moisture. Pre-emergence weed control consisted of glyphosate (900 g ae ha^{-1}) with MCPA (494 g ai ha^{-1}) applied uniformly across all plots. To augment weed pressure at Carman in 2024, wild oat seeds were broadcast at a density of approximately 50 seeds m^{-2}, while volunteer canola seeds were broadcast at a density of about 40 seeds m^{-2} during plot preparation. No supplemental seeding of wild oats and volunteer canola was performed at Kernen in 2024 or at either site in 2023. No post-emergence herbicides were applied throughout the study. Cumulative seasonal precipitation, average temperature and growing degree days (GDD with base temperature 5^{0}C) were calculated for the four site-years.

Table 1. Experimental treatments that were used in the field experiment.

Treatment	Timing of N application	N Fertilizer rate	N Fertilizer placement	Weed management
1	Spring seeding	100%	Side banded	Standard
2	Spring seeding	100%	Side banded	IWM
3	Spring seeding	100%	Broadcasted	Standard
4	Spring seeding	100%	Broadcasted	IWM
5	Spring seeding	50%	Side banded	Standard
6	Spring seeding	50%	Side banded	IWM

7	Spring seeding	50%	Broadcasted	Standard
8	Spring seeding	50%	Broadcasted	IWM
9	Fall	100%	Side banded	Standard
10	Fall	100%	Side banded	IWM
11	Fall	100%	Broadcasted	Standard
12	Fall	100%	Broadcasted	IWM
13	Fall	50%	Side banded	Standard
14	Fall	50%	Side banded	IWM
15	Fall	50%	Broadcasted	Standard
16	Fall	50%	Broadcasted	IWM

(Note: IWM treatments consisted of higher crop density (400 plants m^{-2}), narrow row spacing (15 cm), and early seeding date (2nd week of May). Standard weed management consisted of lower crop density (200 plants m^{-2}), wide row spacing (30 cm), and late seeding date ,14 days after IWM treatment (4th week of May).

3.2 Data Collection

3.2.1 Weed Abundance

Weed phenology was evaluated by monitoring specific emergence cohorts, tagged by time of emergence. Weed emergence cohorts were determined by using two 1 m² permanent quadrats placed at the front and back of each plot, 0.5 m away from the edges. Within each quadrat, weed emergence was monitored weekly, and each individual within each species that emerged on a particular week was tagged with a specific color tag indicating the week of emergence. Four different color tags were used to mark different cohorts. Individuals of a weed species that belonged to a specific-colored cohort were referred to as the species cohort. All weed phenological events were monitored within designated permanent quadrats in each plot for each cohort. Fully extended/outstretched weed plant height at maturity was measured by randomly selecting five representative plants from each species cohort within each plot. Flowering duration was determined separately for each species and cohort, beginning at full flowering, defined as the stage when approximately 50% of the flowers on the main raceme were open and older petals had started to fall (BBCH 60), and ending when no new flowers appeared (BBCH 67). At weed maturity, all seed heads from each cohort of weed species from the permanent quadrats were collected once they reached harvest maturity, and they were dried, cleaned, and processed in the laboratory. Wild oats seeds were maintained at room temperature (20–22 °C, 50–70% relative humidity) for three months to facilitate after-ripening before subsequent evaluation.

3.2.2 Weed Phenological Data

Weed phenology evaluation was carried out by monitoring specific emergence cohorts tagged based on their time of emergence. Weed emergence cohorts were determined by using two 1 m^2 permanent quadrats placed at the front and back of each plot, 0.5 m away from the edges. Within each quadrat, weed emergence was monitored weekly, and each weed seedling within each species that emerged on a particular week was tagged with a specific color tag indicating the week of emergence. Four different color tags were used to mark different cohorts. Individuals of a weed species that belonged to a specific-colored cohort were referred to as the species cohort. All weed phenological events were monitored within designated permanent quadrats in each plot for each cohort. Fully extended/outstretched weed plant height at maturity was measured by randomly selecting five representative plants from each species cohort within each plot. Flowering duration was determined separately for each species and cohort, beginning at full flowering, defined as the stage when approximately 50% of the flowers on the main raceme were open and older petals had begun to fall (BBCH 60), and ending when no new flowers appeared (BBCH 67). At weed maturity, all seed heads from each cohort of weed species from the permanent quadrats were collected once they reached harvest maturity, and they were dried, cleaned, and processed in the laboratory. Wild oats seeds were maintained at room temperature (20–22 °C, 50–70% relative humidity) for three months to facilitate after-ripening before subsequent evaluation.

3.2.3 Germination and Dormancy Testing

Cleaned wild oats seeds were subjected to germination and dormancy tests after being separated into three size classes via sieving. Two sieves with dimensions: 1.785 mm width × 12.74 mm length (4½/64 × ½) and 1.389 mm width × 12.7 mm length (3½/64 × ½) were used to get 3 seed size classes. which consisted of 1582 g of large seeds, 962 g of medium-sized seeds and 662 g of small-sized seeds in total. For the germination test, twenty-five wild oat seeds were placed in Petri dishes lined with two layers of moistened Whatman No. 42 filter paper. Each treatment included four replicates, and 9 mL of distilled water was added to each dish to maintain moisture. The germination test was conducted in an incubator under controlled conditions, maintaining a day/night temperature cycle of 10°C/20°C and a photoperiod of 16 hours of light and 8 hours of darkness specifically for wild oats (Khalid and Siddiqui, 2002). During the incubation period, the number of germinated seeds in each petri dish was recorded every two days. Seed germination was determined based on the emergence of the radicle approximately 2 mm in length until the 14th day of incubation. Non-germinated seeds after 14 days were tested for dormancy by pinching the embryo of wild oats seeds with a sharp point and subsequent germination test (Murray et al., 1995). The final germinated seed count was taken after 14 days under the same controlled conditions. Seeds that germinated after dormancy removal were considered dead seeds and removed.

3.2.4 Crop Data Collection

Crop emergence was assessed three weeks after seeding by counting emerged wheat seedlings along randomly selected 4-m row crop segments in each plot. Meantime, to evaluate crop biomass, wheat plants from two 1 m^{-2} permanent quadrats were also collected at harvesting maturity by cutting 2.5cm above the soil surface. Collected wheat plants were dried in a 60 °C oven until equilibrium was achieved (4-5 days) to record wheat aboveground biomass after drying. Then grains were threshed, and seed weights were recorded.

3.3 Data Analysis

Statistical analysis was performed by first combining all site-year data. This analysis indicated significant site-year × treatment interactions, necessitating separate analyses by site-year to account for environmental variability. Therefore, data were subsequently analyzed separately for each site-year to account for environmental variability and to discern location- and year-specific treatment effects. Statistical analyses were conducted using R software (R Core Team, 2025). Linear mixed-effects models (LMMs) were fitted using the lmer function from the lme4 package (Bates et al., 2015) for variables including weed biomass, weed height, flowering duration, weed seed weight, and crop density, biomass, and yield. Fertilizer timing, placement, rate, and weed management were considered as fixed effects. Block was included as a random effect, with main plots and subplots specified as nested random factors (e.g., block/main-plot/sub-plot) to account for the split-plot experimental structure. Model selection followed a stepwise approach in which all random effects were initially included, and the structure was subsequently simplified by sequentially removing non-informative random factors. Competing models were compared using AIC and BIC criteria, with support from diagnostic plots. Residuals were visually inspected for normality and homoscedasticity using Q-Q plots and residual vs. fitted value plots. Further, model diagnostics were carried out using the Shapiro-Wilk test and Levene's test, respectively. Data transformations (log) were applied to these variables (weed biomass, weed height, flowering duration, weed seed weight, and crop density, biomass, and yield) to improve homogeneity of variances and approximate residual normality. For response variables that did not meet model assumptions even after transformation (weed density), generalized linear mixed-effects models (GLMMs) were fitted using the glmer() function with appropriate error distributions (Poisson) and link functions. The Poisson distribution was selected based on theoretical expectations for count data (Bolker et al., 2009). Type III ANOVA was conducted to test main effects and interactions. Mean separation was carried out using a protected LSD test using the EMMEANS package in R (Lenth, 2024). Global contrast analyses were performed on the combined site-year data to compare major treatment factors, IWM versus standard management, half-rate N versus full-rate N, spring versus fall application, and side-banding N versus broadcasting N, for key parameters including grain yield, weed density, and weed biomass. Global contrasts (for combined site years data) analysis was done to compare major treatments based on prior hypotheses; IWM vs. standard, half rate N vs. full rate N, spring application vs. fall application, and side banding vs. broadcasting for key parameters such as grain yield, weed density, and biomass. Further, contrasts were conducted to compare weed density, biomass, and grain yield between the most contrasting treatment combinations (spring application, broadcasting, full rate N, standard weed management, to a fall application, side banding, half rate N, IWM to provide clear, actionable insights, highlighting which combinations offer the most significant benefit in terms of yield or weed suppression.

Weed seed germination and dormancy were analyzed separately from the field experiment. Germination and dormancy proportions were analyzed using a generalized linear mixed model (GLMM) using the glmmTMB package with a beta-distribution (Gianinetti, 2020). This was separately run for each size category (small, medium and large) for the wild oat seeds collected from the first cohort. The model included fertilizer timing, fertilizer placement, fertilizer rate, and weed management as fixed effects, along with their full factorial interaction (fertilizer time × fertilizer place × fertilizer rate ×weed management). Block was included as a random effect. Model diagnostics, including checks for overdispersion, zero/one inflation, and residual structure, were conducted using the *DHARMa* package (Hartig, 2022). Finally, to investigate the main effects and interactions, type III ANOVA was performed. Mean comparison was carried out using protected LSD test, using the EMMEANS package in R.

CHAPTER 4

4.0 RESULTS

4.1 Weather

During the 2023 growing season in Carman, Manitoba, the average temperature ranged from 20°C to 22°C with 1484.8 seasonal cumulative GDD (base temperature 5^0C). The month of May experienced a notably dry period, receiving only 14 mm of rainfall. The early part of June (1st to 20th) also had limited precipitation (Figure 1). However, most of the seasonal rainfall occurred in late June and early July. In comparison to Carman, Kernen Research Farm in 2023 experienced higher rainfall throughout the growing season with an average temperature ranging from 17°C to 20°C and approximately 1400 cumulative GDD. Notably, Kernen in 2023 received more frequent precipitation events between May 20th and June 5th, despite an initially dry season onset (Figure 1). Carman 2024 was comparatively wet compared to 2023, where the cumulative rainfall during the growing season in Carman 2024 was approximately three times greater than the cumulative rainfall during the growing season in Carman 2023 (Figure 1). The growing season temperature at Carman 2024 was around 17 °C to 23 ^{0}C with 1323.8 cumulative GDD. The rainfall data from Kernen in 2024 showed significant daily precipitation variability from May 1st to August 30th, with an average temperature of 15°C to 20°C and approximately 1300 cumulative GDD. May and June experienced more frequent rainfall, with the highest rainfall occurring early June, with a peak exceeding 25 mm. However, cumulative rainfall at Kernen exhibited little variation between 2023 and 2024, with rainfall in 2024 being only 1.125 times greater than in 2023 (Figure 1).

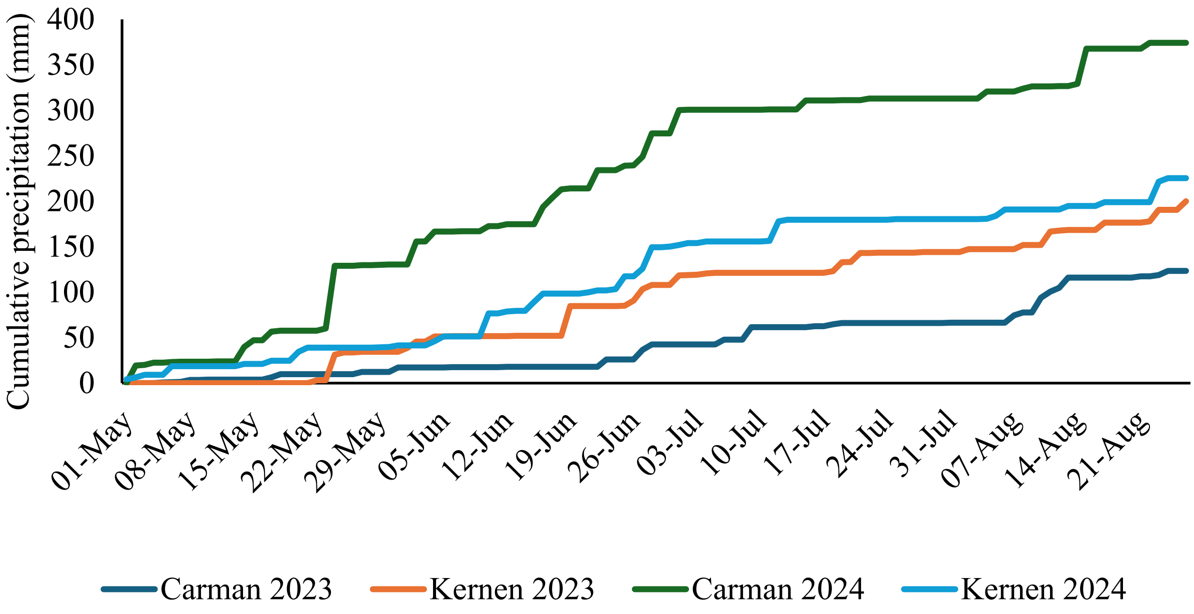


Figure 1: Cumulative precipitation during the growing seasons of 2023 and 2024 at Carman and Kernen.

4.2 Weed Abundance

4.2.1 Weed Density

The composition of dominant weed species varied slightly among the four site-years. Wild oats (*Avena fatua*) and redroot pigweed (*Amaranthus retroflexus*) were the dominant weed species in Carman 2023, wild oats and volunteer canola (*Brassica napus* L.) in Kernen 2023 and Carman 2024, while wild oats and redroot pigweed in Kernen 2024 were the dominant weed species. Apart from these dominant species, lamb's quarters (*Chenopodium album*) and green foxtail (*Setaria viridi*) were present at all four experiments. At the same time, Kochia (Bassia scoparia L.) was present at Kernen 2023 and 2024, as demonstrated in Figure 2A-D, along with other species.

Integrated weed management reduced weed density across all experiment sites (Figure 2, Table 2). Weed density reduction ranged from 45% at Kernen 2023 to about 79% at Carman 2024.

Nevertheless, nitrogen management (rate, placement, and/or time of application) also influenced weed density at Kernen 2023 and 2024 and at Carman 2024. At Carman in 2023, a significant fertilizer-timing × weed-management interaction was observed. Under standard weed management, weed density did not differ between spring and fall fertilizer applications; however, under IWM, weed density did differ between the two fertilizer application times. The fall application of N under IWM reduced weed density by 75% compared with the spring application under standard weed management (Fig. 2A; Table 2). Even within standard weed management, fall application tended to result in lower weed densities than spring application. However, this difference was not statistically significant compared to spring-applied standard weed management and spring-applied IWM (Figure 2A). At Kernen 2023, the interaction between fertilizer placement and weed management exhibited that side-banding reduced weed density more than broadcasting in both systems, with the largest reduction (45%) observed under sideband IWM compared to the broadcast standard (Fig. 2B; Table 2). At Carman 2024, an interaction among placement, rate, and weed management indicated that side-banding at half the recommended N rate resulted in a 66 % lower weed density compared with others under both IWM and standard weed management conditions (Figure 2C). All the IWM treatments had lower weed density compared with standard weed management. Weed density at Kernen 2024 was significantly influenced by the weed management method, with no detectable influence of fertilizer timing, placement, or rate. IWM had a 79% lower weed density than standard weed management (Figure 2D).

