INTEGRATING CROP DIVERSITY, FORAGE CROPS, AND TARGETED GRAZING TO MANAGE *AVENA FATUA* L.

by

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DEDICATION

To my grandmother Di, to my parents Liang and Mei, and to my brother Fung. To my mentor Lois Hill. To God Almighty for His grace and love.

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ABSTRACT

Wild oat *(Avena fatua* L.) is one of the most difficult weeds to manage in spring cereal crops and causes large economic losses throughout the Northern Great Plains. The continual use of herbicides for wild oat management has selected for herbicide resistant and multiple herbicide resistant biotypes and has left no selective herbicide options for farmers in small-grain fields. To sustain crop production, this thesis aimed to develop ecologically based practices to manage wild oat populations. We evaluated the impact of spring wheat height, seeding rate, crop type, forage termination method, and tillage on wild oat tiller density, biomass, and seed production. Two studies were conducted: (1) from 2017 through 2019 in Bozeman, Montana and (2) from 2018 through 2019 in Moccasin, Montana.

The first study examined the combined effect of spring wheat height and seeding rate on its competitiveness against wild oat. We found that the tall near-isogenic wheat line did not have greater wild oat suppression than the short line. Spring wheat seeded at a higher than recommended rate reduced wild oat biomass and seed production only when nitrogen fertilizer was applied.

The second study assessed management practices including integrating lentil, fall and spring forage mixture, sheep grazing and tilled fallow, in addition to spring wheat height and seeding rate. Forage mixtures, sheep grazing, and tillage were the most successful tactics in suppressing wild oat growth and seed production. However, wild oat suppression was not different between spring wheat and lentil, regardless of spring wheat height and seeding rate.

Our results indicate that spring wheat height was not correlated with increased suppression of wild oat. A higher seeding rate of spring wheat also did not increase wild oat suppression; we suggest that fertilization may be needed to enhance crop competitiveness. Integrating forage crops with sheep grazing has the best potential to reduce the wild oat seed bank. This information can help redesign cropping systems. However, there is a continual need to develop other integrated weed management techniques to limit wild oat growth and seed production and to reduce reliance on herbicides.

CHAPTER ONE

REVIEW OF LITERATURE

Introduction

Global agricultural production must increase to meet the food, feed, fiber, and bioenergy demands as population increases to 9.7 billion by 2050 (United Nations, 2019). Since the early 1950s, global food production has been dramatically increased by the improvement of agricultural technologies including irrigation systems, genetic-engineering, mechanization, and the extensive use of off-farm inputs such as synthetic fertilizers and pesticides (Pretty, 2008). Concomitantly, adverse effects from modern agricultural practices have raised concerns on the sustainability of agroecosystems (Kleinman et al., 2018).

Pesticides have helped improve crop yields by reducing pest populations but have also had negative effects on the environment and non-target organisms including pollinators and humans (Brühl & Zaller, 2019; Bünemann et al., 2006; Sánchez-Bayo & Wyckhuys, 2019; Topping et al., 2020). In the United States, 0.5 million tons of pesticides, at a cost of $10 billion, are used annually, and herbicides account for nearly 60% of these expenditures (Sharma et al., 2019). In industrialized agriculture, weed management shifted to an almost total dependence on synthetic herbicides for weed control beginning in the 1950s (Peterson et al., 2017). The repeated, intensive, and widespread use of herbicides increased selection pressure and led to the evolution of herbicide resistant biotypes of weeds, i.e., the inherited ability to survive after being exposed to lethal rates of herbicides (WSSA, 1998).

Since the 1970s, the number of resistant weed biotypes and the number of cases of resistance to several modes of action have been steadily increasing. Currently, there are 521 unique cases (i.e., plant species and site of action combinations) of herbicide-resistant weeds reported globally comprising 263 species (Heap, 2021). Weed biotypes may evolve resistance to herbicides with different modes of action, a phenomenon known as multiple herbicide resistance (Hall et al., 1994). Multiple herbicide resistance greatly limits herbicide management options, as recommendations of mixing herbicides or rotating herbicides for preventing resistance no longer apply. In many cases, the selection of multiple herbicide resistant biotypes results in an increased likelihood of farmers using highly toxic and non-selective herbicides, a practice that further increases the risk of selecting biotypes with resistance to additional modes of action (Menalled et al., 2016), and negatively impacts the environment and human health (Gardner & Nelson, 2008). Herbicides with new modes of action have not been introduced in the market for almost three decades (Duke, 2012; MacLaren et al., 2020), creating the need for alternative management practices that favor ecological processes to regulate weed populations.

Throughout the Northern Great Plains of the United States and Canada, wild oat (*Avena fatua* L.) is one of the most economically detrimental weeds in spring cereal crops (Beckie & Shirriff, 2012; Van Wychen, 2020). Over 11 million hectares of croplands across the Northern Great Plains is infested with wild oat, causing crop losses of over $1 billion annually (Beckie et al., 2012). Despite massive efforts to manage wild oat with herbicides, it persists as one of the most dominant and competitive weeds in small-grain crops. The continual use of a few herbicide groups to control this species has selected for herbicide resistant and multiple herbicide resistant wild oat biotypes, and it has resulted in the exclusion of selective herbicide options for farmers in small-grain fields (Heap, 2021). Therefore, my thesis focus was to develop integrated weed management (IWM) strategies to alleviate multiple herbicide resistant wild oat populations. Specifically, I evaluated individual and integrated use of three ecological components on wild oat growth: enhanced crop competitiveness, diverse crop rotation, and targeted sheep grazing. Chapter 1 summarizes the ecological reasoning supporting integrated weed management in semi-arid agroecosystems.

Biology and Ecology of *Avena fatua* L. in the Northern Great Plains

Wild oat is a cool-season annual grass weed, emerging between April 15 and May 15 in the Northern Great Plains (Beckie et al., 2012). Plants are self-pollinating and can produce more than 150 seeds per tiller, with individuals averaging three to six tillers (Beckie et al., 2012). Wild oat seeds exhibit primary or inborn dormancy when scattered initially from the mother plants (Benech-Arnold et al., 2000). The seeds require dry and warm surroundings while transitioning from a dormant to non-dormant state (Myers et al., 1997). When the environmental conditions are unfavorable for plants to survive, secondary dormancy will be induced to prevent seeds from germinating (Benech-Arnold et al., 2000). Seed dormancy enables wild oat seeds to survive up to nine years in the seed bank, though most of the seeds geminate within four to five years (Beckie et al., 2012; Miller & Nalewaja, 1990; Van Acker, 2009)

Burial depth, nitrogen fertilizer, and soil moisture modify the longevity and germination of wild oat seeds. Miller and Nalewaja (1990) observed that more viable wild oat seeds were found buried at a 12- to 34-cm soil depth than at a 0- to 10-cm soil depth. Seed viability declined faster on the soil surface than when buried because seeds were exposed to extreme weather, predation, and pathogen inflection (Anderson, 2005). In the same study, applying nitrogen fertilizer increased the loss of seed viability compared to the control. Overall, the viability of wild oat seeds at burial decreased gradually through time (Miller & Nalewaja, 1990). Even though wild oat seeds have enough reserves to germinate below ground from depths up to 20 cm (Beckie et al., 2012), seedlings that emerge are less competitive than seedlings that geminate from a shallower depth and earlier (Chauhan et al., 2006). Moreover, wild oat seed mortality increases with increased soil moisture content because soil microbes are more active under higher water content (Mickelson & Grey, 2006).