The global contrasts (combined across all site-years) comparing weed density under IWM versus standard, spring versus fall application, full rate versus half rate N, and side banding versus broadcasting showed no significant differences (Table 3). Moreover, no significant difference in weed density was detected ($p = 0.9393$) among all site-years when comparing the most contrasting treatment combinations (spring application, broadcasting, full rate N, and standard weed management) to a fall-applied, side-banded, half-rate N treatment in IWM.

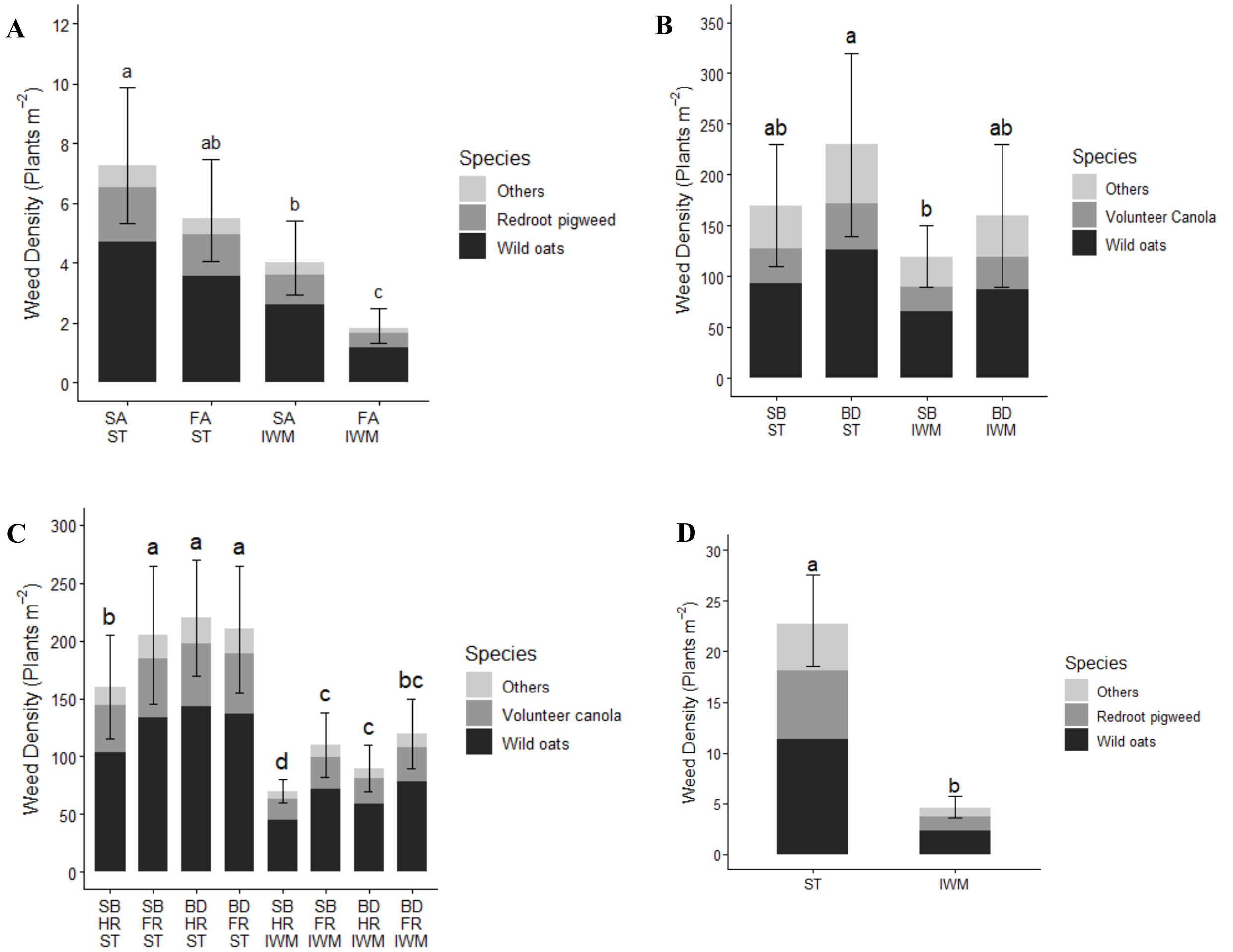


Figure 2 - The effect of fertilizer placement and weed management interaction on weed density at Carman 2023 (A), weed management method on weed density at Kernen 2023 (B), fertilizer placement, rate, and weed management method on weed density at Carman 2024 (C), weed management method on weed density at Kernen 2024 (D). Within each panel, bars sharing the same letter are not significantly different according to Fisher's protected LSD at the 0.05 level. Error bars represent ± standard error of the mean (SEM), (ST: Standard weed management, IWM:

Integrated weed management, SA; Spring application, FA: Fall application, FR: Full rate N, HR: Half rate N, SB: Side-banding, BD: Broadcasting).

4.2.2 Weed Biomass

Integrated Weed Management was the strongest and most consistent determinant of weed biomass among all experiments, despite this, nitrogen management factors (rate, placement, and timing) also exerted measurable effects on weed density at Kernen in 2023 and 2024 and at Carman in 2024 (Figure 3, Table 2). At Carman 2023, a significant interaction between fertilizer placement and weed management on weed biomass was observed (Table 2). Side-banding with standard weed management had 25% lower weed biomass compared with broadcasting with standard weed management. However, there was no significant difference in weed biomass between side-banding and broadcasting N under standard weed management (Figure 3A). Side-banding with IWM resulted in the least weed biomass among the treatments, 86% lower than broadcasting under standard weed management (Figure 3A). In contrast, at Kernen 2023, weed biomass was driven solely by the weed management system. IWM plots exhibited 78% lower weed biomass than standard weed management, regardless of fertilizer practices (Figure 3B). At Carman in 2024, a three-way interaction among nitrogen rate, placement, and weed management was observed (Table 2). In particular, treatments with half-rate nitrogen applied by side-banding under both standard and IWM regimes tended to produce lower crop biomass (67%) than full-rate N, broadcasting with standard weed management. However, the half-rate N, side-banding under standard conditions showed significantly lower weed biomass than other standard weed management treatment combinations. In this environment, both weed management regimes showed that applying half-rate nitrogen with side banding generally resulted in slightly lower weed biomass than using the full-rate nitrogen with broadcasting. Overall, 73% lower weed biomass was observed in half-rate

N, side banding with IWM compared with half-rate N, broadcasting together with standard weed management (Figure 3C). Consistent with observations from Kernen 2023, weed biomass in Kernen 2024 was also significantly affected by the weed management treatment. IWM plots showed a 94% reduction in weed biomass compared with standard practice (Figure 3D).

The global contrasts comparing weed biomass under IWM versus standard weed management revealed a significant ($p < 0.0001$) reduction (90%) in weed biomass under IWM, whereas contrasts between other key treatments showed no significant effects on weed biomass, likely due to site-year variations (Table 3). However, when comparing the most contrasting combinations (spring application, broadcast placement, full N rate, standard weed management) with fall application, side-banded, half rate N, and IWM, weed biomass was significantly lower (95%) under the latter ($p = 0.0067$; Table 3).

Weed density reflects the success of early-season weed establishment, while weed biomass integrates these effects over time, providing a more complete picture of in-season crop–weed competition. Across all site-years, IWM consistently reduced both weed density and biomass compared with standard weed management, often by 70–90%. This demonstrates the strong competitive advantage conferred by cultural practices used in the experiment. Integrated weed management strategies, such as high crop density, narrow row spacing, and early seeding, have been widely recognized for their additive and synergistic effects on weed suppression, particularly reducing the weed density and biomass.

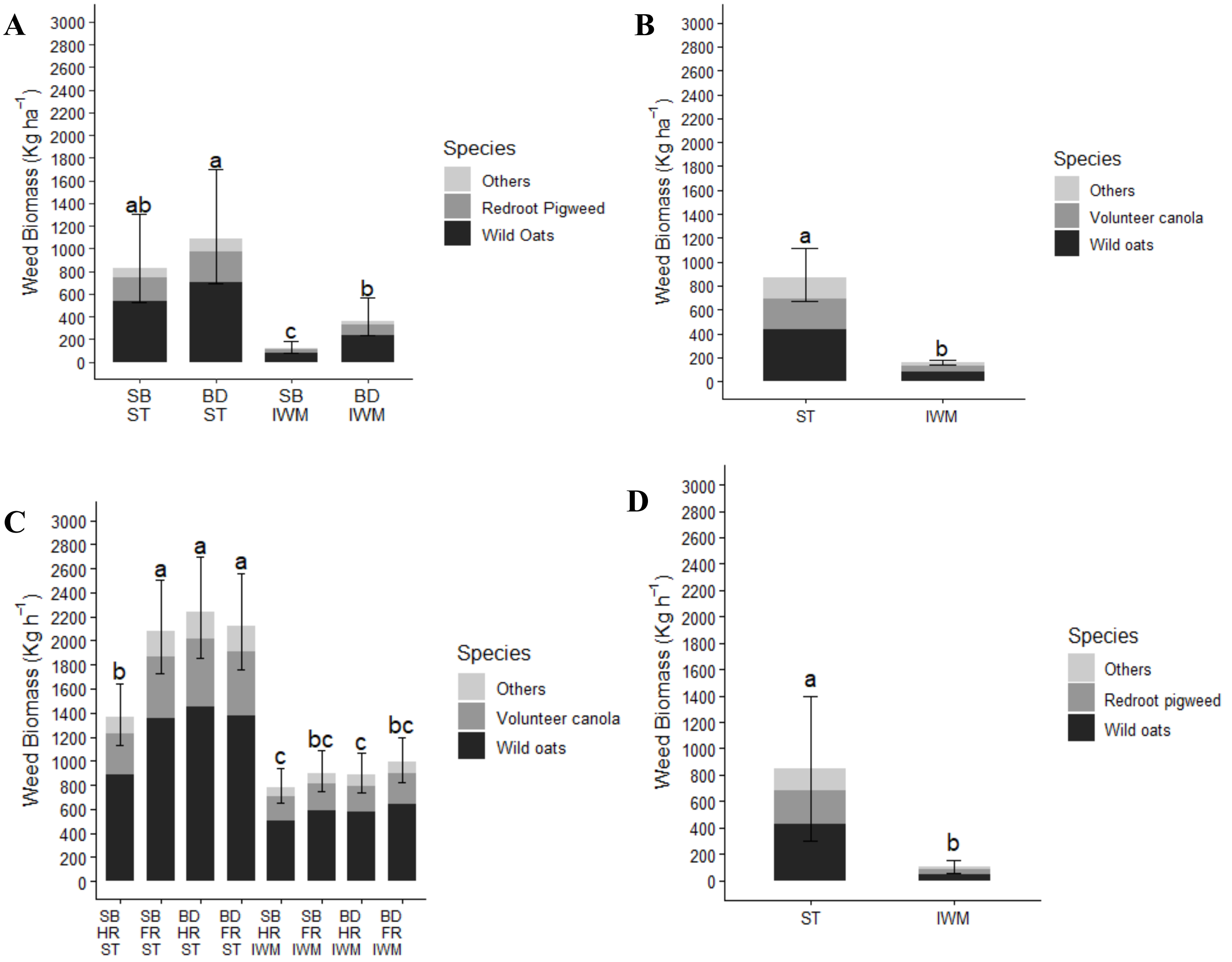


Figure 3 - The effect of fertilizer placement and weed management interaction on weed biomass at Carman 2023 (A), weed management method on weed biomass at Kernen 2023 (B), fertilizer placement, rate, and weed management method on weed biomass at Carman 2024 (C), weed management method on weed biomass at Kernen 2024 (D). Within each panel, bars sharing the same letter are not significantly different according to Fisher's protected LSD at the 0.05 level. Error bars represent ± standard error of the mean (SEM), (ST: Standard weed management, IWM: Integrated weed management, FR: Full rate N, HR: Half rate N, SB: Side-banding, BD: Broadcasting).

4.3 Weed Phenology

4.3.1 Weed Emergence

The total weed emergence (the combined emergence of all weed species) was recorded at regular intervals (1 week) for up to 4 weeks to evaluate the temporal patterns of weed emergence in the field. The data presented here were exclusively derived from the 2024 field experiment conducted at Carman, as the 2023 weed emergence was very low and contained many zero values. Weed emergence patterns at Carman 2024 showed clear evidence that both fertilizer placement and nitrogen availability interacted with the weed management system to shape early-season recruitment dynamics. Among cohorts, treatments involving IWM consistently reduced emergence compared with standard weed management, reflecting the strong competitive advantage created by early crop establishment, higher seeding rates, and narrower row spacing. At Carman 2024, the emergence of weed seedlings from the first cohort was significantly influenced by the interaction of nitrogen fertilizer placement, N rate, and weed management method (Table 2). Side-banding, half-rate N with IWM showed significantly lower (52%) weed emergence compared to broadcasting, full-rate N with standard weed management, which had the greatest emergence. All other treatment combinations were not significantly different from each other (Figure 4A). Weed emergence in the second cohort was significantly influenced by the interaction of fertilizer placement, timing, and weed management (Table 2). The spring application, side-banding, and IWM displayed significantly lower (35%) weed emergence than fall application, broadcasting, and standard weed management practices. There were no significant differences among all IWM combinations (Figure 4B). The third cohort was significantly influenced by the interaction of fertilizer timing and weed management method (Table 2). Either spring or fall application with IWM showed 21% lower weed emergence compared with the standard weed management application (Figure 4C). The emergence of weeds in the fourth cohort was solely influenced by the weed management method ($p < 0.01$) (Figure 4D). IWM displayed 9% lower weed emergence compared to standard weed management.

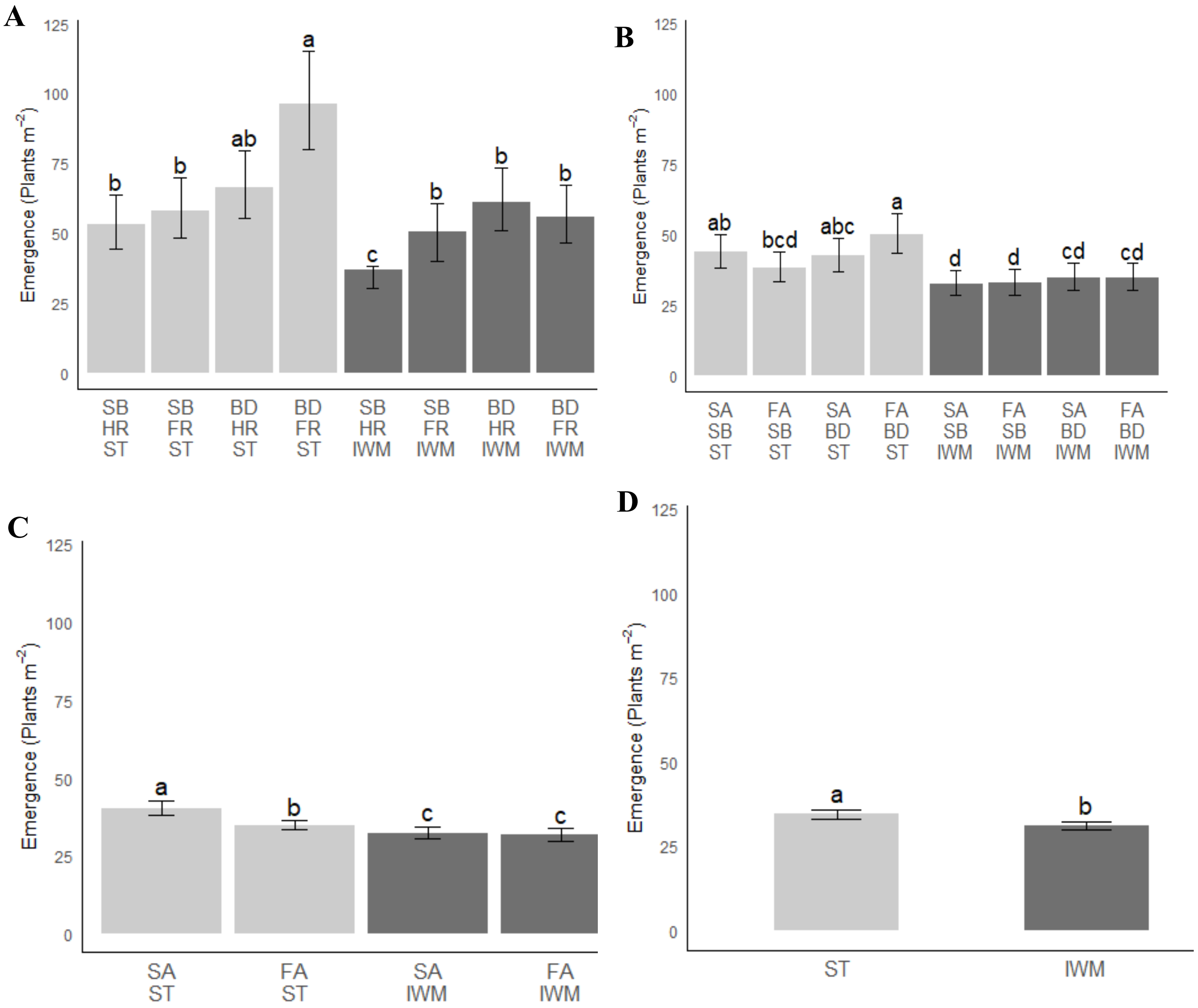


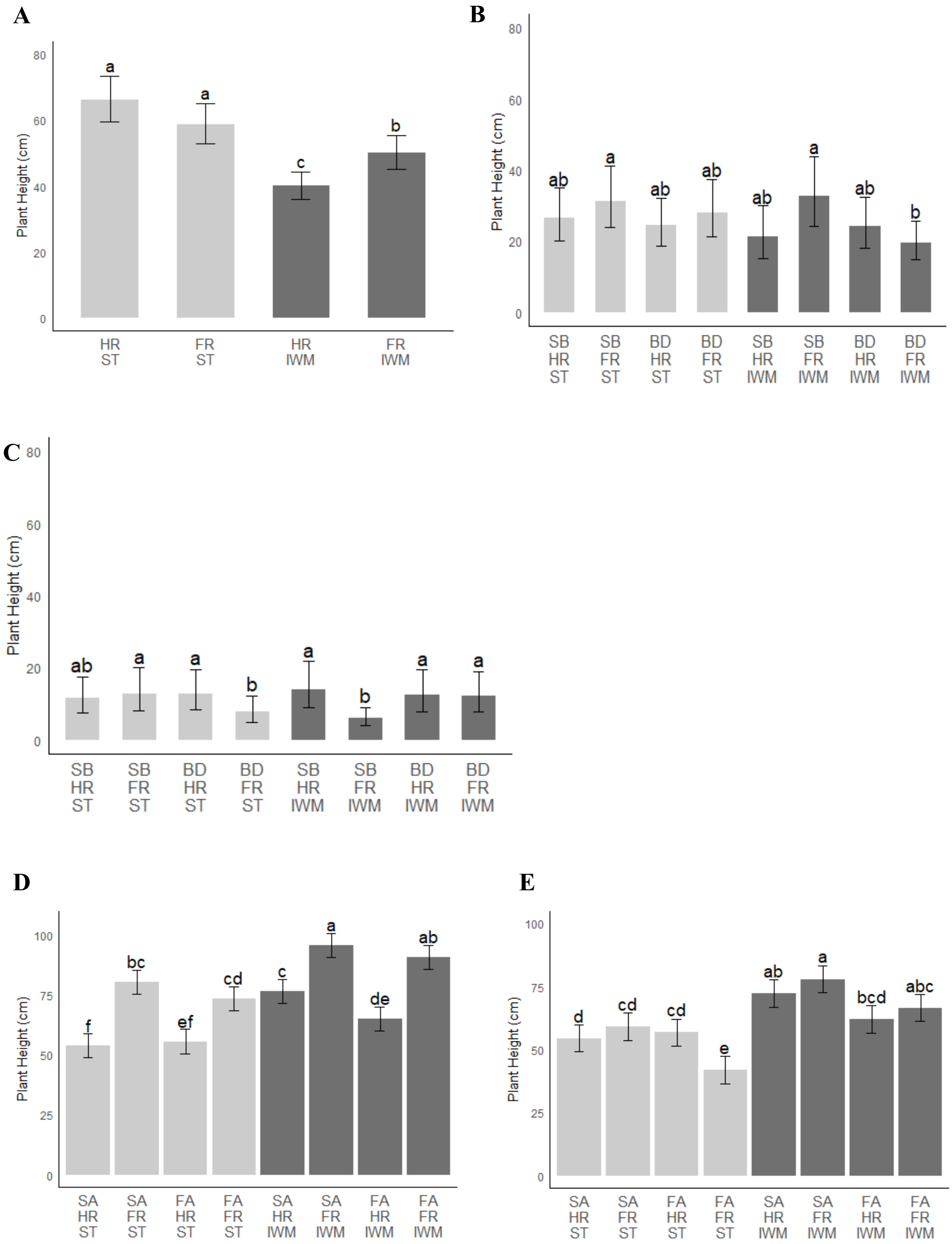
Figure 4 - The effect of fertilizer placement, rate, and weed management interaction on weed emergence at Carman 2024 (A), effect of fertilizer application timing, placement, and weed management interaction on weed emergence at Kernen 2024 (B), fertilizer application timing and weed management method on weed emergence at Carman 2024 (C), weed management method on weed emergence at Kernen 2024 (D). Within each panel, bars sharing the same letter are not

significantly different according to Fisher's protected LSD at the 0.05 level. Error bars represent ± standard error of the mean (SEM), (ST: Standard weed management, IWM: Integrated weed management, FR: Full rate N, HR: Half rate N, SB: Side-banding, BD: Broadcasting).

4.3.2 Weed Plant Heights

Matured weed plant heights of dominant weed species: wild oat (*Avena fatua* L.), redroot pigweed (*Amaranthus retroflexus* L.), and volunteer canola (*Brassica napus L.*) were determined in 2023 and 2024. Plant height was evaluated as an ecological indicator of how fertilizer management and cultural weed management influence resource capture, competition intensity, and reproductive potential. Height reflects a plant's ability to access light and respond to competitive pressure, which links this measurement to the study's main hypotheses regarding crop–weed interactions and maternal effects on seed traits. Weed height varied widely depending on species identity, site conditions, and the combination of fertilizer and weed management practices applied.

In Carman 2023, the heights of the first cohort of wild oat plants were significantly influenced by the interaction effect of nitrogen fertilizer rate and weed management (Table 2). The effect of N rate on wild oat heights was significant only under IWM, but not under standard weed management. Under IWM, half-rate N had shorter plants than full-rate N (Figure 5A). Overall, wild oats were 28% shorter under IWM compared to standard weed management (Figure 5A). Mature heights of redroot pigweed were significantly influenced by the interaction effect of nitrogen fertilizer placement, rate, and weed management (Table 2). There was no difference in heights due to N rate and placement under standard weed management. However, in IWM, broadcasting, full-rate N with IWM showed comparatively (40%) shorter plant height than the tallest plants observed under side banding, full-rate of nitrogen with IWM (Figure 5B). Other treatment combinations under both IWM and standard weed management did not show significant differences from each other. Redroot pigweed plant height at maturity in Kernen 2023 was significantly influenced by the interaction of fertilizer rate, placement, and weed management (Table 2). Under standard weed management, broadcasting with full rate N resulted in comparatively shorter red root pigweed plants than other treatment combinations, while under IWM, side banding with full rate N resulted in shorter redroot pigweeds (Figure 5C). At Carman 2024, the heights of wild oats at maturity from the first cohort were significantly affected by the interaction effect of fertilizer timing, rate, and weed management (Table 2). Wild oat plants exhibited significantly reduced height under half-rate nitrogen application, regardless of timing (spring or fall), within the standard weed management treatments (Figure 5D). The same interaction was significant for volunteer canola plant height (Table 2). The shortest plant height was observed with full-rate N, fall application, and standard weed management. Full-rate N, spring application, and IWM exhibited the highest plant height, but this difference was not significant compared to other IWM treatments (Figure 5E). At Kernen 2024, wild oat emergence was lower than at Carman, and plants were abscent.


A
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FA FR IWM

Figure 5 - The effect of fertilizer rate and weed management interaction on wild oat height from the first cohort at Carman 2023 (A), effect of fertilizer placement, rate, and weed management method on redroot pigweed from the first cohort at Carman 2023 (B), effect of fertilizer rate, placement, and weed management interaction on redroot pigweed heights from the first cohort at Kernen 2023 (C), effect of fertilizer application timing, rate, and weed management interaction on wild oat heights from the first cohort at Carman 2024 (D), effect of fertilizer application timing, rate, and weed management interaction on volunteer canola at Carman 2024 (E). Within each panel, bars sharing the same letter are not significantly different according to Fisher's protected LSD at the 0.05 level. Error bars represent ± standard error of the mean (SEM). (ST: Standard weed management, IWM: Integrated weed management, FR: Full rate N, HR: Half rate N, SA: Spring application, FA: Fall application).

4.3.3 Duration of Flowering

Flowering duration data for wild oats and volunteer canola from the first cohort were collected at the Carman 2024 site-year. Flowering data could not be collected from other site years due to inconsistent weed survival during flowering period across treatments. At Carman 2024, the duration of flowering of wild oats and volunteer canola was influenced significantly by weed management method (Table 2). Weeds grown under IWM displayed comparatively early flowering and early senescence with shorter flowering duration (2 days) for wild oats, and (3 days) for volunteer canola than standard weed management (Figure 6A, B). However, neither nitrogen rate nor placement affected anthesis duration in either weed species.

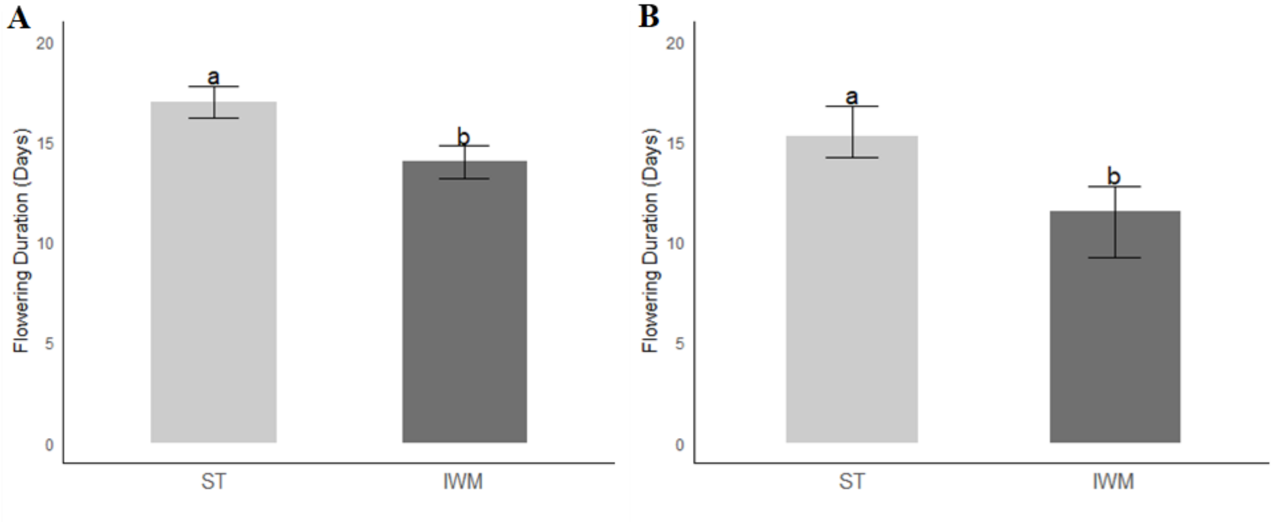

Figure 6- The effect of weed management method on flowering duration of wild oat (A) and volunteer canola (B) from the first cohort at Carman 2024. Within each panel, bars sharing the same letter are not significantly different according to Fisher's protected LSD at the 0.05 level. Error bars represent ± standard error of the mean (SEM). (ST: Standard weed management, IWM: Integrated weed management).

4.3.4 Total Weed Seed Production

The interaction between fertilizer placement and weed-management strategy had a profound effect on seed production for both dominant (wild oat and redroot pigweed) and secondary (lamb's quarters) species at Carman in 2023 (Table 2). When fertilizer was side-banded and IWM was employed, the total weed seed output declined by 85% relative to either side-banding or broadcasting under standard weed control (Figure 7A). The weed seed samples collected in 2023 from the Kernen site were insufficient to allow for a comprehensive comparison across all treatment combinations due to low seed production. The interactions among fertilizer placement, rate, and weed management strategy were significant for weed seed production at Carman 2024 (Table 2). This site was dominated by wild oat, volunteer canola, redroot pigweed, and other broadleaf species. The integration of side-banding, full-rate N, and IWM resulted in a 93% reduction in total weed seed weight from all weed species compared to the treatment with the highest seed production, which was broadcasting at full-rate N under standard weed management (Figure 7B). Weed seed production is the outcome of crop-weed competition and resource availability, integrating the cumulative effects of weed density, weed biomass, and growth dynamics. Our results demonstrate that management practices targeting early-season suppression translated into substantial reductions in weed seed production. Weed seed production pattern closely mirrored those observed for weed biomass. Across species and site-years, treatments that reduced weed biomass also produced the lowest seed outputs, underscoring the strong link between vegetative growth and reproductive capacity. Under IWM, lower weed biomass (fewer tillers in wild oat, reduced rosette size in redroot pigweed, and limited branching in volunteer canola) meant fewer resources were available for seed production.