Wild oat has several characteristics that make it well-adapted as a troublesome weed to the Northern Great Plains. First, wild oat can emerge earlier than, or concurrent with, spring-seeded crops, making it more competitive with crops for resources (O'Donovan et al., 1985). Second, wild oat typically reaches physiological maturity earlier than spring-seeded crops, shattering up to 80% of seeds before crops are harvested (Shirtliffe et al., 2000). Third, wild oat seed has moderate to long persistence in the soil seed bank, remaining viable and capable of germinating for up to nine years (Beckie et al., 2012).

Herbicide Management of *Avena fatua* L. in the Northern Great Plains

Management of wild oat in the Northern Great Plains has relied primarily on herbicides since the 1970s, with yearly expenditures over $500 million (Lehnhoff et al., 2013). There are few selective grass herbicide options to wild oat control in wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.); however, there is no selective herbicide available in cultivated oat (*Avena sativa* L.) due to the genetic similarity between wild oat and cultivated oat (Willenborg et al., 2005). Triallate was first introduced in 1962 to control wild oat, and difenzoquat was also used starting in the 1970s (Haddock & Turner, 1982). In the 1980s, acetyl-CoA carboxylase (ACCase) inhibitor herbicide families such as phenylprazoline, aryloxyphenoxypropionate, and cyclohexanedione were introduced to the market to control wild oat populations. Furthermore, imazamethabenz and flucarbazone, both acetolactate synthase (ALS) inhibitors, were commercially released for wild oat control in 1988 and 1998 respectively (Keith et al., 2015). Over three decades, the repeated use of these herbicides imposed strong pressure to select for herbicide resistant wild oat populations.

In the Northern Great Plains, wild oat has developed resistance to ACCase (Group 1), ALS (Group 2), lipid synthesis (Group 8), long chain fatty acid (Group 15), protoporphyrinogen oxidase (PPO) (Group 14), and photosystem I (Group 22) inhibitors, along with herbicides having an unknown mode of action (Group 25) (Heap, 2021). Even more concerning, two wild oat populations (MHR3 and MHR4) from Montana developed resistance to herbicides having five of the sites of actions: ACCase, ALS, long chain fatty acid, photosystem I (MHR3 only), and lipid synthesis inhibitors (Burns et al., 2018a; Keith et al., 2015). These sites of action represent the most widely used in-crop wild oat herbicides and their failure has resuled in an inability to manage multiple herbicide resistant (MHR) wild oat populations. At present, managing MHR wild oat has become a regional challenge and the MHR seeds can spread from one farm to another (Ervin & Jussaume, 2014). The MHR3 and MHR4 wild oat biotypes underscore the urgent need to develop herbicide alternatives to control MHR wild oat in the Northern Great Plains.

Integrated Weed Management in Agroecosystems

For more than 30 years, weed scientists have been advocating for integrated weed management (IWM) strategies to reduce the reliance on any exclusive practice (Moss, 2019). IWM is a comprehensive strategy that combines cultural, biological, mechanical, and chemical management methods to reduce the long-term spread and impact of weeds (Harker & O’Donovan, 2013). Cultural methods suppress weed development and spread through practices such as the establishment of competitive crops, crop diversification, and crop rotation (Anderson, 2005; Liebman et al., 2001). Biological methods use living organisms that are natural enemies to regulate weed growth and reproduction. Mechanical methods involve a physical action to remove, kill, or injure weeds, such as hand weeding and cultivation. Chemical methods are synonymous with herbicides.

Liebman and Gallandt (1997) refined the concept of IWM by proposing the use of multiple practices or “many little hammers” rather than a single direct practice, “one big hammer”. A “little hammer” is a tactic that may not be effective to suppress weeds when used alone but, when integrated with other practices, can suppress weeds synergistically. The “many little hammers” approach places a strong emphasis on ecologically-based tactics to manage weeds. In contrast, a “big hammer” is a tactic that imposes extreme selection pressure on weeds such as herbicides.

Despite a significant amount of proof-of concept research in non-chemical methods on weed management, continued efforts are needed to increase the acceptance of IWM programs in agroecosystems (Liebman et al., 2016; Moss, 2019). In many cases, inadequate adoption of IWM is not due to a lack of scientific consensus, but social, economic, and political factors influencing farmers’ management decisions (Neve et al., 2018). As a result, researchers are suggesting using transdisciplinary frameworks to improve IWM adoption (Jordan et al., 2016; Neve et al., 2018)

From a social perspective, many farmers prefer to adopt new ideas (e.g., ecological practices) based on individual experience; i.e., only once they experience a herbicide resistance problem at their own farms will they seek alternative solutions for weed management

(Dentzman, 2018). Many farmers are techno-optimists and believe that new herbicides will be made available very soon to deal with current herbicide resistance issues (Bagavathiannan & Davis, 2018; Dentzman et al., 2016; Jussaume et al., 2019). Farmers are more likely to incorporate non-herbicide practices if they see successful cases in their farming communities. Finding a farmer willing to act as a model for others is paramount for community change (Ervin et al., 2019). Consequently, a community-based movement is required to gain greater adoption of IWM strategies (Ervin et al., 2019; Jordan et al., 2016; Moss, 2019).

Economic advantages have the most influence on farmers' management decisions (Hurley & Frisvold, 2016). In general, farmers have positive perceptions of herbicides due to cost-effectiveness, convenience, and instant effect to manage weeds (Owen, 2016). However, farmers are less familiar with the long-term economic returns from non-chemical practices (Smith et al., 2018). Economic analyses demonstrating the effectiveness of IWM are needed to convince farmers to adopt this weed management approach. Additionally, if there are financial subsidies or incentives for farmers, they may be more willing to implement IWM strategies (Liebman et al., 2016; Moss, 2019). A carrot-stick approach could be used where farmers who apply multiple weed management practices on their farms are awarded while, simultaneously, greater restrictions could be placed on the use of herbicides (Liebman et al., 2016; Moss, 2019).

As the issue of herbicide resistant weeds become more prevalent and herbicide options more limited, the pressure on farmers to implement non-herbicide management practices has increased. Historically, farmers in the U.S. made decisions at the farm-level, and it is rarely easy to for outside pressures to suddenly change their behaviors (Barrett et al., 2016; Moss, 2019). Hence, adoption of IWM requires more than conducting research on alternative methods. Rather, farmers must be convinced that IWM is economically sound, efficacious, and easy to adopt. To close the gap between "proof-of concept" and putting it into practice, future research that allows for the co-development of weed management techniques and IWM strategies through interdisciplinary approaches will be underpinned by strengthening the collaboration linking public, private, lawmakers and scientists together (Jordan et al., 2016; Neve et al., 2018).

Cultural Components of an Integrated Weed Management Program

Enhanced Crop Competitiveness

Crop competitive ability contains two categories. The first is crop suppression of weeds, which is the ability of crop to suppress weed growth (Andrew et al., 2015; Fradgley et al., 2017). The second is crop tolerance to weeds, which is the ability to resist crop yield loss in the presence of weeds (Andrew et al., 2015; Fradgley et al., 2017). Crop competitiveness can vary within a crop species due to genetic variation across cultivars resulting in different morphological traits (Andrew et al., 2015; Mohler, 2001). For example, plant height and tiller density differences were implicated in crop competitive differences in previous research (Andrew et al., 2015). Traits associated with increasing weed suppression do not necessarily imply an increase in weed tolerance (Andrew et al., 2015; Fradgley et al., 2017).