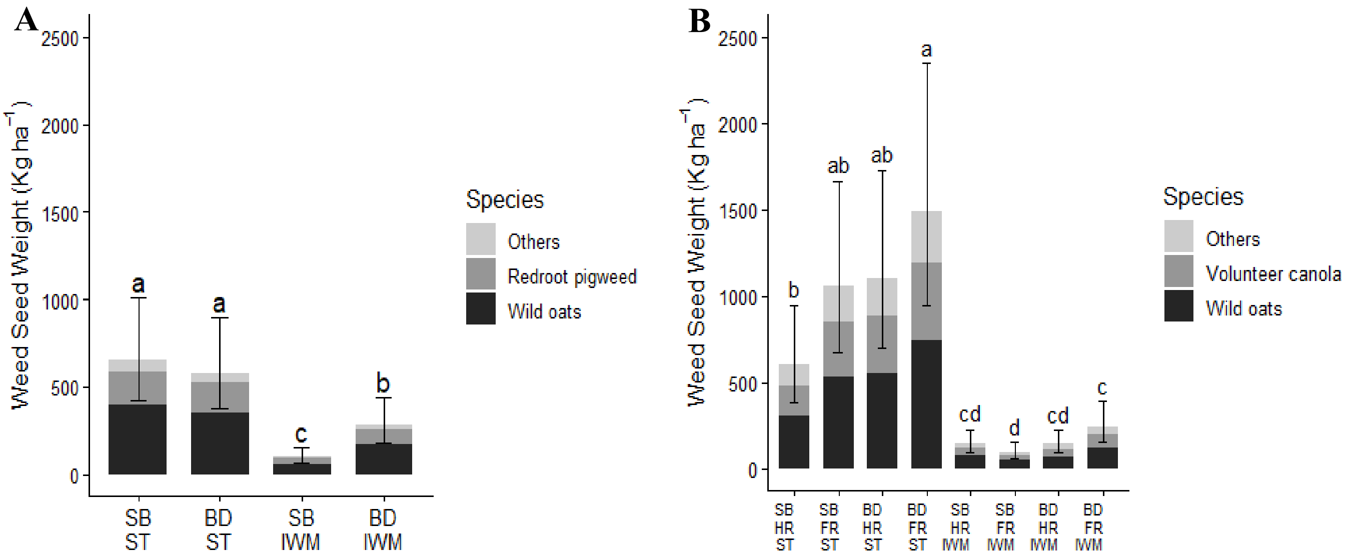

Figure 7 - The effect of fertilizer placement and weed management on total weed seed weight at Carman 2023 (A), effect of fertilizer placement, rate, and weed management interaction on total weed seed weight at Carman 2024 (B). Within each panel, bars sharing the same letter are not

significantly different according to Fisher's protected LSD at the 0.05 level. Error bars represent ± standard error of the mean (SEM), (ST: Standard weed management, IWM: Integrated weed management, FR: Full rate N, HR: Half rate N, SB: Side banding, BD: Broadcasting).

4.3.5 Weed Seed Size Distribution

In 2024 Carman, wild oats seeds were separated into three seed categories based on their sizes. The three seed size classes consisted of 1582 g of large seeds, 962 g of medium-sized seeds, and 662 g of small-sized seeds in total. The proportion of large seeds varied significantly among treatment combinations and the highest large-seed proportions were observed under standard weed management with fall broadcast full-rate fertilization (43%), whereas the lowest proportions occurred under IWM with fall sideband half-rate fertilization (7%). Treatments under standard management generally exhibited higher large-seed proportions than corresponding IWM treatments, indicating a strong reduction in large-seed production under IWM. The proportion of medium-sized seeds generally ranged between 30% and 6%. The share of small seeds varied more widely across treatments, with some treatments showing close to 26% and others much lower (3%).

The influence of fertilizer and weed management practices on the proportion of large wild oat seeds was examined. The proportion of large seeds (0–1) across fertilizer and weed management treatments was quantified based on replicated subsample counts. In general, treatments under standard weed management and higher nitrogen rates produced the highest proportions of large seeds (up to ~43%), whereas combinations of IWM with half-rate or side-banded nitrogen rates yielded markedly lower proportions of small seeds (as low as ~7%) (Figure 8).

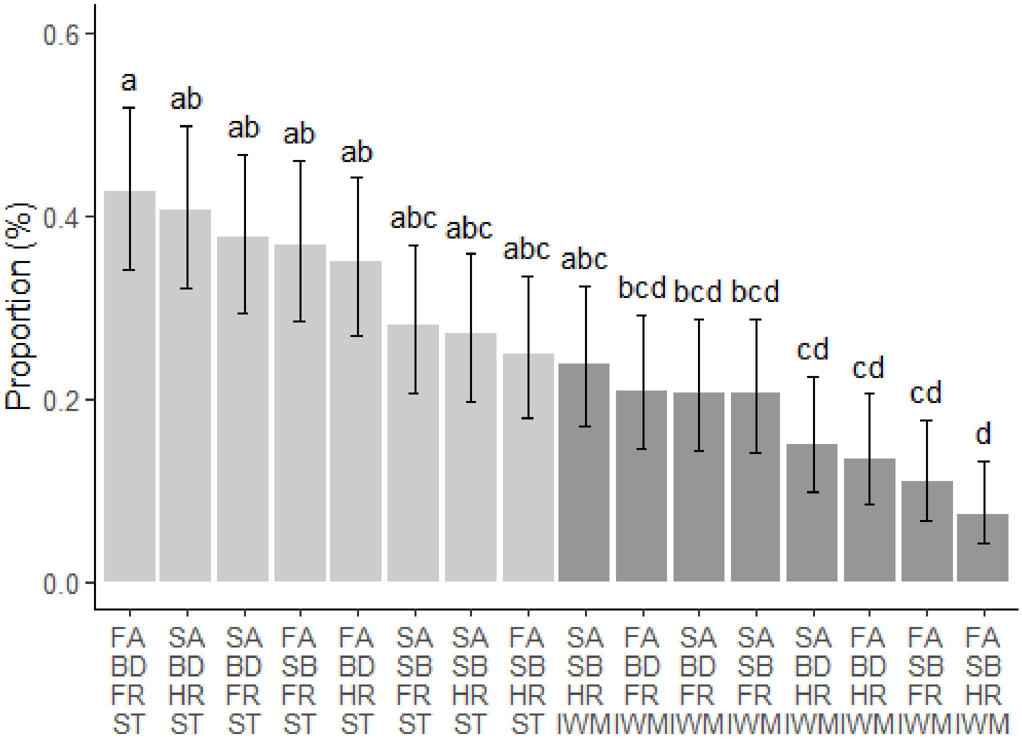

Figure 8 –The effect of treatments used in the field on large wild oat seed size category. (Within each panel, bars sharing the same letter are not significantly different according to Fisher's protected LSD at the 0.05 level. Error bars represent ± standard error of the mean (SEM). (ST: Standard weed management, IWM: Integrated weed management, SA: Spring application, FA: Fall application, FR: Full rate N, HR: Half rate N, SB: Side banding, BD: Broadcasting).

4.4 Germination and Dormancy Percentages

Germination in the large wild oat seed fraction ranged from 40% to about 75% (Figure 9A). Interestingly, differences in wild oat seed germinability were only observed between the fall-applied, full-N treatments in IWM (40%) and the fall-applied, full-N treatment using standard weed management (75%). Spring-applied and half-rate N treatments resulted in intermediate germinability in both weed management systems, which was not different among treatments. The reason for the difference between fall-applied, full N treatments in the standard and IWM treatments likely reflects the contrasting competitive environments created by the two weed management strategies rather than the fertilizer treatment itself. Under IWM, dense crop stands (higher seeding rates, narrow rows, early seeding) impose strong maternal competition stress, reducing the resources available to wild oat plants during seed filling even when nitrogen is abundant. This stress can produce lower-vigor seeds with reduced germination.

The final germination percentage in the medium-sized seed fraction ranged from approximately 40% to 50% (Figure 10B). The only factor influencing germinability in this size class was fertilizer rate, where seeds produced under half-rate N showed markedly lower germination (20%) than those produced under full-rate N (Figure 9B). This pattern suggests that reduced maternal N availability limited assimilate supply during seed development, thereby reducing germination.

For the smallest seed fraction, germination ranged from about 10% to 20% and was influenced by the interaction between fertilizer timing and weed management. Either fall application or spring application with IWM displayed the lowest germination percentage (47%) compared to fall application with standard weed management (Figure 9C). These germination differences likely reflect variation in the maternal competitive environment rather than fertilizer timing alone. Under IWM, wild oat plants experienced stronger crop competition, reducing resource availability during seed filling and producing small seeds with reduced germinability. In contrast, under standard weed management, reduced crop competition allowed mothers to allocate relatively more resources to developing seeds, resulting in higher germination even within the smallest size class.

The dormancy percentage of large-sized wild oat seeds was significantly influenced by the interaction effect of fertilizer rate and weed management (Table 3). Half-rate N with IWM displayed 49% lower dormancy compared with the full rate N with standard weed management in the large-sized seeds (Figure 10). Dormancy percentages from medium and small-sized wild oats did not show any significant difference between fertilizer and weed management treatments.

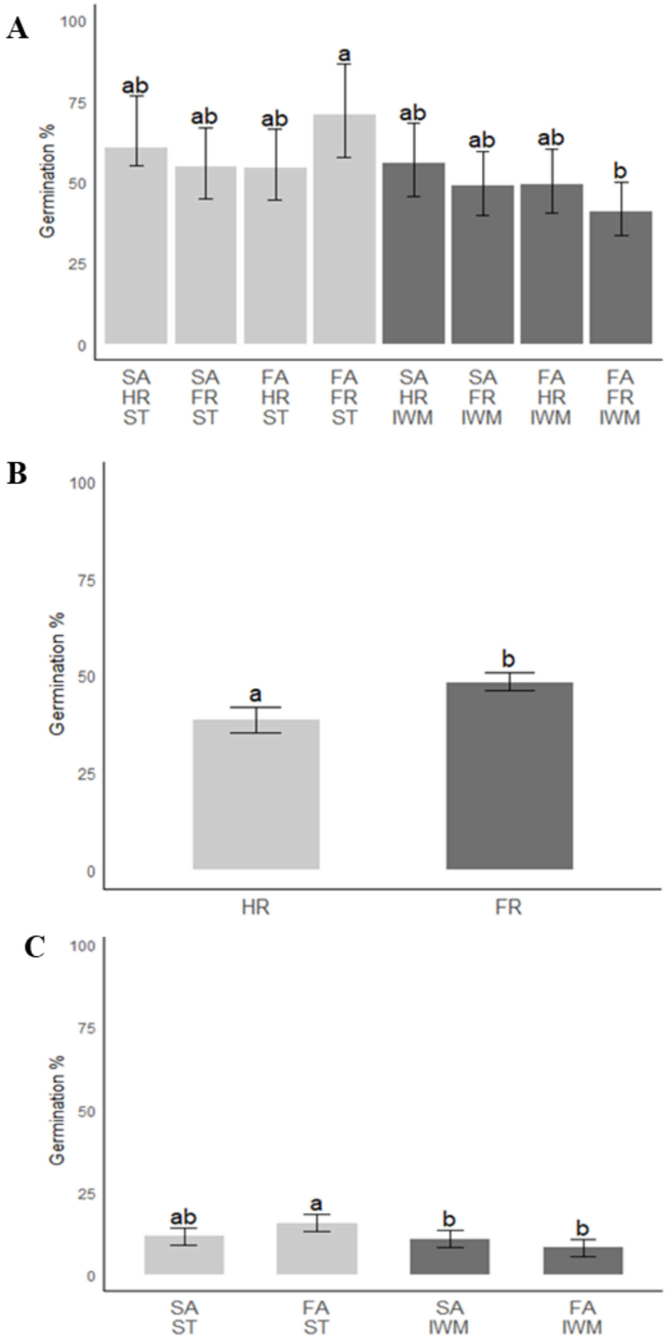

Figure 9- The effect of fertilizer application timing, rate, and weed management interaction on the final germination percentage of large size wild oat seeds from Carman 2024 (A), effect of fertilizer

rate on the final germination percentage of medium size wild oat seeds from Carman 2024 (B), effect of fertilizer application timing and weed management interaction on the final germination percentage of small size wild oat seeds from Carman 2024 (C). Within each panel, bars sharing the same letter are not significantly different according to protected LSD at the 0.05 level. Error bars represent ± standard error of the mean (SEM). (ST: Standard weed management, IWM: Integrated weed management, FR: Full rate N, HR: Half rate N, SA: Spring application, FA: Fall application).

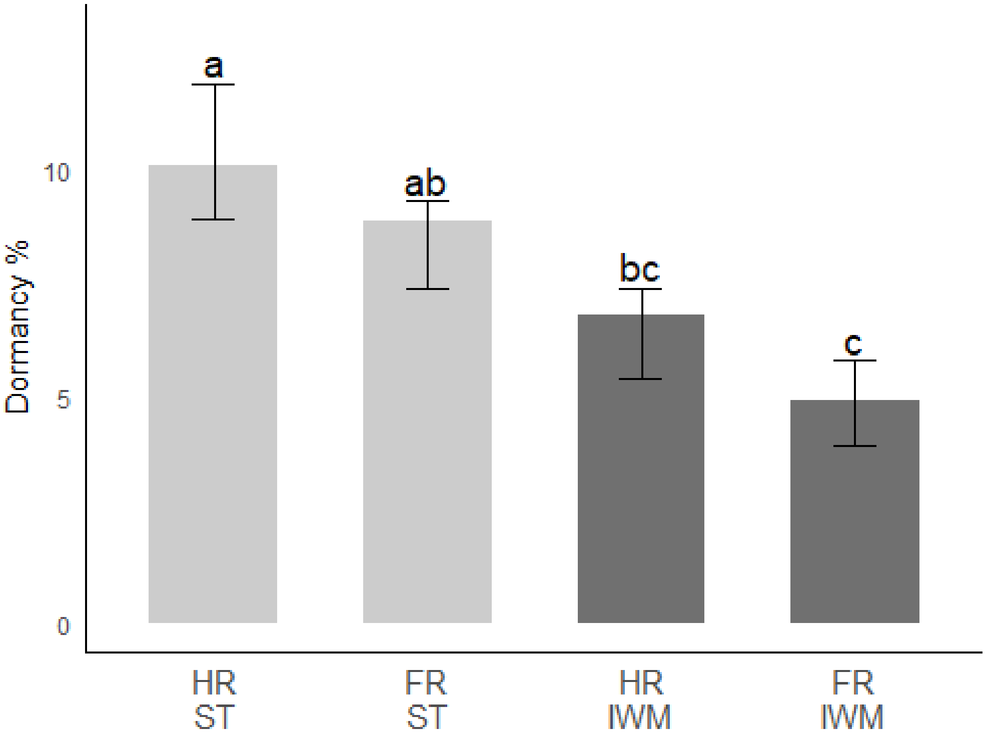

Figure 10- The effect of fertilizer rate and weed management interaction on dormancy percentage of large-sized wild oat seeds from Carman 2024. Within each panel, bars sharing the same letter are not significantly different according to protected LSD at the 0.05 level. Error bars represent ± standard error of the mean (SEM). (ST: Standard weed management, IWM: Integrated weed management, FR: Full rate N, HR: Half rate N).

4. 5 Crop Emergence and Biomass

Across four site years, IWM treatments consistently produced higher crop emergence than standard weed management (Table 2). Doubling the seeding rate from 200 plants m^{-2} to 400 plants m^{-2} increased mean wheat density by 81% and 182% at Carman in 2023 and 2024, respectively, and by 135% and 216% at Kernen in the same years (Figure 11 A–D). Some treatments produced crop emergence levels exceeding expectations, with IWM resulting in more than a 100% increase in wheat emergence compared to standard practices. Likely reflects enhanced moisture retention, and more stable seedbed microclimates created by higher seeding rates and narrow row spacing in IWM, while in the standard weed management, where gaps in the canopy may have exposed seedlings to higher weed pressure, soil moisture loss, or drought in some locations, reducing crop survival. In contrast, the higher seeding rate under IWM generated denser, more uniform stands. Although greater crop emergence might have been expected under conditions of higher fertilizer availability (full rate, side banding, or spring application), emergence was independent of nitrogen (N) rate, placement, or timing. This demonstrates that crop density, rather than N management, plays a dominant role in determining competitive stand formation.

Crop biomass at harvest maturity showed that IWM increased aboveground biomass by 45% at Kernen in 2023, 65% at Carman in 2024, and 30% at Kernen in 2024 compared to standard weed management (Figure 12B–D). However, at Carman 2023, characterized by drought during May and June, a significant interaction emerged between weed management and N rate on crop biomass (Table 2). Under standard weed control, halving the N rate increased biomass by 27% compared with the full rate of N (Figure 12A).

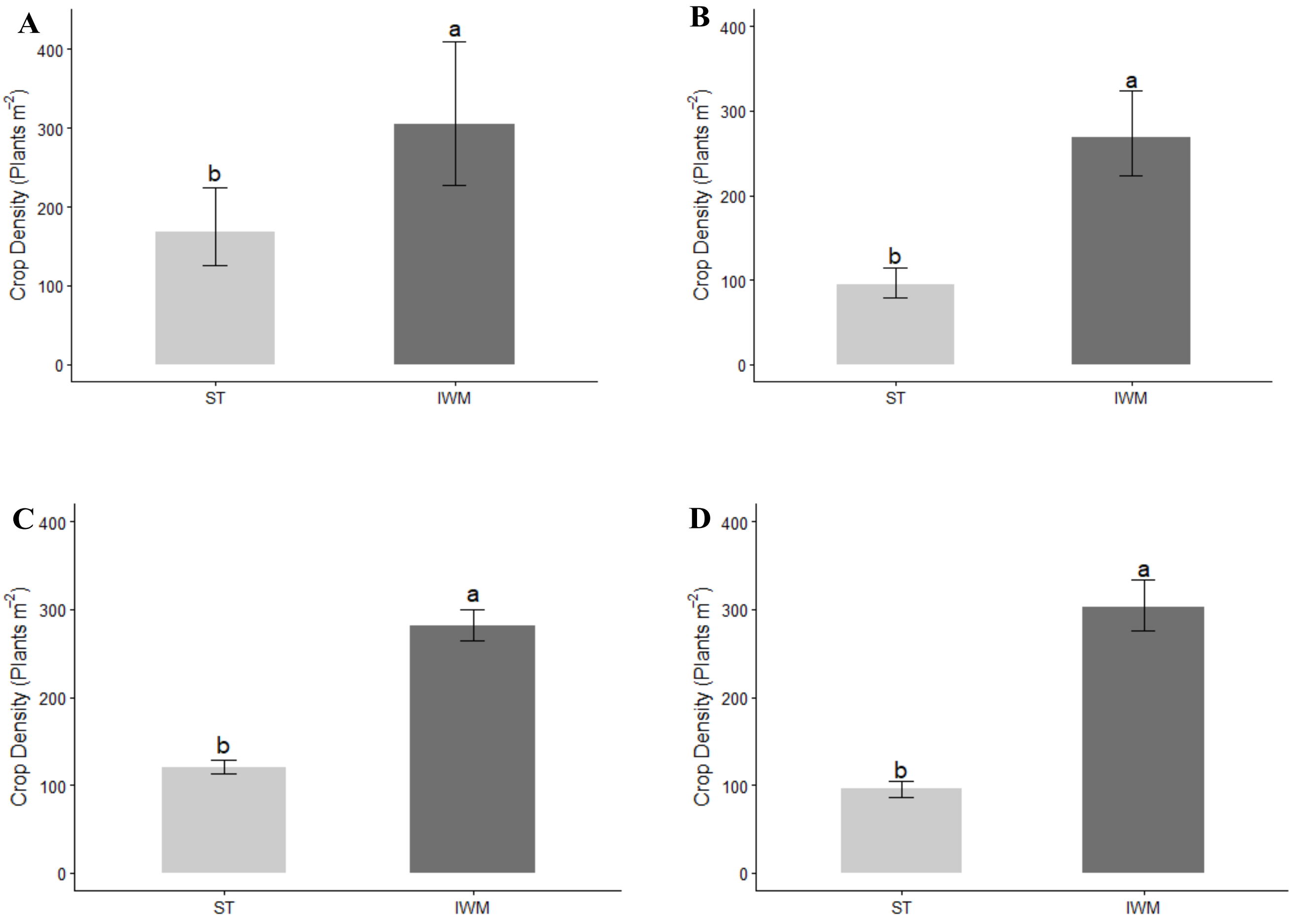

Figure 11 - The effect of weed management on crop emergence at Carman 2023 (A), Kernen 2023 (B), Carman 2023 (C) and Kernen 2024 (D). Within each panel, bars sharing the same letter are not significantly different according to Fisher's protected LSD at the 0.05 level. Error bars represent ± standard error of the mean (SEM). (ST: Standard weed management, IWM: Integrated weed management).

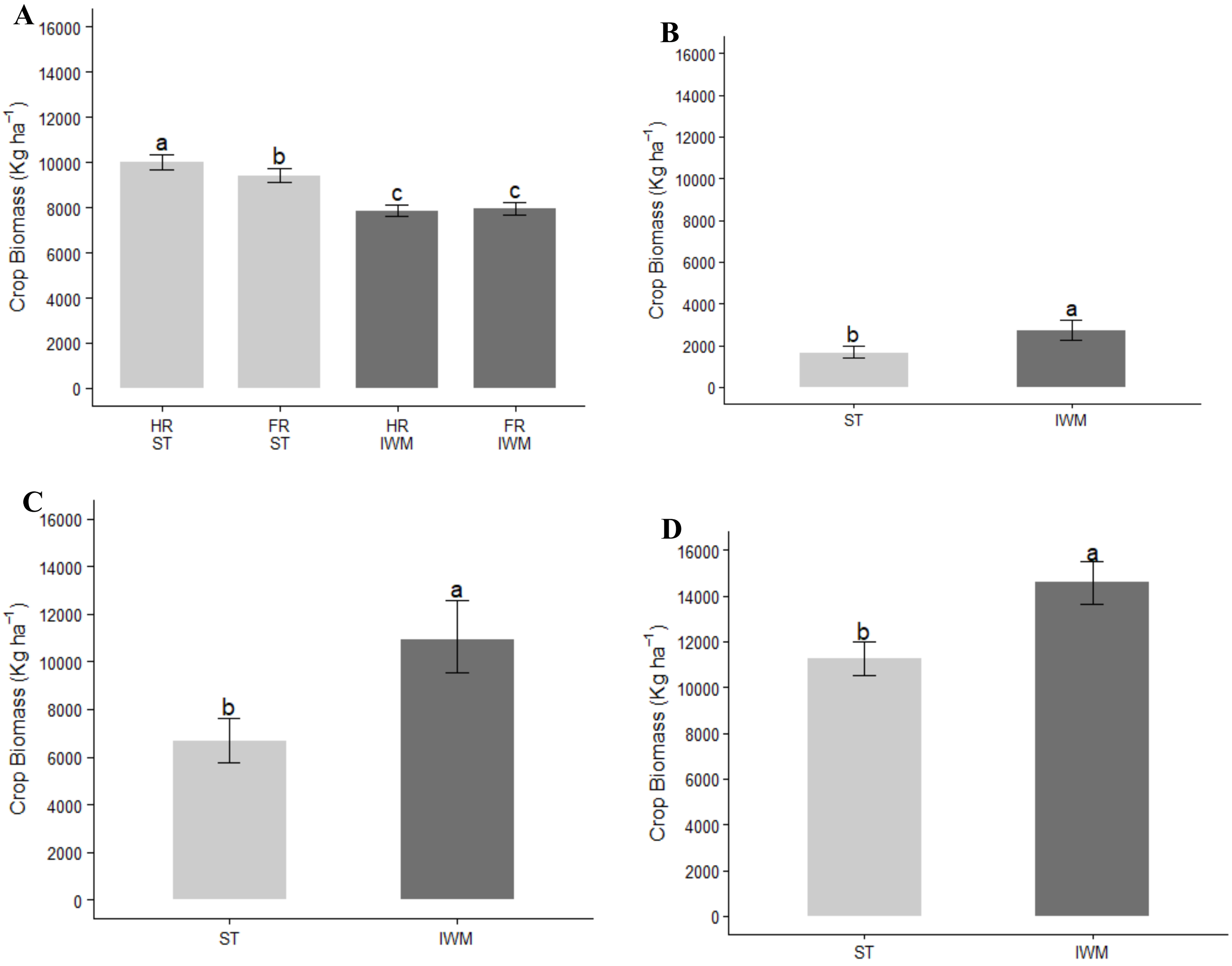

Figure 12 - The effect of fertilizer rate and weed management on crop biomass at Carman 2023 (A), weed management method on crop biomass at Kernen 2023 (B), weed management method on crop biomass at Carman 2024 (C), effect of weed management method on crop biomass at Kernen 2024 (D). Within each panel, bars sharing the same letter are not significantly different according to Fisher's protected LSD at the 0.05 level. Error bars represent ± standard error of the mean (SEM). (ST: Standard weed management, IWM: Integrated weed management, FR: Full rate N, HR: Half rate N).

4.6 Spring Wheat Grain Yield

Integrated weed management resulted in greater wheat yields in all experiments (Figure 13, Table 2). Yield improvement ranged from 10% at Carman 2023 to about 100% at Carman and Kernen 2024. Increase yield under IWM was caused by the increased wheat stand densities and improved spatial arrangement of wheat plants in that system. Nevertheless, nitrogen management (rate and/or time of application) also influenced wheat grain yields at Kernen 2023 and 20204 and at Carman 2024. At Kernen 2023, spring fertilizer application resulted in significantly higher grain yields under standard weed management, but there was no difference between spring and fall applications under IWM. Under standard management, when N is applied in spring, wheat has more immediate access to fertilizer placed in the root zone, allowing the crop to capture N before weeds fully establish. This early N capture improves crop vigor, compensates for competitive pressure, and results in higher grain yield. The spring application of nitrogen with IWM was the highest-yielding combination, yielding 98% more than the lowest-yielding combination, which was fall application under standard weed management (Figure 13B). At Carman 2024, significant differences in grain yields were observed among fertilizer timing and rates under standard weed management practices; however, these differences were not observed among fertilizer management strategies under IWM. Fall applied, full rate N, under IWM had the highest yield. Under standard weed management, spring-applied, half-rate N displayed the lowest yield, but it was not significantly different from other fertilizer treatment practices. Overall, 140% higher grain yield was achieved in fall-applied, full-rate N with IWM compared with spring-applied, half rate N with standard weed management (Figure 13C). At Kernen 2024, wheat grain yield was significantly influenced by the interaction of fertilizer rate and weed management (Table 2). Under IWM, full and half-rate N application rates did not differ significantly in grain yield; however, under standard weed management, half-rate N fertilizer had significantly higher yields (14%) than full-rate N (Figure 13D). A global contrast (combined data across all site-years) comparing IWM with standard weed management revealed a statistically significant difference (36%) in grain yield (p <0.0001), indicating a strong advantage of IWM over standard practices for spring wheat yield. However, global comparisons between spring and fall applications, full-rate and half-rate nitrogen, and broadcasting and sideband placement showed no significant differences in wheat yield (Table 3). Finally, comparing the most contrasting combinations, (spring application, broadcast placement, full rate N, standard weed management) alternative (fall application, sideband placement, half rate N, IWM) revealed a significantly higher yield (92%) for fall application, sideband placement, half rate N, IWM (p = 0.0508) (Table 3).

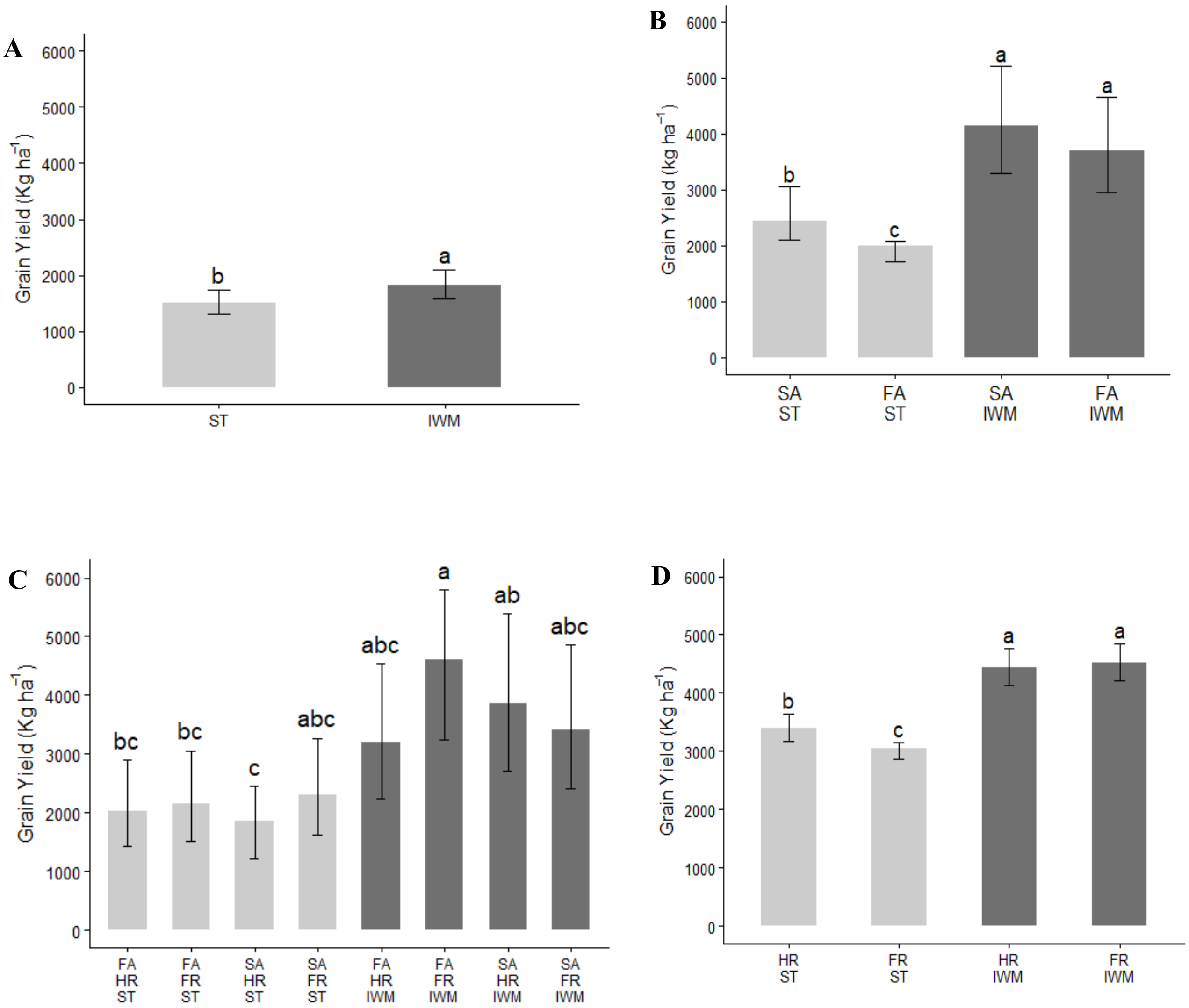

Figure 13- The effect of weed management method on grain yield at Carman 2023 (A), effect of fertilizer application timing x weed management interaction on grain yield at Kernen 2023 (B), effect of fertilizer application timing x rate x weed management method on grain yield at Carman 2024 (C), effect of fertilizer rate x weed management method on weed biomass at Kernen 2024 (D). Within each panel, bars sharing the same letter are not significantly different according to Fisher's protected LSD at the 0.05 level. Error bars represent ± standard error of the mean (SEM), (ST: Standard weed management, IWM: Integrated weed management, FR: Full rate N, HR: Half rate N, SB: Side banding, BD: Broadcasting, SA: Spring application, FA: Fall application).