Taller crop cultivars can have a competitive advantage over shorter cultivars with neighboring weeds due to better access to light and shading ability (Andrew et al., 2015; Mason & Spaner, 2006). Several studies found that weed suppression was correlated to crop height (Beres et al. 2010; Harker et al. 2009; Mason et al. 2008). Oat cultivar height did not impact weed suppression, but a semi-dwarf cultivar was a poorer weed tolerator since it suffered the greatest yield loss than taller cultivars (Fradgley et al., 2017). In another study comparing 13 wheat cultivars, Wicks et al. (2004) found that two semi-dwarf cultivars had higher ability in suppressing weeds than taller cultivars. This inconsistent result of height effect was also confirmed by other studies which suggests that crop competitive ability is not linked to a single trait, but rather to a combination of traits (Andrew et al., 2015; Watson et al., 2006). Studies indicated that seeds that were developing on plants in shade may have a low viability, germinability, dormancy, and pathogen susceptibility (Brainard et al., 2005; Jha et al., 2010). For example, wild oat seeds that were collected from stalks growing underneath barley canopies were found to be 10% to 30% less viable than those collected above barley canopies (Lehnhoff et al., 2013). This study suggests that the use of a tall crop canopy in relation to the wild oat panicle position may be able to reduce wild oat populations as a result of the decreased seed viability.

Enhancing crop competitiveness with weeds can also be done through manipulating crop seeding rate (Lemerle et al., 2004). For example, Evans et al. (1991) indicated that wild oat seed production was reduced by increasing barley density. A study demonstrated that increasing barley seeding rate decreased wild oat biomass and seed production. When in combination with competitive barley cultivars, wild oat was further suppressed (O’Donovan et al., 2000). Using a higher crop seeding density to suppress weeds is a widely adopted cultural practice, especially in organic farming systems (Mason et al., 2007).

The use of crop height and seeding rate can increase crop competitiveness with weeds, but it may not necessarily increase crop yield. Previous research showed that when crop competitiveness increases, the potential crop yield decreases (Creissen et al., 2013). For example, taller cereal varieties are often reported with lower yields under the weed-free environments compared to semi-dwarf varieties (Zerner et al., 2016). Most previous research related to height strategies was based on different crop cultivars in which genotypes are different, but there is little known information of height effect on crop competitive ability and yielding potential in near-isogenic lines. Additionally, the potential yield benefit may be compromised at higher seeding rates because of the law of constant final yield (Weiner & Freckleton, 2010). At higher densities, plants experience more intraspecific competition for resources compared to low densities, causing some individuals to die in a process called self-thinning (Weiner & Freckleton, 2010). Maximizing yield and crop competitive ability could be factored into breeding for the early vegetative growth rate and leaf area index in the growing seasons. As a result, resources can be allocated to grain fill later in the growing seasons (Fradgley et al., 2017).

Diverse Crop Rotations

Diversifying cropping systems gives rise to many advantages in agroecosystems. Cropping systems can be diversified through intercropping (spatially) and crop rotation (temporally) (Anderson, 2009; Blanco-Canqui et al., 2013; Farahani et al., 1998b; Rosenzweig et al., 2018). Intercropping is growing multiple crops in a field during the same season, and crop rotation is growing alternate crops over a series of years. Diverse cropping can improve soil fertility and soil health, reducing reliance on synthetic fertilizers. It also can positively influence soil water availability and water use efficiency (Anderson, 2009; Blanco-Canqui et al., 2013; Farahani et al., 1998b; Rosenzweig et al., 2018). Moreover, pollinators and natural enemies of pests can benefit from increased crop diversity as it provides food, shelter, and habitat (Guzman et al., 2019; Tamburini et al., 2020). Herbivores and seed predators can then also facilitate weed management (Altieri, 1999; MacLaren et al., 2020). Diverse cropping systems will also allow farmers to incorporate different planting and harvesting times as well as management practices to break the life-cycle of pests (Anderson, 2009; Neve et al., 2018). These systems have the potential to stabilize or increase crop yields, optimize long-term profit, and reduce production risk (Chen et al., 2012; Smith et al., 2018; Zentner et al., 2002).

Despite the ecological and economic benefits of diverse crop rotations, continuous cropping can lower plant-available soil moisture and result in yield reduction in the subsequent crop, especially during drier years (Unger & Vigil, 1998; Unger et al., 2006). The Northern Great Plains has annual precipitation around 300 to 500 mm per year. This low precipitation limits what types of crops farmers can grow and the productivity of those crops (Padbury et al., 2002). A suggested method to reserve soil moisture for winter crop planting is to terminate crops 90 days prior to planting to avoid crop yield drag (Poore, 2013). Another method for water conservation is no-till management. This method can enhance precipitation use and soil-water storage efficiency during non-crop periods (Farahani et al., 1998a; Nielsen & Vigil, 2010). After harvest, leaving crop stubble in the field during winter helps trap snow and acts as a cover to the soil surface which limits water evaporation and runoff (Nielsen & Vigil, 2005). Practicing no-till in the long-term could increase soil organic matter (Peterson & Westfall, 2004; Shaver et al., 2002). Also, the porosity and proportion of macroaggregates in soil were increased, while the bulk density was decreased (Peterson & Westfall, 2004; Shaver et al., 2002). All of these factors enhanced the rate and amount of captured rainfall (Peterson & Westfall, 2004; Shaver et al., 2002). Many research efforts are still in progress to determine alternative crops' compatibility with the climate of the Northern Great Plains and to investigate how to efficiently use water in crop rotation (Holman et al., 2018; Nielsen et al., 2005; Obour et al., 2018).

Wheat-Fallow. Wheat is the primary crop grown in the Northern Great Plains. Traditionally, in this semiarid region farmers grow wheat usually rotated with uncropped fallow periods to preserve soil moisture (Aiken et al. 2013; Lenssen et al. 2007; Nielsen & Calderón 2015; Padbury et al. 2002; Stewart 2016). A typical fallow period in this region is 14 months after winter wheat or 21 months after spring wheat is harvested (Anderson, 2009). Although fallow conserves soil moisture for subsequent cropping, the simplified wheat-fallow rotation has been found to reduce the overall sustainability in agroecosystems.

Tillage in fallow periods can lead to some deleterious impacts to the environment. During the 20th century, intensive tillage was often implemented under fallow for preparing seedbeds, incorporating fertilizers and herbicides into soil, and controlling weeds. However, the excessive soil disturbance from tillage elevates soil organic matter oxidation and water evaporation (Bowman et al., 1999; Peterson & Westfall, 2004), which exacerbates the loss of water and organic matter in the soil. Furthermore, tillage-based fallow can lead to prominent soil degradation through wind and water erosion (Bowman et al., 1999; Peterson et al., 1998), and increases greenhouse gas emissions due to the consumption of fossil fuels (Maraseni & Cockfield, 2011).

For weed management, weed seedling density is reduced after tillage but seedling emergence could be enhanced in the following years. Tillage can mix seeds into the soil, which can stimulate seed germination through the improved diffusion of air in the soil, nitrogen mineralization, and soil temperature and moisture fluctuation (Benech-Arnold et al., 2000). Anderson (2005) indicated weed seedling emergence after tillage was twofold greater in the second year and eightfold greater in the third year, compared to the no-till treatment. Another study also found that wild oat populations were greater under intensive tillage management (Medd, 1990). Additionally, under till-managed soil, seed survival could be increased due to the reduced of number of seed predators like ground beetle species (Weiss et al., 1990). In the no-till practice, seeds can die naturally or be consumed by predators on the soil surface (Anderson, 2008).