Table 2: Analysis of variance (ANOVA) for crop and weed parameters measured at Carman and Kernen in 2023 and 2024. (ST: Standard weed management, IWM: Integrated weed management, FR: Full rate, HR: Half rate, SA: Spring application, FA: Fall application, CD: Crop Density, CB: Crop Biomass, TWSW: Total Weed Seed Weight, WD: Weed Density, WB: Weed Biomass, FD: Flowering Duration, Germ: Germination %, Dorm: Dormancy %, L: Large, M: Medium, S:Small).

Treatments	**CD**	**CB**	**TWSW**	**WD**	**WB**	**Yield**	**Height (RRPW)**	**Height (WO)**	**CD**	**CB**	**WD**	**WB**	**Yield**	**Height (RRPW)**
Site Year	**Carman 2023**								**Kernen 2023**					
Fertilizer Time (FT)	0.637	0.289	**0.006**	**0.033**	**6.599e-05**	**0.002**	0.758	**0.0003**	0.987	0.418	0.520	**0.05**	0.078	0.420
Fertilizer Placement (FP)	0.879	0.937	0.065	0.551	**0.01**	**0.004**	**0.0390**	0.1949	0.669	0.870	0.292	0.321	0.952	0.708
Fertilizer Rate (FR)	0.352	0.104	0.166	0.091	0.877	0.064	0.061	0.146	0.576	0.689	0.99	0.617	**0.035**	0.755
Weed Management (WM)	**7.229e-08**	**< 2e-16**	**4.467e-08**	**1.824e-07**	**5.214e-10**	**6.27e-05**	**0.042**	**3.747e-12**	**< 2e-16**	**5.384e-08**	**0.017**	**< 2e-16**	**< 2.54e-**	**0.031**
FT x FP	0.626	0.689	0.121	0.633	0.088	0.354	0.313	0.0826	0.711	0.270	0.201	0.703	0.055	0.755
FT x FR	0.692	0.181	0.453	0.905	0.963	0.108	**0.003**	0.062	0.328	0.319	0.333	0.549	**0.014**	0.909
FP x FR	0.273	0.311	0.459	0.864	0.297	0.7355	**0.017**	0.058	0.381	0.439	0.701	0.052	0.364	0.059
FT x WM	0.268	0.446	**0.005**	**0.031**	0.056	0.761	0.483	0.319	0.286	0.353	0.493	0.635	0.092	0.707
FP x WM	0.837	0.122	**0.001**	0.283	0.063	0.088	0.441	0.055	0.296	0.904	**0.01**	0.601	0.177	0.479
FR x WM	0.398	**0.02**	0.171	0.697	0.541	0.275	0.724	**1.565e-05**	**0.035**	0.434	0.935	0.311	0.243	0.091
FT x FP x FR	0.237	0.802	0.173	0.698	0.342	0.286	0.4087	0.063	0.434	0.577	0.582	0.941	0.629	0.416
FT x FP x WM	0.878	0.097	0.152	0.768	0.0028	0.457	0.071	0.101	0.488	0.536	0.851	0.258	0.471	0.533
FT x FR x WM	0.971	0.869	0.666	0.566	0.333	0.427	0.738	0.889	0.335	0.514	0.971	0.359	0.335	0.443
FP x FR x WM	0.666	0.913	0.363	0.498	0.648	0.061	**0.027**	0.528	0.388	0.644	0.925	0.578	0.429	**0.016**
FT x FP x FR x WM	0.272	0.215	0.665	0.633	0.854	0.081	0.127	0.582	0.73	0.396	0.74	0.152	0.943	0.572

Treatments	CD	CB	TWSW	WD	WB	Yield	Height (WO)	Height (VC)	FD-WO	FD-VC	Emerg C1	Emerg C2	Emerg C3	Emerg C4	CD	CB	WD	WB	Yield
Site Year	**Carman 2024**														**Kernen 2024**				
Fertilizer Time (FT)	**0.05**	**0.091**	0.256	0.399	0.423	0.436	**7.984e-6**	**7.984e-6**	0.235	0.062	0.064	0.077	0.058	0.059	0.454	0.626	**0.022**	0.968	0.436
Fertilizer Placement (FP)	0.599	0.567	**0.007**	0.823	0.061	0.933	0.139	0.986	0.192	0.296	0.074	0.055	0.061	0.061	0.973	0.931	0.658	0.363	0.933
Fertilizer Rate (FR)	0.189	0.929	0.115	0.058	**0.0072**	0.232	**0.013**	**0.013**	0.474	0.056	0.052	0.061	0.167	0.132	0.141	0.622	0.487	0.958	0.232
Weed Management (WM)	**2e-16**	**2.649e-08**	**3.092e-14**	**1.569e-10**	**2.2e-16**	**1.436e-11**	**7.234e-12**	**7.234e-12**	**5.726e-07**	**4.809e-11**	**0.004**	**0.003**	**0.03**	**0.04**	**2e-16**	**4.188e-09**	**3.01e-09**	**0.04**	**1.436e-11**
FT x FP	0.321	0.823	0.761	0.771	0.122	0.798	0.241	0.241	0.811	0.296	0.129	0.481	0.054	**0.032**	0.332	0.118	0.909	0.933	0.798
FT x FR	0.989	0.661	0.514	0.876	0.074	0.418	**0.007**	**0.007**	**0.077**	0.935	0.067	0.568	0.436	0.436	0.337	0.211	0.602	0.495	0.418
FP x FR	0.116	0.711	0.281	0.209	**0.031**	0.409	0.572	0.572	0.065	0.132	**0.045**	0.812	0.786	0.428	0.683	0.353	0.499	0.686	0.409
FT x WM	0.365	0.152	0.149	0.823	0.102	0.753	0.348	0.348	0.125	0.368	0.542	0.076	**0.035**	0.543	0.081	0.15	0.718	0.623	0.753
FP x WM	0.41	0.249	0.937	**0.044**	0.196	0.665	0.124	0.124	1.000	0.067	0.147	0.672	0.376	0.674	0.438	0.756	0.912	0.617	0.665
FR x WM	0.567	0.377	0.148	0.063	0.633	**0.041**	**0.017**	**0.007**	0.721	0.126	0.673	0.745	0.679	0.678	0.312	0.91	0.872	0.731	**0.041**
FT x FP x FR	0.856	0.166	0.777	0.69	0.424	0.654	**0.002**	0.051	0.912	0.375	0.853	0.483	0.769	0.567	0.051	0.729	0.116	0.146	0.654
FT x FP x WM	0.616	0.871	0.735	0.771	0.643	0.896	0.348	0.348	0.904	0.934	0.563	**0.041**	0.067	0.098	0.063	0.328	0.209	0.604	0.896
FT x FR x WM	0.370	0.516	0.084	0.887	0.322	**0.025**	**0.014**	**0.014**	0.235	0.565	0.835	0.562	0.089	0.721	0.161	0.578	0.452	0.286	0.523
FP x FR x WM	0.333	0.960	**0.019**	**0.037**	**0.032**	0.999	0.315	0.315	0.192	0.680	**0.032**	0.623	0.576	0.465	0.059	0.795	0.824	0.560	0.999
FT x FP x FR x WM	0.317	0.867	0.541	0.438	0.582	0.886	0.299	0.299	0.811	0.289	0.284	0.523	0.112	0.553	0.059	0.137	0.318	0.357	0.886

Table 3: Analysis of variance (ANOVA) for lab works done on evaluating seed traits (ST: Standard weed management, IWM: Integrated weed management, FR: Full rate, HR: Half rate, SA: Spring application, FA: Fall application, Ger: Germination %, Dor: Dormancy %, L: Large, M: Medium, S:Small, C: Cohorts).

Treatments	**Ger L%**	**Ger M%**	**Ger S %**	**Dor L (%)**
Site Year				
Fertilizer Time (FT)	0.349	0.863	0.587	0.237
Fertilizer Placement (FP)	0.896	0.688	0.258	**0.033**
Fertilizer Rate (FR)	0.337	**0.0009**	**0.0016**	0.32
Weed Management (WM)	**0.0012**	0.059	0.2201	**2.188e-09**
FT x FP	0.179	0.774	0.311	0.820
FT x FR	0.136	0.231	0.107	**0.002**
FP x FR	0.239	0.774	0.391	0.034
FT x WM	0.228	0.125	0.113	0.622
FP x WM	0.889	0.688	0.729	0.068
FR x WM	0.182	0.605	0.656	**0.002**
FT x FP x FR	0.307	0.688	0.521	0.058
FT x FP x WM	0.099	0.605	0.729	0.346
FT x FR x WM	**0.022**	0.231	0.258	0.676
FP x FR x WM	0.871	0.45	0.882	0.081
FT x FP x FR x WM	0.756	0.231	0.587	0.969

Table 4: Contrasts result for major crop and weed parameters measured at Carman and Kernen in 2023 and 2024

Contrasts	Weed density	Weed biomass	Grain yield
		P values	
IWM vs Standard	0.939	**<.0001**	**<.0001**
Half rate vs Full rate	0.526	0.104	0.453
Spring vs Fall	0.626	0.233	0.423
Sideband vs Broadcast	0.740	0.384	0.961
spring_broadcast_full_standard_vs.fall_sideband_half_IWM	0.939	**0.006**	**0.05**

CHAPTER 5

5.0 DISCUSSION

5.1 Weed Density and Biomass

Weed density and biomass together provide complementary insights into the dynamics of crop–weed competition. Numerous studies have shown that increasing crop density limits light availability for germination, thereby reducing weed emergence and growth (Lemerle et al., 2004; Mason et al., 2007; O’Donovan et al., 2012; Weiner et al., 2011). O’Donovan et al. (2012) found that wheat sown at higher seeding rates (150 – 400 seeds m^{-2}) reduced wild oat (*Avena fatua* L.) density. Similarly, Blackshaw et al. (2000) reported a 53–95% reduction in redstem filaree (*Erodium cicutarium* L.) density and emergence when wheat seeding rates increased from 50 to 300 kg ha^{-1}. Xue and Stougaard. (2002) also stated that increasing the seeding rate of winter wheat from 175 to 280 seeds m^{-2} resulted in a 20% decrease in density and biomass of wild oats. Apart from wheat, the effect of elevated crop density was examined in other cash crops as well. Increasing seeding rates in crops like barley and soybean led to substantial weed density reduction and crop yield improvement (Blackshaw et al. 2005; Geddes and Gulden, 2018; Kirkland, 1993). While IWM reduced weed density and biomass across all sites, the magnitude of fertilizer-related interactions varied with the growing conditions at each site-year. At Carman 2023 and 2024, both weed density and biomass were strongly shaped by fertilizer timing, placement, and rate when combined with IWM, whereas at Kernen, weed suppression was primarily driven by weed management alone, with fertilizer practices having a minor effect. Fertilizer placement effects were most evident in Carman 2023 and 2024, where side banding consistently reduced weed density and biomass relative to broadcasting, particularly at half N rates. This pattern suggests that concentrating N near the crop root zone and below the soil surface enhances crop uptake while reducing access for shallow-germinating weeds. The stronger response at half rates further indicates that placement becomes especially critical under lower N availability, as targeted delivery to the crop maximizes the competitive advantage. At full rates, excess nitrogen likely diffused into the surface soil (Malhi & Nyborg, 1991), allowing weeds to exploit the resource and diminishing the benefit of side banding. Fall-applied nitrogen under IWM reduced weed density at Carman 2023 compared with spring applications, due to the nitrogen applied during seeding (spring) not having sufficient time to move into deeper soil layers and thus remains more readily available for uptake by germinating weed seeds.

These findings are consistent with previous literature demonstrating that crop–weed interference is strongly influenced by fertilizer management (Blackshaw and Brandt, 2008). Nitrogen fertilization can stimulate weed emergence by acting as a cue to break dormancy in certain species (DiTomaso, 1995). Ross and Van Aker (2005) demonstrated that N inputs substantially increased wild oat competitiveness in wheat, underscoring the need for optimized fertilization strategies that suppress weeds, enhance crop competitiveness, and avoid excessive N use and associated environmental impacts (Sweeney et al. 2008). Broadcasting N at seeding, especially in spring, has been shown to promote weed germination and emergence, leading to higher weed densities but sometimes reducing biomass through intensified intra-specific competition (Sweeney et al., 2008). This pattern has been observed across wheat, barley, canola, and field pea systems (Blackshaw et al. 2004, 2005). Moreover, side banding often reduces weed biomass compared to broadcasting. Blackshaw et al. (2004) showed that the nitrogen placement method had greater, more consistent effects on crop-weed competition than the timing of fertilizer application. Comparing subsurface banded or point-injected N to surface broadcast N, the biomass of weeds and shoot N concentration were frequently lower, and these N placement treatments typically resulted in higher spring wheat yield. Plenty of studies have been conducted to manipulate fertilizer placement to reduce weed interference in crops. For example, Blackshaw et al. (2002) documented that wheat accumulates more nitrogen than weeds when nitrogen is placed 10 cm below the soil surface (away from surface-germinating weeds) rather than broadcast. As small weed seeds' propensity to recruit from close to the soil surface (Yenish et al., 1992), banding of fertilizer may be most effective. Consistent with our findings, Petersen (2003) found that fertilizer banding reduced weed biomass and N uptake of weeds by 50% as compared with broadcasting. The competitive ability of wild oat (*Avena fatua* L.), foxtail barley (*Hordeum jubatum* L.), and jointed goatgrass (*Aegilops cylindrica* L.) has been shown to decrease when fertilizer is banded below the soil surface rather than broadcast on the surface (Blackshaw et al., 2000; Kirkland & Beckie, 1998; Mesbah & Miller, 1999).

Differences in growing conditions and crop density also influence the inconsistent effects of nitrogen management on weed biomass across site-years. At Carman 2024, Kernen 2023 and 2024, with favorable rainfall and strong crop growth under IWM, likely diminished fertilizer effects, as the competitive crop canopy suppressed weeds effectively regardless of N placement or rate. In contrast, Carman 2023 characterized by early-season drought showed stronger N management effects on weed biomass, where side-banded and reduced N rates reduced weed biomass and density, likely by enhancing crop access to limited nutrients and minimizing weed exploitation of N fertilizer.

In comparison to most previous studies, this study importantly explored how IWM and fertilizer management can benefit managing in-season weed competition. According to the global contrast that compared the treatments across all the site years, we found that applying fertilizer in the fall with sideband placement and adopting IWM can maintain weed biomass at levels comparable to full-rate N, spring-broadcast N under standard management, while achieving superior suppression of weed biomass. These results identify a management combination that supports more sustainable weed control by reducing nitrogen inputs, enhancing crop competitive ability, and maintaining strong suppression across contrasting environments.

5.2 Weed Height

Weed plant height provides an important phenological measure, as it reflects both competitive ability for light and neighbour-driven interactions, particularly responses to shading and crowding. In the current study, the heights of wild oat, redroot pigweed, and volunteer canola were affected by interactions between nitrogen management and weed management. At Carman 2023, wild oat plants were shorter (28%) under IWM than under standard management, particularly when nitrogen was supplied at half the rate. Shorter heights in wild oats under half-rate with IWM are likely due to nitrogen limitation, as nitrogen is essential for leaf and stem development, and a reduced rate can limit plant height, especially in competitive conditions created by IWM practices (higher crop density, narrow rows). Redroot pigweed exhibited more complex interactions among N placement, rate, and weed management at both Carman and Kernen in 2023 (Kernen 2023). Here, at Carman 2023, broadcast, full-rate N under IWM produced shorter plants than side-banded full-rate N, a pattern that may reflect nutrient accessibility and spatial competition. Broadcasting with full rate under IWM resulted in shorter pigweeds, which may be due to IWM strategies such as narrow row spacing, higher density, and early canopy closure, promoting a dense crop stand that limits access to nutrients, water, and photosynthetically active radiation, which reduces stem elongation in a competitive setting. Moreover, in 2023, at Carman, weed heights under IWM treatments were lower, as dry conditions retarded weed growth, and IWM enhanced competition to suppress weeds. However, this intensified competition with either half-rate N or broadcast N can also limit the crop's growth, especially under suboptimal conditions such as drought. Overall, in the drier 2023 season, both wild oats and redroot pigweed at Carman and redroot pigweed at

Kernen exhibited reduced plant height under IWM compared to the standard weed management system. In contrast, during the comparatively wetter 2024 season at Carman, wild oats and volunteer canola showed shorter stature under standard weed management than IWM, suggesting that weed height response is not solely determined by management strategy, but by its interaction with seasonal climatic conditions. This suggests that under dry conditions, weeds experience moisture stress that limits their height. In such environments, IWM becomes particularly effective at further suppressing weed height due to compounded stress from low water availability and reduced nutrient access to weeds. As a result, weeds tend to remain shorter under IWM in drought-prone settings. Under favorable growing conditions (Carman 2024), crops established under IWM may exert strong competitive pressure, especially for above-ground resources such as light and space. In response to this competition, weeds adaptively allocate more resources toward stem elongation to outgrow the crop canopy and access light. This elongation strategy is a classic example of shade-avoidance behavior, driven by the need to maintain photosynthetic activity under canopy-induced light limitation. Aboveground growth dynamics play a significant role in crop-weed competition, particularly in high-nutrient environments (DiTomaso, 1995; Saberali et al., 2016). Weeds often have a significant competitive advantage over crop species due to their greater uptake of mineral nutrients, especially nitrogen (Rajcan and Swanton,, 2001). Crop-weed interactions extend beyond direct resource competition, and Rajcan and Swanton, 2001 showed that crops detect the presence of weeds at early growth stages through changes in light quality (spectral shifts) and subsequently adjust their growth strategies, such as altering plant height and architecture.

The impact of nitrogen on weed growth is not uniform across all weed species. Some weeds exhibited pronounced growth spurts with increased nitrogen, while others may show minimal response (Cathcart et al. 2004). Accordingly, this study reveals that weed plant heights in the two locations were not always taller in IWM treatments than in standard weed management or with the same nitrogen application method. This might be due to to site-specific climatic conditions and the presence of different weed species, which can alter the degree of crop-weed competition. There is limited research specifically examining weed height across weed and fertilizer management systems. These findings highlight a potentially critical and underexplored trait that may influence light capture and competition in weeds.

5.3 Flowring Duration

Flowering duration provides an important phenological measure that integrates how weeds allocate resources to reproduction and how long they remain in competition with crops. In Carman 2024, both wild oats and volunteer canola displayed shorter flowering durations under IWM compared with standard weed management. However, no effects of N fertilizer management on flowering duration were identified. Variations in the intensity of crop competition between IWM and standard practices resulted in measurable differences in weed flowering duration. Understanding flowering duration is important as it relates to weed reproductive duration, seed return to the soil seedbank, and the timing of potential late-season control strategies (Bagavathiannan and Norsworthy, 2012). Depending on their sowing density, row spacing, and morphological traits, different crops compete with weeds to varying degrees (Swanton et al. 2015). There is limited empirical evidence on the impact of IWM practices —such as crop density, row spacing, and seeding time— on weed flowering phenology. However, some studies comparing the weed phenology of field margins with that of the center provide some insights into the impact of crop competition on weed flowering phenology. Franklin and Whitelam (2005) found that weeds in the field core of cereal crops displayed an earlier and shorter blooming and pod initiation period due to greater competition in the center of the field compared with the boundary weeds. They also experienced substantial mortality before reaching the flowering stage. Under IWM in some site-years, resulted in weeds being often taller, likely due to increased early-season competition, which allowed better access to light. Differences in light quantity and quality can delay flowering and the onset of seed production (McLachlan et al. 1995; Yasin et al. 2019). Additionally, variations in agronomic practices, such as tillage and crop sowing dates, are often associated with differences in weed phenological development (Zhou et al. 2005; Gunton et al. 2011). Clarifying the combined effects of nitrogen fertilization, cultural weed management, and climatic factors on weed flowering phenology is a complex process that requires long-term study. The practical implications of these shifts in Prairie cropping systems are limited because the short growing season constrains the extent to which variation in flowering time can meaningfully affect management outcomes.

5.4 Total Weed Seed Production.

Research on how cultural practices, such as seeding rates, planting dates, and row spacing, influence weed seed production has emerged as a critical area of research, mainly due to increasing concerns about herbicide resistance management (Travlos, 2023). Present results demonstrate that cultural IWM treatments consistently suppress weed reproductive output more effectively than standard tactics, and that pairing site-specific nutrient placement and rate with IWM measures can further curtail seedbank inputs. For example, May et al. (2009) showed that increasing oat density from 250 to 350 plants m^{-2} reduces wild oat panicle density by 33% and their seed production by 47%. In a complementary study, Willenborg et al. (2005) demonstrated that the individual seed output of wild oats declines nonlinearly as weed density increases, particularly when emergence is delayed relative to the crop, indicating a negative density dependence in seed production. Harker et al. (2009) found that barley cultural practices, such as tall cultivars, high seeding rates, and crop rotation, significantly reduce weed seed production. Moreover, total weed seed production at Carman in 2024 was approximately twice that of 2023, highlighting the influence of annual variation in environmental conditions and weed seed production.

Fertilizer inputs can inadvertently boost weed reproduction (Zanin and Sattin, 1988). Jørnsgård et al. (1996) observed that higher nitrogen rates generally elevated weed seed production, although species responses varied. Strategic fertilizer management, optimizing placement and rate, combined with IWM practices tailored to local climatic conditions, can effectively reduce weed seed production. Kegode (1999) emphasized that high herbicide inputs are not always necessary; instead, integrated approaches such as crop rotation and targeted management can significantly reduce seed production in both grass and broadleaf weeds, with outcomes influenced by site- and year-specific factors. Importantly, results from Carman 2023 and 2024 demonstrate a clear linkage between vegetative growth and reproductive output: the treatment combinations that suppressed weed density and biomass were the same ones that produced the largest reductions in weed seed production. This connection indicates that the drivers of early-season competitive suppression directly translate into constraints on weed reproduction.

5.5 Weed Seed Germination and Dormancy

In the large-seed category, any treatment-related differences are particularly important to interpret. Here, standard weed management and high nitrogen rates produced the greatest proportion of large seeds (up to ~43%), whereas integrating IWM with either half-rate or side-banded nitrogen significantly reduced the proportion of large seeds, in some cases to as low as ~7%. Overall, a greater proportion of large seeds was observed under standard management, while IWM treatments generally resulted in a smaller proportion.

Large seeds are known to contain greater nutrient reserves, which enable more vigorous emergence, faster root growth, and higher survival under stressful field conditions (Fenner, 1992; Gardarin et al., 2010). Accordingly, they also displayed the highest germination rates (50–70%). However, large seeds were also the only size class that showed a significant dormancy response, about 5–10%. Our results further highlight that within large seeds category from fall-applied, full-rate N, IWM plots exhibited substantially lower germination (40%) compared with those from standard weed management. This reduction likely reflects maternal stress imposed by dense crop canopies and intense resource competition, which can alter assimilate allocation during seed filling and reduce seed vigor. Such competition-induced declines in seed germinability are consistent with earlier findings that shaded, or nutrient-stressed maternal plants often produce less viable offspring (Brainard et al., 2005; Fenner, 1991).

In addition, under IWM with full rate N, dormancy of large seeds decreased by nearly 49% compared with half rate N under standard management. This pronounced reduction in dormancy aligns with the concept that maternal stress and competition intensity under IWM can alter seed physiological traits. In competitive environments with dense crop canopies, reduced light quality and limited nutrient availability experienced by maternal plants can accelerate resource allocation to reproduction, trying to finish the life cycle more rapidly. These stressors often accelerate reproductive resource allocation, prompting maternal plants to complete their life cycle more rapidly and invest less in dormancy-inducing mechanisms.

The competition-induced differences in crop canopy structure have been found to influence weed dormancy rates without significantly altering seed weight (Brainard et al., 2005). Nitrate-Nitrogen fertilization has been shown to act as a signal influencing dormancy release and germination, although responses vary with genotype, seed size, and environmental conditions (Watkins, 1966).

Fertilizer rate interacts with weed fecundity, as higher rates can increase seedling survival and seed production, thereby contributing more seeds with variable dormancy status to the seedbank (Blackshaw et al., 2003). Liebman & Mohler (2001) noted that abundant nitrogen availability often promotes the germination of nitrophilous weeds such as wild oats and foxtails, particularly when fertilizer is broadcast. Conversely, they showed that lower nitrogen rates can restrict seed germination and early seedling vigor by creating nutrient stress at the soil surface, especially in competitive crop stands. In contrast to our findings, Benech-Arnold et al. (1992) showed that, when parent plants were subjected to maternal stress during seed production, the germination rates of the offspring seeds were greater than those of plants grown under control irrigation conditions in a number of other weed species, including johnsongrass [*Sorghum halepense* (L.) Pers.] and *A. retroflexus* (Karimmojeni et al., 2014). This discrepancy may stem from species-specific physiological responses, differences in the timing and intensity of maternal water stress, environmental variables like nitrogen and temperature during seed development, and other environmental variations that can influence how maternal stress impacts seed dormancy and germination. Generally, when crops experience maternal stress, their seeds often exhibit reduced germination, typically in the opposite direction to that observed under non-stressed conditions (Fenner, 1991). This decline in germination potential is often attributed to physiological disruptions during seed development, such as reduced nutrient allocation, hormonal imbalances (elevated abscisic acid levels), or premature desiccation triggered by environmental stressors such as drought, nutrient deficiency, or competition. These stress-induced conditions can impair embryo development and seed maturation, ultimately resulting in smaller, poorly filled, or physiologically dormant seeds that are less likely to germinate efficiently under favorable conditions. Exposure to crop competition in the maternal environment may induce stress memory in weed populations, enhancing dormancy expression, improving survival potential, and ultimately persisting them in agroecosystems.

In this study, treatments that reduced weed biomass, such as IWM combined with side-banding or lower N rates, not only suppressed weed seed output but also altered progeny seed traits. The observed reduction in germination of large seeds under IWM with full-rate nitrogen, coupled with decreased dormancy under full-rate nitrogen, underscores how maternal nutrient and competitive environments can shift offspring physiological strategies. When maternal plants experience high competition for light and nutrients under dense crop canopies, they often undergo stress-induced adjustments. Consequently, progeny from such stressed maternal environments may exhibit lower dormancy but reduced initial germination, which may be due to incomplete maturation or delayed after-ripening. These responses indicate that IWM can indirectly shape the intergenerational dynamics of weed populations, producing seeds that are less persistent in the soil seedbank, which could enhance the long-term effectiveness of IWM in depleting weed seed reserves.

5.6 Crop Emergence and Biomass

Crop emergence and biomass are central indicators of crop competitive ability, and their enhancement under IWM provides a key mechanism explaining reductions in weed density, biomass, and seed production. Increases in wheat emergence under IWM (81–216% across site-years) compared with standard weed management were a key driver of the substantial reductions in weed density, biomass, and seed production.

Crop biomass at maturity generally mirrored crop density trends: IWM increased aboveground biomass (Carman, 2024; Kernen, 2023, 2024). Among these three site-years, no significant nitrogen × weed management interactions were observed, indicating that the enhanced biomass accumulation under IWM was likely associated with denser crop stands rather than nitrogen effects. However, at Carman 2023, characterized by drought during May and June, a significant interaction emerged between weed management and N rate. Half N rate under standard weed management increased crop biomass relative to the full rate N under standard weed management. The Carman 2023 crop biomass response may reflect seedling phytotoxicity from concentrated high nitrogen (N) in low-moisture conditions, or alternatively, more rapid depletion of soil moisture under higher N availability, which could have limited later growth and development (Sarwar et al. 2025). In contrast, IWM plots in Carman (2024) didn't show a crop biomass response to N rate. With more plants present, the nitrogen supply may be distributed across a larger population, creating a dilution effect. Increased intraspecific competition among wheat plants at higher densities may have led to a more even distribution of nitrogen within the crop, thereby buffering the differential growth responses to high nitrogen rates. Although high nitrogen levels can stress seedlings, the observed reduction in shoot biomass is more likely due to limited soil moisture. Water stress inhibits shoot growth, causes early chlorosis, and restricts root development, symptoms consistent with the study's conditions. While excess ammonium can also induce stress, no visible signs of nutrient toxicity were observed, suggesting water limitation was the dominant factor. These findings underscore that high seeding density and narrow row spacing, key components of IWM, can markedly enhance crop establishment and yield potential, as documented in wheat and other cereals (Murphy et al., 1996; Boyd et al., 2009; Harker et al., 2016; Chauhan & Gill, 2014; Van der Meulen & Chauhan, 2017). Nevertheless, their benefits are strongly influenced by environmental conditions and fertilizer management; applying appropriate N rates enhances nutrient-use efficiency and supports greater productivity in dense stands (Kristensen et al. 2008) but may exacerbate phytotoxicity under drought conditions (Sarwar et al., 2025). However, under drought-stressed conditions (Carman, 2023), high crop density along with fertilizer strategies were insufficient to ensure higher biomass and weed suppression, demonstrating the importance of adequate moisture availability in realizing the full benefits of ICM.

Overall, these results demonstrate that a higher seeding rate under IWM was the dominant driver of wheat density and biomass. These crop biomass gains reflect more efficient conversion of soil nitrogen into crop growth when weeds are suppressed. In turn, higher crop biomass, consistent with the observed reductions in weed biomass (73–94%) and total seed production (85–93%) under IWM. Overall, this study reinforces the importance of establishing a competitive crop stand as the most fundamental requirement for IWM to manage weeds both in the short term and long term.