Mechanical-based practices for weed control were no longer predominant in the late 20th century due to the advent of herbicides, except in organic systems. Conventional farmers increased their reliance on synthetic herbicides to control weeds during the fallow period, while tillage was gradually substituted with zero tillage or conservation tillage (Ghimire et al., 2015; Peterson & Westfall, 2004). Even though herbicides are more effective in eliminating weeds than mechanical-based practices, they lead to other obstacles to agroecosystem sustainability. As such, herbicides reduce the insect community, increase the potential of selecting herbicide resistant weed biotypes, and are potential hazards to human health (Liebman et al., 2016; Sánchez-Bayo & Wyckhuys, 2019). These unfavorable impacts prompted research to assess alternative cropping systems in the Northern Great Plains to reduce the duration and frequency of fallow (Hansen et al., 2012), including the adoption of oilseed, pulse, forage or cover crops (Smith et al., 2017; Carr et al., 2020).

Pulse Crops. Leguminous crops that are grown for their edible seeds are known as pulse crops. These represent a strong regional alternative for the fallow period in the Northern Great Plains. Pulse crop production, especially of dry pea (*Pisum sativum* L.) and lentil (*Lens culinaris* Medik.), have been steadily increasing since 1990 because of their economic and environmental values such as nitrogen retention (Cutforth et al., 2007; MacWilliam et al., 2014; Miller et al., 2015; Miller & Holmes, 2005; O’Dea et al., 2015).

Legumes have a symbiotic relationship with *Rhizobium* species, which are able to fix atmospheric nitrogen, making it available in the soil for plants. The additional nitrogen and increased nitrogen use efficiency contributed by legumes could enhance the subsequent crop productivity or quality, reducing the dependence on nitrogen fertilizer in rotating pulses with wheat (Beckie & Brandt, 1997; Lupwayi & Kennedy, 2007; Miller et al., 2002a). Miller et al. (2002b) reported that wheat yield and grain protein were 21% and 8%, respectively, higher when grown in the legume crop stubble than in wheat stubble. Another study compared soil nitrogen content in spring following pulse crops and wheat at clay and loam soil sites (Miller et al., 2003). That study detected that at the clay sites, soil nitrogen on average was 28 kg ha^{-1} higher under pulse crop stubble than wheat stubble. At the loam soil sites, an average of 12 kg ha^{-1} greater soil nitrogen was found in fields with pulse crop stubble compared to wheat stubble (Miller et al., 2003). Hence, the use of synthetic nitrogen fertilizer in cropping systems can be minimized when rotated with pulse crops. Zentner et al. (2001) determined that nearly 9 kg ha^{-1} less nitrogen fertilizer is needed for a wheat-lentil rotation over a continuous spring wheat rotation. Allen et al. (2011) determined that after three cycles of wheat-lentil cropping, no nitrogen fertilizer was required for yield and grain quality comparable to the conventional wheat-fallow cropping. With the decline in synthetic nitrogen fertilizer input, greenhouse gas emissions of grain production will decrease as well (MacWilliam et al., 2014, 2018).

Pulse crops not only contribute available soil nitrogen, but also improve soil organic matter. According to Gan et al. (2015), summer fallow systems and pulse cropping systems both enhance the nitrogen soil availability, but the nitrogen mineralization that takes place in summer fallow systems can exhaust soil organic matter. In an eight-year study, O'Dea et al. (2015)

observed that including legumes together with no-till provided a higher degree of potential mineralized carbon and nitrogen, wet aggregate stability, and microbial biomass carbon than in wheat-fallow systems, suggesting that soil organic matter loss in the fallow year can be replenished by adding pulse crops.

Integrating pulse crops into wheat-based cropping systems has other rotational benefits. Pulse crops use 15-35% less water compared to cereal and oilseed crops, which could allow for more soil moisture to be retained for following crops (Gan et al., 2015). Furthermore, the inclusion of pulse crops can reduce pest and disease stresses caused by continuous wheat cropping systems (Miller et al., 2002a). Pulse-based rotations are economically successful when compared to continuous cereal cropping because of their higher net returns and more stable incomes (Khakbazan et al., 2020; MacWilliam et al., 2014)

Pulse intensified rotations, however, could lead to negative impacts to cropping systems. There is potential for disease buildup such as the root rot complex and foliar diseases (Bainard et al., 2017). The shallow root character of pulse crops (e.g., lentil) limits the capture of rainfall by their stubble compared to cereal crop stubble. Lastly, weed control in pulse crops can be very challenging. Legumes are recognized as poor weed competitors for early growth and tall stature weeds, such as wild oat (Jha & Kumar, 2017; Thill et al., 1994), and there are few selective herbicide options for controlling broadleaf weeds in pulse crops (Jha & Kumar, 2017). Therefore, judicious crop rotation sequences are required to maximize the benefits of growing pulse crops in agroecosystems.

Cover Crops and Forage Crops. Cover crops are crops that do not result in a direct profit, but have positive influence on cropping systems in conventional and organic farming (Osipitan et al., 2018; Wittwer et al., 2017). Previous studies have suggested that replacing summer fallow with no-till cover crops could improve soil properties, soil water availability, water use-efficiency, and prevent wind and water soil erosion (Blanco-Canqui et al., 2013; Farahani et al., 1998a; Wittwer et al., 2017). Cover crops can also increase land productivity through soil carbon sequestration and nutrient cycling (Blanco-Canqui et al., 2013; Farahani et al., 1998a; Wittwer et al., 2017). Row crop production is usually monocropped; however, cover cropping gives an opportunity to temporarily increase the degree of crop diversity to provide multiple functions and services for the agroecosystems.

An option for increasing farmers' income is to grow forage crops for animal feed instead of cover crops. Growing forage crops could have similar agroecological benefits as cover crops and growers can sell forage crops to get additional economic return for their farms (Holman et al., 2018; Nielsen et al., 2017). Nielsen et al. (2017) compared the average net revenue between wheat-corn-fallow and wheat-corn-triticale cropping systems and showed that the system with the triticale forage crop had earned 17% more income than the system that included the fallow period. However, the available soil water was lower for the subsequent wheat and caused a reduction in yield (Holman et al., 2018).

In addition, replacement of fallow by cover or forage crops can be utilized as a management strategy to suppress weeds. Cover crops and forage crops can modify environmental conditions (e.g., light penetration and soil temperature) and can be used to reduce weed germination and emergence (Osipitan et al., 2018). They also can release phytotoxins to inhibit weed growth (Liebman & Davis, 2000). The efficacy of planting cover crops for early-season weed control can be similar to herbicide application and tillage (Osipitan et al., 2018). It has been observed that increasing cover crop diversity may increase weed-suppressive ability and prevent weed invasion because more resources are used by cover crops (Kennedy et al., 2002; Tilman, 1999). Furthermore, recent research indicated that the weed control potential appeared to be associated with the biomass production of crop species or species composition, rather than the number of crop mixes (Baraibar et al., 2018; Finney et al., 2016; MacLaren et al., 2019b; Weisberger et al., 2019).

Cereal grasses suppress weeds because of early vigor, rapid growth and resource uptake, and allelopathic metabolites, which reduces weed competition and results in less weed biomass (Brainard et al., 2011; MacLaren et al., 2019b). In the Northern Great Plains, fall-seeded annual triticale forages and spring-seeded annual barley forages are favored by farmers (Carr et al., 2020; Meccage et al., 2019). The early establishment of winter cereal crops gives them a competitive advantage against weeds (Bere et al. 2010), and they are recommended as fall-seeded forage crops in spring wheat-based cropping systems for weed management. Studies have shown that among triticale, barley, and wheat, triticale is the most competitive and wheat is the least competitive small grain (Andrew et al., 2015; Beres et al., 2010; Lemerle et al., 1995).

Legumes can be used as cover crops or harvested for forage. Some legume species may not be suppressive (e.g., lentil), but legume-cereal cover mixtures can retain the weed suppressive ability and enhance other ecosystem services such as carbon sequestration and nutrient cycling (Baraibar et al., 2018; Finney et al., 2016). Intercropping legume with cereal forage has been gaining attention as it has been demonstrated to increase forage crude protein concentration and yield (Carr et al., 1998, 2004; Miller et al., 2018). Similarly, the subsequent crop production and quality can also benefit. Miller et al. (2018) found that wheat yield and grain protein were increased after an annual barley with pea mixture forage crop. Additionally, cereal crops mixed with legumes achieve higher nutritive value and higher fiber concentrations (Sanderson et al., 2018). This can enhance livestock growth performance which is preferable for livestock producers compared to sole forage grasses or legumes (Kumar et al., 2019).

Cover crop or forage termination timings can be decisive for either further hampering or improving the sustainability of cropping systems. For example, plant-available water is positively correlated with crop yield (Nielsen et al., 2002, 2006); the longer the crops stay in the fields, the less soil water is available for the following crops (Holman et al., 2018). Researchers in the Northern Great Plains showed that early termination of cover or forage crops can give rise to positive or neutral effects on grain yields. Miller et al. (2006) demonstrated that midseason harvesting of pea before maturity provided a 14% higher succeeding wheat yield and a 9% higher grain protein. Burgess et al. (2014) did not detect a negative effect on the subsequent wheat yield and grain protein when terminating legume green manure at pod stage. Another study noted that the subsequent wheat yield and grain protein were the highest following a harvest of winter pea at the flower stage, rather than at pod or maturity stages (Miller et al., 2018). Besides the benefits for the following crop production and quality, the early terminated legume companion forages have greater production advantages than at maturity. Miller et al. (2018) investigated the effect of termination timing (flower, pod, and maturity) on pea forage production. The study showed that forage yield was the highest when it was harvested at the pod stage compared to harvesting at the flower and maturity stages. However, forage quality was not different among harvesting stages. As a result, strategic timing of crop termination before planting the next crop can avoid potential yield penalty and optimize the productivity and quality of the crop.

The timing of crop harvest can also affect weed dynamics (Mirsky et al., 2011; Thill et al., 1994). Implementing cover crops suppresses weed growth (Osipitan et al., 2018), and early termination can foster a decline in competitive weed vigor and seed production. For example, there was a greater reduction in wild oat populations when barley silage was harvested earlier (a week after heading) compared to the normal harvest time (soft-dough stage) (Harker et al., 2003). The early-cut strategy gives wild oat less time to grow and develop viable seeds, preventing wild oat seeds from replenishing the soil seed bank. Further research should continue to justify the optimal termination timing with a goal: minimizing the detrimental impact on grain yield, maximizing forage production and quality, and mitigating weed populations effectively. This goal will help to successfully maintain the sustainability of agroecosystems.

Integrated Crop-Livestock Systems

Integrating livestock into cropping systems has been practiced for thousands of years. When agricultural specialization was introduced in the second half of the 20th century, livestock and crop productions diverged with an accompanying loss of knowledge of how to run animals on croplands (Hilimire, 2011). Considering the long-term sustainability of agroecosystems, researchers have promoted the idea of reintroducing the combination of crop and livestock production (Carvalho et al., 2018; Garrett et al., 2017; Kumar et al., 2019; Russelle et al., 2007; Smith et al., 2020). For example, livestock grazing in crop residue or forages increases agroecosystem complexity and gains synergies in ecological services, including enhancing soil fertility and quality (Russelle et al., 2007), nutrient recycling, and biological pest control

(Goosey et al., 2005; Hilimire, 2011; Smith et al., 2020). These integrated systems can improve land use efficiency and be more profitable than isolated livestock or crop-only systems (Garrett et al., 2017; Kumar et al., 2019).

There are different approaches to integrate livestock grazing in cropping systems. In addition to herbicides and tillage, grazing fallow fields represents an alternative for weed and residue management (Goosey et al., 2005; Sainju et al., 2014). Similarly, integrating livestock to graze cover crops or forages provides an alternative to chemical or mechanical termination. However, livestock grazing may not be easy for farmers to implement, especially those who do not have access to livestock on their farms and the initial resource investment including infrastructure, land, and livestock may be higher than specialized livestock or crop production. Besides the aggregate operational costs, farmers may not have the experience and knowledge to manage both systems together in the beginning (Kumar et al., 2019). A plan to overcome these challenges would be to create a partnership between livestock and crop farmers in the communities to achieve “win-win” opportunities. Through these cooperative integrated systems, the communities could benefit, saving feed costs for livestock farmers in exchange for pest control and enhancement in soil quality for crop farmers.

Although more research regarding integrated crop-livestock agriculture focused on cattle (*Bos taurus* L.) than other livestock species (Hilimire, 2011), integrating small ruminants like sheep (*Ovis aries* L.) into cropping systems has potential. Montana ranks 7th for the total number of sheep in the U.S. (USDA NASS, 2019) and sheep grazing could promote entrepreneurial opportunities for weed management as well as meat, milk, and fiber production. In addition, it requires less labor because sheep are easier to move from farm to farm, and sheep have more flexibility in diet selection compared to cattle (Marten and Anderson, 1975). A few studies have been done in the Northern Great Plains to help producers better understand the role of sheep grazing in agroecosystems and how to employ beneficial crop-sheep regimes. (Barroso et al., 2015; Barsotti et al., 2013; Goosey et al., 2005; Hatfield et al., 2007a, 2007b, 2007c; Lenssen et al., 2013; Miller et al., 2015; Sainju et al., 2011, 2014).

Targeted grazing has been used as a biological control method for insect pests. One of the most problematic pests in wheat production is wheat stem sawfly, *Cephus cinctus* Norton (Hymenoptera: Cephidae) and studies demonstrated the overwintering larval populations were reduced because of trampling and grazing (Hatfield et al., 2007a) and mortality was nearly 12% higher than on ungrazed fields (Goosey et al., 2005). In addition, the crop-livestock systems were found favorable for both native and non-native bird communities compared to crop-only systems (Smith et al., 2020). It is possible that insectivorous birds could suppress crop pests and help maintain crop yields (Garfinkel & Johnson, 2015; Smith et al., 2020). However, researchers should distinguish which bird species would be beneficial to the agroecosystems and how to manage them properly to control pests without damaging crops.

Grazing represents an ecological filter that alters weed abundance, diversity, and community composition (Barroso et al., 2015; MacLaren et al., 2019a; Miller et al., 2015). It may be used to switch from troublesome weeds (e.g., herbicide resistant species) to less threatening weeds. However, further research is needed to assess how grazing interacts with crop diversity affects weed community dynamic. In addition to the changes in weed communities, grazing can reduce weed pressure and herbicide application (MacLaren et al., 2019a). Weed biomass and density following grazing were comparable to tilling and greatly decreased relative to ungrazed fields (Goosey et al., 2005; Hatfield et al., 2007c). Many common annual weeds in the Northern Great Plains that are highly nutritious and palatable in their vegetative stages, such as cheatgrass (*Bromus tectorum* L.), kochia (*Bassia scoparia* L.), and wild oat (Marten & Anderson, 1975), and will presumably be selected during ruminant grazing.