5.7 Spring Wheat Grain Yield

The spring wheat grain yield patterns observed across the four site-years reflect the combined influence of crop density, crop biomass, and weed suppression under varying nitrogen (N) management and weed control strategies. The consistently higher yields under IWM with up to 140% increases mirror the higher crop densities and biomass observed in IWM. At Kernen 2023, the spring application yielded more under standard weed management, but there was no difference between spring and fall applications under IWM. This indicates that when weeds are poorly controlled (standard weed control), N timing becomes critical, but under IWM, crop competitiveness essentially overrides N fertilizer timing effects. At Carman 2024, fall-applied full-rate N, under IWM, had the highest yield compared with spring-applied half-rate N with standard weed management. Although fall-applied N is typically considered less efficient than spring-applied N (~80% efficiency; Johnston & Bruulsema, 2014), our results showed strong yields under fall-applied, half-rate N when combined with IWM. This likely reflects enhanced crop competitiveness under IWM, limited nitrogen (N) losses primarily through leaching and volatilization, and possible soil residual N, which together improve crop access and reduce weed uptake. At Kernen 2024, under IWM, full- and half-rate N applications yield greater results. IWM plots were seeded earlier, which could have improved synchronization between crop growth stages and fertilizer availability. Early seeding likely allowed the crop to establish quickly, take advantage of applied nitrogen more efficiently, and outcompete weeds more effectively during critical early growth stages (O'Donovan et al., 2007). Although higher nitrogen rates are typically associated with increased wheat yield, our results demonstrate that nitrogen response is strongly modified by weed management intensity. Spring-applied nitrogen enhanced early-season weed competition, reducing crop yield potential. In contrast, fall-applied reduced nitrogen limited early weed access to nitrogen while providing sufficient availability during key crop growth stages. Under IWM, where crop competitiveness was maximized through early seeding, narrow rows, and high plant density, half-rate nitrogen improved nitrogen-use and resulted in equal or greater yield than full-rate nitrogen.

Despite variability in treatment responses arising from contrasting environmental conditions across site-years, the global contrast between IWM and standard weed management revealed a consistent yield advantage, with IWM increasing spring wheat yield by 36% on average. Despite variations in treatment effects due to contrasting environmental conditions prevailing among site-years. The global contrast comparing IWM with standard weed management revealed a strong advantage of 36% for IWM over standard weed management for spring wheat yield. The most contrasting combinations: (spring application, broadcast placement, full rate N, standard weed management) Vs. (fall application, sideband placement, half rate N, IWM) revealed a significant (19%) yield advantage for the latter combination. The present study showed that the combination of IWM with side-banded, reduced-rate nitrogen maintained higher grain yield while lowering in-season weed pressure. However, past studies report mixed effects of nitrogen timing (fall vs. spring) and rate on wheat yield under Prairie conditions; outcomes are strongly site- and season-dependent. Accordingly, we present these results as context-dependent observations and emphasize that adopting fall fertilizer application with reduced nitrogen rates and side-dressing with IWM may help maintain higher grain yields while reducing fertilizer costs and minimizing the environmental impacts associated with using higher N fertilizer rates. Such treatments could offer a more sustainable and cost-efficient approach, particularly in systems where weed control is proactive and diversified.

Furthermore, this study revealed that under favorable growing conditions (Kernen 2023, 2024; Carman 2024), fall-applied, full-rate N application with IWM showed a trend for higher spring wheat yields at some site-years (Kerne 2023, 2024; Carman 2024). This additive influence of fertilizer and cultural weed management aligns with Kristensen et al. (2008), who found that spring wheat yield increased with nitrogen application (80 kg ha^{-1}), particularly when combined with IWM practices. Benaragama et al. (2022) demonstrated that a combined regimen of moderate seeding density, narrow row spacing, 130 % N rate, and fungicide conferred a 23 % mean yield improvement over the wide rows, low N, no fungicides treatments. Similar synergistic effects have been documented in other oilseed crops (Brandt et al. 2007; Lewis & Knight, 1987) and small grains (Lafond, 1994), where higher seeding densities, narrower rows, and elevated N rates collectively boost productivity. Therefore, a sensible fusion of several cultural and fertilizer techniques can significantly increase the consistency of crop grain yield. Overall, yield improvements under IWM, combined with fertilizer strategies (timing and rate) result from multiple linked factors, such as denser crops, increased biomass, and reduced weed pressure and seed production, rather than any single cause.

6.0 General Discussion and Conclusions

The present research study was undertaken with the main aim of exploring how combined N fertilizer and cultural weed management strategies influence weed management in spring wheat production systems. Two major objectives guided this study: first, to determine the effects of 3Rs' of N fertilizer management (right time, right place, right rate) and cultural weed management practices on in-season weed management (crop–weed competition and it s impact on grain yields); and second, to evaluate the impacts of these combined management practices on long-term weed management (weed phenological traits and weed seed dormancy that are important for weed persistence). Based on these objectives, the study tested two central hypotheses. The first proposed hypothesis was that integrated cultural weed management combined with optimized nitrogen (N) rate, timing, and placement will interact positively to reduce weed density and weed biomass and increase grain yield compared with IWM or N management alone. The second hypothesis is that 3R of N management and cultural weed management interactively influence the maternal growing environment of weeds, thereby differentially influencing seed persistence traits such as weed seed dormancy.

Based on the four-site years of data, this thesis revealed that cultural weed management practices in wheat, such as increased seeding rate, narrow row spacing, and early seeding in combination did not negatively interact with the N management (time, place and rate) for weed suppression. To further illustrate this, the three cultural strategies together suppressed weeds and increased crop yields compared with the common/standard cultural practices (standard seeding rate, row spacing, and late seeding), irrespective of N fertilizer management practices.

IWM consistently reduced weed density and biomass by 70–90% compared with standard weed management in all site-years. In the absence of negative interactions, this study found some additive effects of IWM and N management depending on the environmental conditions. Weed suppression of IWM was strong when combined with side-banded nitrogen at half rates at some site-years with favorable moisture (wet) conditions. Such fertilizer strategies concentrated nitrogen closer to the crop root zone, minimizing nutrient availability to shallow-germinating weeds like wild oats and redroot pigweed. These findings support the idea that cultural IWM with N fertilizer management (N placement and N rate) can additively suppress weeds by intensifying crop competition and limiting resource access. The global comparisons (comparisons made across site-years) between fall application-sideband N-half rate N- with IWM significantly reduced (95%) weed biomass compared with spring application-broadcast N-full rate N with standard weed management highlighting its potential for better weed suppression.

The improvements in weed suppression under IWM translated into stronger crop establishment, as reduced early-season competition allowed wheat to capitalize on available resources. In this study, the crop responded to ICM practice by first getting a good early crop growth and biomass development. Crop emergence and crop biomass consistently responded positively to IWM across three of the four site-years, reinforcing the synergistic effect of combined cultural practices such as narrow row spacing, higher seeding rates, and early seeding. The exception, Carman 2023, showed that even robust IWM practices could be undermined by early-season drought, highlighting the critical role of timely rainfall in determining biomass outcomes.

Beyond in-season weed suppression, this research offers insights into how cultural weed management and 3R N management interactively influence weed phenology. Weed height at maturity was variable among species, site-years, and treatments. In the dry year (2023), IWM resulted in shorter weed height, likely due to reduced resource availability and early crop competition. In contrast, under the favorable moisture conditions in 2024, weeds were taller under IWM, potentially reflecting shifts in crop-weed competitive dynamics towards light competition under good growing conditions. There were some interaction effects of fertilizer placement, rate, and timing with IWM on weed height; however, these fertilizer effects were not consistent across weed species or site-years. The flowering duration was shortened under IWM for both wild oats and volunteer canola. Weed seed production was substantially reduced under IWM, particularly when combined with side-banded fertilizer, resulting in an 85–93% decrease across the two site-years. This substantial reduction of weed seeds mirrors the patterns observed for weed biomass, indicating that treatments that suppressed vegetative growth also effectively limited reproductive output. This finding is significant for long-term weed management, as even modest reductions in annual seed return can translate into substantial depletion of the seedbank over time. The consistent declines in weed density, weed biomass, and weed seed production observed under IWM underscore the effectiveness of cultural practices in limiting weed establishment and reproductive output. Moreover, under IWM combined with half-rate N, side-banding, and fall application of nitrogen management, wild oat seeds tended to be smaller in size and of lower vigor, with notably fewer large, high-vigor seeds (<10%) and those smaller seeds exhibiting reduced germination potential. Overall considering the above results, they collectively support the first hypothesis that combined application of cultural weed management and 3R N management positively influence to reduce weed density and weed biomass and increase grain yield compared with IWM or N management alone.

Beyond in-season weed management effects, this study revealed some new insights into long-term weed management via influencing seed persistence traits. The germination percentage of the large wild oats seed category significantly reduced under the IWM when combined with fall-applied, full-rate N, indicating a strong maternal environment effect mediated by crop competition under IWM. The germination percentage of medium-sized seeds was lower in half-rate N-treated mother plants, suggesting a direct maternal effect of nutrient status on offspring germination traits. Small seeds generally exhibit reduced germination under fall-applied IWM, further showing that resource limitations in the maternal environment influence weed seed germination ability. Dormancy results revealed another dimension of the effects of competition and maternal stress, showing that under IWM, seeds exhibited lower dormancy levels compared to those produced under standard management. Consequently, seeds produced under IWM conditions are more likely to have lower dormancy potential, increasing their tendency to germinate earlier when favorable conditions occur and thereby reducing their long-term persistence in the seedbank. These results support the second hypothesis that competitive cultural weed management and nitrogen management interactively influence the maternal growing environment of weeds, thereby differentially influence seed persistence traits such as weed seed dormancy. Furthermore, these patterns suggest that maternal plant exposure to stress, whether from interspecific competition or nutrient limitation, can influence seed germination and dormancy, potentially as an adaptive mechanism to avoid unfavorable conditions. However, the data gathered from this study on weed phenology and weed seed traits are limited due to variable weather conditions that influence weed emergence. Thus, the findings should be interpreted cautiously.

The agronomic implications of these findings are highly relevant to Prairie farmers seeking to balance spring wheat productivity with sustainable weed control. Grain yield outcomes paralleled the trends observed in weed suppression. IWM consistently enhanced grain yield in all site-years, over standard weed management. Among all site-years, spring wheat grain yield was consistently higher under IWM, with yield advantages ranging from 10% to 140%. According to the global comparison, IWM with fall-applied, side-banded, half-rate nitrogen, produced 92% higher yield compared with standard management with full-rate N, spring-broadcast nitrogen. These findings clearly illustrate the weed suppression benefits of integrated crop management; however, broad adoption will ultimately depend on the extent to which these practices also improve or sustain crop yields. It is also important to emphasize that the yield advantages observed in this study occurred under no in-crop herbicide application conditions; thus, they may vary under conventional practices, where farmers typically apply in-crop herbicides. Overall, this study concludes that cultural IWM and 3R of N (N fertilizer application timing, rate, and placement) practices used in this study have no negative interactions but additively influence weed suppression and grain yields. Thus, farmers can alter their N management practices based on their needs as well as on the growing conditions. Further, this study reveals that with good crop competition with cultural practices like high seeding rate, narrow row spacing and early planting, farmers would be able to reduce N fertilizer application rate without affecting their crop yields even under high weed competition.

The evidence generated in this study is not sufficiently strong to draw definitive conclusions about the long-term impacts on weed phenology and weed seed persistence. In this study, early-season weed emergence (1– 4 weeks after seeding) was evaluated at the community level to characterize overall weed recruitment patterns. However, C3 and C4 weeds exhibit fundamentally different emergence cues and recruitment periods, and aggregating species may obscure important ecological differences. Future research should separate emergence patterns by functional group (C3 grasses vs. C4 broadleaves). Further, the impact of the maternal growing environment on weed seed traits was evaluated only on wild oats using one site-year of data. Despite the data revealing some interesting patterns, more studies are required for strong conclusions. Also, this study was only conducted to evaluate the maternal effects on the first generation of weed seed, but it would be interesting to study whether these maternal effects would carry over more than one generation.

Primarily this study focused on weed emergence, their heights, flowering duration, and seed dormancy like phenological traits; however, additional phenological traits strongly influence weed persistence, including seed shattering, which determines the proportion of seed entering the seedbank before harvest. Examining these traits would provide a more complete understanding of how maternal environments shape weed reproductive strategies and long-term persistence. Similarly, given the strong influence of weather variability in the present study, future research should conduct coordinated multi-year, multi-site trials spanning diverse Prairie environments.

Taken together, our results show that cultural integrated weed management (IWM) can sustain spring wheat yields at lower nitrogen (N) rates, delivering additive benefits for both weed suppression and crop productivity across Prairie environments. By reducing weed density, biomass, and seed rain while improving crop establishment and yield, cultural IWM not only enhances in-season competitiveness but also contributes to longer-term population management: seeds produced under competitive, IWM-managed maternal environments exhibited reduced dormancy, implying faster seedbank depletion over time. Building on these findings, future work should quantify the long-term consequences of lowered N inputs on soil health, tracking soil organic matter dynamics, nutrient cycling, and microbial community structure and function within IWM + 4R programs. To accelerate adoption, studies should also incorporate partial-budget analyses that explicitly compare fertilizer savings, yield responses, and any additional input or management costs, alongside risk and sensitivity analyses across variable seasons. Finally, embedding these agronomic and economic outcomes within an integrated crop-management (ICM) framework coupled with robust, multi-year trials it will provide the evidence base needed for producers and policy makers to adopt IWM + 4R practices at scale. In conclusion, combining cultural IWM with some of the N management offers a practical, systems-level strategy to curb weed pressure, sustain yields, and set Prairie grain systems on a more resilient, resource-efficient trajectory.

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Appendices

Used statistical model example for lmer.

```
model <- lmer(CD ~ftime*fplace*frate*wmgmt+(1|block)+(1|ftime:fplace:frate:block),
data=WICM24)

residuals1<- residuals(model)

shapiro.test(residuals1)

qqnorm(residuals1)

results_cd <- data.frame(residuals = residuals,

                         ftime = X20241$ftime,

                         fplace = X20241$fplace,

                         frate = X20241$frate,

                         wmgmt = X20241$wmgmt)

leveneTest(residuals ~ ftime * fplace * frate * wmgmt, data = results_coh3)

CD<-lmer(log(coh3)~ftime*fplace*frate*wmgmt+(1|block)+(1|ftime:fplace:frate:block),
data=p20241, REML=TRUE,)

summary(CD)

anova(CD)

plot(CD)

emms.CD <- emmeans(CD,  ~ ftime:wmgmt,type = "response")

mod_means_contr <- emmeans::emmeans(object =emms.CD,

                                    pairwise ~ "ftime:wmgmt",

                                    adjust = "none")

summary(mod_means_contr)

mod_means <- multcomp::cld(object = mod_means_contr,Letters =letters,reversed =TRUE)

summary(mod_means)
```

Used statistical model for glmm

```
phenology1$fgermg1p <- phenology1$fgermg1p / 100

model5 <- glmmTMB(fgermg1p ~ ftime * fplace * frate * wmgmt +

                   (1 | block) + (1 | ftime:fplace:frate:block),

                 data = phenology1,
```

```
              family = beta_family())
Anova(model5, type = "III")
emms.cd <- emmeans(model5,  ~ "ftime:frate:wmgmt",type =  "response")
mod_means_contr <- emmeans::emmeans(object =emms.cd,
                          pairwise ~ "ftime:frate:wmgmt",
                          adjust = "LSD")
mod_means <- multcomp::cld(object = mod_means_contr,Letters =letters,reversed =TRUE)
summary(mod_means)
```

Used statistical model for global contrasts

```
emm_4way <- emmeans(model1, ~ fplace * ftime * frate * wmgmt, type = "response")
contrast_results <- contrast(
  emm_4way,
  method = list("spring_broadcast_full_standard_vs.fall_sideband_half_IWM" = c(1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,-1)) # Adjust coefficients as needed
)
```