Manure and urine from livestock enhance soil organic matter through augmenting soil carbon and nitrogen cycling processes. For example, adding livestock to a legume-cereal crop rotation increased the rate of carbon accumulation due to the manure additions (Russelle et al., 2007). Several studies also revealed that soil organic carbon and nitrogen storage increased in grazed fields through sheep excreta (Barsotti et al., 2013; Hunt et al., 2016). Increasing soil organic matter can improve water infiltration and soil quality; as a result, enhancing crop productivity and substituting the need for inorganic fertilizers (Weil & Magdoff, 2004).

Despite some studies showing that crop yield was greater under grazed systems than ungrazed (Maughan et al., 2009), others indicated that grazing had little impact on succeeding wheat yield and grain protein (Lenssen et al., 2013; MacLaren et al., 2019a; Miller et al., 2015; Sainju et al., 2011; Snyder et al., 2007). These conflicting findings could be related to the cropping systems, rather than the grazing regime. For example, MacLaren et al. (2019a) found that crop yields were the greatest in the most diverse cropping systems whether or not grazing was integrated. Regardless, research has not found that grazing is harmful to crop production. While cattle grazing could lead to an uneven spread of natural fertilizers, which may cause irregular plant development (Sanderson et al., 2013), sheep grazing can distribute manure and urine more evenly creating more uniform crop growth (Abaye et al., 1997).

Another concern for farmers is that livestock grazing can lead to soil compaction damage by trampling, causing poor soil drainage, and decreased water storage and use efficiencies. Consequently, seedling emergence and crop performance are imperiled (Hatfield et al., 2007b). When properly implemented, livestock grazing compacts soil to a negligible extent (Greenwood & McKenzie, 2001). For example, research indicated that the soil bulk density, soil organic matter, and soil nutrient contents were not negatively affected under sheep-grazed cereal stubble compared with non-grazed fields (Goosey et al., 2005; Hatfield et al., 2007b). Additionally, available soil nitrogen and soil moisture were not different compared with tillage and herbicide management practices (Snyder et al., 2007). Thus, integrating livestock grazing does not necessarily involve tradeoffs between crop profitability and environmental quality but requires to carefully manage grazing intensity, preventing overgrazing and high stocking rate which causes environmental degradation (Carvalho et al., 2018; Sainju et al., 2011).

Integrated crop-livestock systems are suitable strategies to reduce the reliance on external inputs while furnishing ecosystem services such as fertilization and biological control. The integration of crop and livestock systems has the potential of providing economic and ecological benefits and can stabilize long-term farm incomes (Hilimire, 2011; Russelle et al., 2007). From the weed management perspective, limited studies have investigated the use of sheep grazing in forage crop termination for weed control in the Northern Great Plains (Barroso et al., 2015; Lenssen et al., 2013; Miller et al., 2015). Therefore, more research is needed to understand how the integration of livestock grazing with diverse crop rotation impacts weed population and community dynamics.

Project Justification and Objective

The selection of MHR wild oat biotypes represents a threat to the viability of current herbicide options. Developing integrated ecologically-based weed management strategies is imperative to meeting the current and predicted crop production demands. My thesis expands the recommendations of Burns, et al. (2018b) by further exploring management practices beyond using synthetic nitrogen fertilizer and crop seeding rate for MHR wild oat management. My work emphasizes employing ecologically based tools that are economically viable and easy-to-adopt for the farmers in the Northern Great Plains. Tools that will be used in my study include the use of a taller wheat canopy, increased wheat planting densities, and the integration of pulse crops, forage crops, and sheep grazing. This research asks the main question: how can current weed management tools be better integrated to suppress problematic weeds? I hypothesize that the synergistic integration of multiple tactics that target different components of the wild oat life cycle will successfully prevent MHR wild oat population growth. The outcome of the research hopes to refine current integrated weed management strategies. My main objective is to evaluate the impact of ecologically-based tools such as the use of taller wheat varieities, increased wheat planting densities, and the integration of pulse crops, forage crops, and sheep grazing on wild oat biomass and seed production. The research is presented in this thesis in four chapters:

Chapter 1—Literature review

Chapter 2—Spring wheat height and density impacts on wild oat (*Avena fatua* L.)

Chapter 3—Integrated wild oat (*Avena fatua* L.) management under diversified cropping systems

Chapter 4—Conclusion

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CHAPTER TWO

SPRING WHEAT HEIGHT AND DENSITY IMPACTS ON WILD OAT (*AVENA FATUA* L.)

Introduction

Wild oat, *Avena fatua* L., is an annual spring grass species and one of the ten most troublesome weeds in the world, especially in spring cereal cropping systems (Holm et al., 1991). Herbicides have been used to manage wild oat in crop fields since the late 1950s, but their repeated and extensive use resulted in the global selection and spread of herbicide resistant biotypes (Heap, 2021). Throughout the Northern Great Plains, an important region for small grain and pulse crop production, wild oat has developed resistance to Acetyl-CoA carboxylase (Group 1), acetolactate synthase (Group 2), lipid synthesis (Group 8), long chain fatty acid inhibitors (Group 15), protoporphyrinogen oxidase (Group 14), and photosystem I (Group 22) inhibitors, along with herbicides with an unknown mode of action (Group 25) (Heap, 2021). Eight wild oat populations have evolved resistance to more than one herbicide with different modes of action when used at the recommended rate, a phenomenon known as multiple herbicide resistance (MHR) (Heap, 2021). In Montana, two wild oat populations (MHR3 and MHR4) were found resistant to five of the modes of action (ACCase, ALS, long chain fatty acid, photosystem I [MHR3 only], and lipid synthesis inhibitors) (Burns et al., 2018a; Keith et al., 2015). These modes of action represent the most widely used in-crop herbicides and have resulted in failure to manage MHR wild oat (Keith et al., 2015).

The selection of MHR wild oat biotypes limits the use of in-crop herbicides, a problem compounded by the fact that no new mode of action has become available for wild oat control since the 1990s (Duke, 2012). In order to impede the evolution of herbicide resistance in wild oat and manage those resistant biotypes that have already been selected, developing alternative weed management tactics is imperative (Baucom, 2019; Menalled et al., 2016). Integrated weed management, a strategy that combines cultural, mechanical, biological, and chemical management tactics, has been suggested as an approach to decrease the selective pressure towards herbicide resistance and reduce the spread and impact of resistance biotypes (Liebman et al., 2001 & 2016; Bagavathiannan & Davis, 2018). In an integrated weed management program, no single tactic may result in successful management outcomes, but their combined synergistic effects can be used to reduce weed populations, an approach known as "many little hammers" (Liebman & Gallandt, 1997; Westerman et al., 2005).

One potential "little hammer" to reduce weed populations is breeding crop genotypes to enhance crop competitiveness (Weiner et al., 2010; Liebman et al., 2016). For example, in utilizing different cultivars of the same species, previous studies have shown that crop height can provide a competitive advantage over neighboring weeds due to better access to light and shading (Andrew et al., 2015; Beres et al., 2010; Harker et al., 2009; Mason et al., 2008; Mason & Spaner, 2006). However, cultivars may have different yielding ability, morphology, phenology, drought tolerance, and disease resistance, all of which will affect the crop competitiveness (Zerner et al., 2008). Therefore, comparisons of previous research results are confounded by crop genotype differences and research is needed to investigate the effect of height on crop competitiveness.

Even though taller canopies may increase competitiveness, there are concerns regarding trade-offs between crop competitive ability associated with height and crop productivity under weed-free conditions. Semi-dwarf cereal varieties are often reported to have higher yields compared to taller varieties when weeds are absent (Mohler, 2001; Mason & Spaner, 2006), suggesting that the taller varieties may allocate more resources in stem elongation rather than grain production. If the potential crop yield decreases as the crop height increases, farmers may have less incentive to adopt the use of a taller crop canopy.

Another desirable and widely used cultural “little hammer” for weed management is increasing crop planting density (Weiner et al., 2001, Andrew et al., 2015). Research has shown that using a higher than recommended crop seeding rate reduced yield loss due to the presence of weeds (Evans et al., 1991; Blackshaw et al., 2000; O’Donovan et al., 1999). In addition, this approach reduced weed biomass and seed production (Evans et al., 1991; Blackshaw et al., 2000; O’Donovan et al., 2000; Thill et al., 1994). Integrating a higher seeding rate with other tactics has shown to synergize weed suppression. For example, seeding rate with nitrogen availability could mitigate the growth of MHR wild oat biotypes (Burns et al., 2018b). Another study indicated that combining taller barley (*Hordeum vulgare* L.) varieties with higher seeding rates led to greater wild oat suppression (O’Donovan et al., 2000).

To our knowledge, how the combination of spring wheat height and seeding rate affects crop competitive ability has yet to be well examined. The goal of this study was to determine whether the joint use of a taller crop canopy with a higher crop seeding rate, would be an effective integrated strategy to suppress wild oat. We hoped to use this strategy to mitigate the MHR wild oat populations and the herbicide reliance in the Northern Great Plains. We utilized two near-isogenic lines of a wheat cultivar (Amidon; Mergoum et al., 2008) with similar crop yield potential to isolate the impact of crop height. These near-isogenic lines were seeded at two rates: 67 kg ha^{-1} (recommended by McVay et al., 2010) and 101 kg ha^{-1}. The impact of crop height and seeding rate on spring wheat grain yield and wild oat tiller, biomass, and seed production was determined in this study. We hypothesized that the use of tall wheat in combination with a high seeding rate would increase spring wheat competitiveness without reducing grain yield.

Materials and Methods

This study was conducted for three consecutive years (2017-2019) at the Montana State University Arthur H. Post Research Farm near Bozeman, Montana (latitude: 45° 47´ N; longitude: 111° 9´ W; elevation: 1461 m). Soil at the site was an Amsterdam silty clay loam (fine-silty, mixed, superactive, frigid Typic Haplustolls) with 2% organic matter and a pH of 7.4. 50-year (1966-2016) average annual precipitation and temperature at this location were 410 mm and 13.8 °C. Average annual precipitation was 458 ± 19.1 mm, and the average annual temperature was 6.2 °C during the three-year study period (NOAA, 2021).

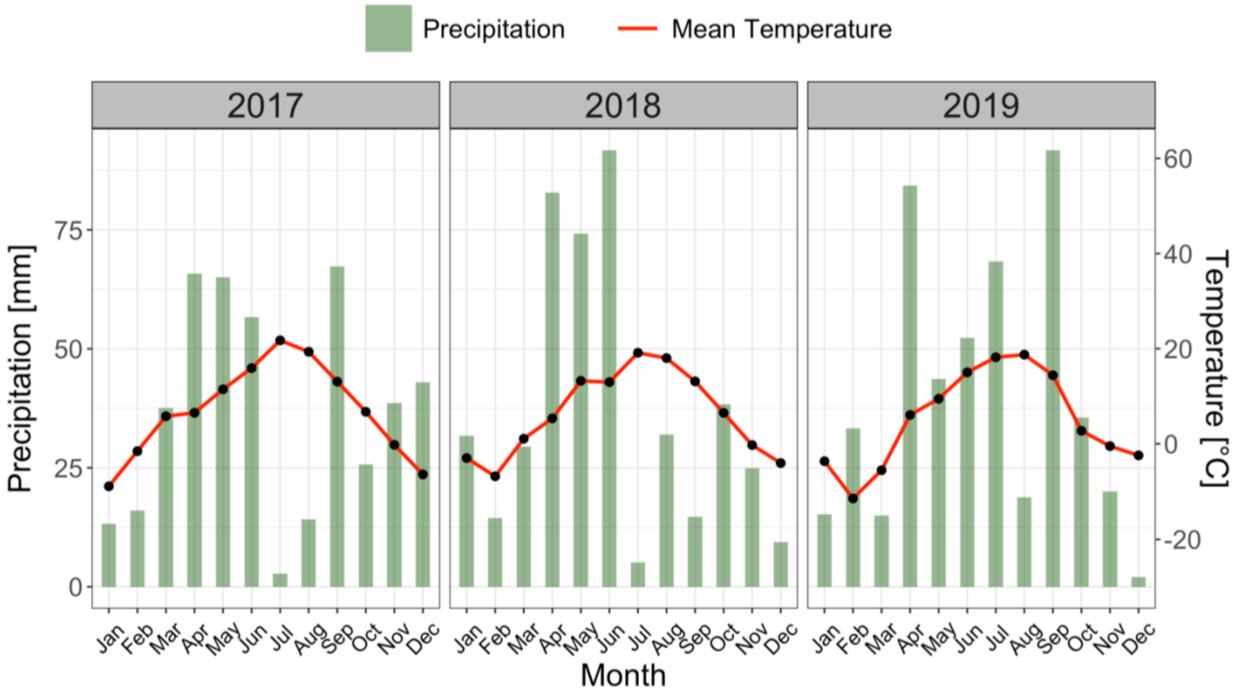

Figure 1. Monthly total precipitation (mm) and monthly mean temperature (°C) from 2017 to 2019 at the Montana State University Arthur H. Post Research Farm near Bozeman, Montana.

Each year throughout the 2017 to 2019 research period, experiment trials were conducted in a different 42 m by 22 m field with natural infestation of wild oat following a randomized split-plot design with four replications and 2 m alleys between replications. The main plots (9 m by 2 m) were assigned to spring wheat treatments with a 2 × 2 factorial arrangement: i) spring wheat height (semi-dwarf or tall) and ii) seeding rate (67 kg ha^{-1} or 101 kg ha^{-1}, low and high, respectively). The wild oat treatment at two levels (present or absent) was randomly assigned at the subplot level (4 m by 2 m), with a 0.5-m buffer separating subplots. No tillage before planting, and spring wheat was sown in rows spaced 30-cm apart with a Kasco Versa disk drill on May 1, 2017, May 4, 2018, and May 14, 2019, respectively. No soil tests were done prior to fertilizer application. Nitrogen was applied pre-plant at 112, 0, and 56 kg ha^{-1} for 2017, 2018, and 2019 respectively. To control dicotyledonous weeds in plots, 2,4 D (2,080 g ae ha^{-1}) was applied with a CO_2 backpack sprayer. Pinoxaden (60 g ai ha^{-1}) was applied to control wild oat in the weed-free split plots.

Spring wheat emergence density was not assessed in 2017. On August 20, 2017 spring wheat heights were determined at physiological maturity by measuring from the ground surface to the tallest part of the crops. Five 0.5-m^2 frames were randomly located in weed-free and wild oat split plots for sampling spring wheat and wild oat final tillers and biomass at harvest. Wild oat was harvested on August 11, 2017, and spring wheat was harvested on August 20, 2017.

In 2018 and 2019, spring wheat emergence was assessed by counting plant stands within five 0.125-m^2 rings in each split-plot approximately two weeks after planting. Wheat height was not measured, but the height differences were visually determined based on field observation. To facilitate plot sampling, the frame size was reduced to 0.25-m^2 frames. We sampled the tillers and biomass of spring wheat and wild oat within three and four frames per split-plot in 2018 and 2019, respectively. Wild oat was harvested on August 15, 2018 and August 7, 2019. Spring wheat was harvested on August 15, 2018 and September 18, 2019. Final tiller number was counted for spring wheat and wild oat. Spring wheat and wild oat samples were clipped at the ground surface and placed in separate paper bags. All plant samples were dried at 40 °C for two days before being weighed for the total dry matter. Spring wheat seed heads were threshed, cleaned, and weighed to determine grain yield.

The number of reproductive tillers and their total dry matter sampled in the 0.25-m^2 frames were used to estimate wild oat seed production. The subsamples from 2019 were a random selection of plant samples with a biomass between 1 and 100 g 0.25 m^{-2}. A linear mixed effect model was fitted based on the subsamples from 2019 to estimate the number of pairs of glumes in response to wild oat biomass (g 0.25 m^{-2}) for all subsamples from 2017 to 2019 (Appendix A-Figure A1). After that, the maximum wild oat seed production was determined by multiplying the number of pairs of glumes by three, as each pair of glumes usually enclose up to three viable wild oat florets (seeds).

Statistical Analyses

All analyses were performed in R software version 4.0.3 (R Core Team, 2020). Linear mixed-effects models were fitted to evaluate the effect of wheat height and seeding rate on spring wheat and wild oat performance, respectively. First, the effects of wheat height and seeding rate on spring wheat tillers (tillers m^{-2}), wheat biomass (g m^{-2}), and grain yield (kg ha^{-1}) were analyzed using the data from the weed-free split plots. Wheat height, seeding rate, and year were used as fixed effects for the response variables spring wheat biomass and grain yield. Second, the effects of spring wheat height and seeding rate on wild oat tillers (tillers m^{-2}), wild oat biomass (g m^{-2}), and seed production (seeds 0.25 m^{-2}) were analyzed using the data from the wild oat split plots. The fixed effects were wheat height, seeding rate, and year. The number of wild oat tillers was included as a covariate for the response variables wild oat biomass and seed production. In both analyses, plot nested within block and year was treated as a random effect (R package *lmerTest*; Kuznetsova et al., 2017).

Type III analysis of variance (ANOVA) with Satterthwaite's method was used to assess if predictor variables accounted for variation in response variables. Analysis of covariance (ANCOVA) was used when wild oat tiller density was included as a covariate. Interaction effects ($p \leq 0.05$) of predictors were tested. Data from each year were analyzed separately if there was a significant year effect or a significant interaction between year and other predictors. Diagnostic plots of models were examined to ensure that normality and homogeneity of variance assumptions were satisfied, and log transformations were used when necessary. The values were back-transformed to present the results. Influential outliers were also checked for all models. Final models were selected based on the p-value ($\alpha \leq 0.05$). Tukey's honest significant difference was used for the post-hoc pairwise comparisons (R package *emmeans*; Lenth, 2020).

Spring wheat grain yield loss (%) was determined as the relative yield loss in wild oat split plot compared to weed-free split plot (Cousens, 1985):

$$\frac{Yield_{\ Weed\ free} - Yield_{Wild\ oat}}{Yield_{\ Weed\ free}} \times 100\ \%$$

where $Yield_{\ Weed\ free}$ is the wheat yield in the weed-free split plots and $Yield_{Wild\ oat}$ is the wheat yield in the wild oat split plots. The relationship between spring wheat grain yield loss (%) and wild oat biomass (g m^{-2}) was evaluated using the rectangular hyperbolic decay equation function with two parameters (i and a) (Cousens, 1985):

$$YL = \frac{i \times N_w}{1 + i \times N_w/a}$$

where parameters i and a represent the initial slope and maximum spring wheat yield loss (asymptote) when wild oat biomass reached infinity, respectively. Parameter N_w is the wild oat biomass. *YL* is the relative spring wheat grain yield loss (%). The rectangular hyperbolic decay curve was fitted using the *drm* function (R package *drc;* Ritz et al., 2015).

Results

Spring Wheat Seedling Density, Height, and Tiller Density

In 2017, the tall isogenic line at maturity was taller (90.1 ± 2.19 cm) than the short near-isogenic line average height of (67.8 ± 2.19 cm) at maturity (data not shown). Spring wheat seedling density (plants m^{-2}) did not differ between years nor heights but differed between seeding rates where a higher crop stand density was observed under the 101 kg ha^{-1} than the 67 kg ha^{-1} in 2018 and 2019 (Table 1).

Table 1. Means ± standard errors of the means of crop stand density (plants m^{-2}) in 2018 and 2019.

Spring wheat treatment		Crop plant stand density	
		2018	2019
Seeding rate		plants m^{-2}	
	67 kg ha^{-1}	177 ± 18.3b	212 ± 20b
	101 kg ha^{-1}	258 ± 18.3a	294 ± 20a

Note. Different letters indicate significant differences in the same column ($\alpha \leq 0.05$, Tukey-adjusted).

The interaction between year and seeding rate on the wheat tiller density (tillers m^{-2}) was significant in weed-free split plots (Table 2); therefore, data are presented for each year separately (Table 3). There was a seeding rate by height interaction on wheat tiller density in 2018, but not in 2017 and 2019. In 2017, wheat tiller density did not differ between seeding rates or near-isogenic lines. In 2018, wheat tiller density was the highest under the short near-isogenic line with the high seeding rate compared to other three combinations of treatments. In 2019, the density of wheat tillers was greater under the higher seeding rate, regardless of spring wheat height ($p < 0.01$; Table 3).

Table 2. Type III test of fixed effects of year, spring wheat height, spring wheat seeding rate, and their interactions on spring wheat tiller density, biomass, and grain yield under weed-free conditions. F values with degree of freedom (numerator, denominator) are shown and significant ($p \leq 0.05$) values are highlighted in bold.

	Spring wheat variables								
Factor	Wheat tiller density (tillers m^{-2})			Biomass (g m^{-2})			Grain yield (kg ha^{-1})		
	DF	F value	*p*-value	DF	F value	*p*-value	DF	F value	*p*-value
Year (Y)	2, 37.7	38.3	**< 0.01**	2, 42.5	64.4	**< 0.01**	2, 42.2	30.3	**< 0.01**
Height (H)	1, 36.8	1.35	**0.01**	1, 42.3	0.1	0.76	1, 42	0.88	0.35
Seeding rate (S)	1, 33	< 0.01	0.93	1, 42.3	1.8	0.19	1, 42	0.12	0.73
Y × H	2, 35	1.78	0.18	2, 37.7	0.07	0.93	2, 37.3	0.42	0.66
Y × S	2, 37.1	5.09	**0.01**	2, 37.7	0.52	0.60	2, 37.3	0.49	0.62
H × S	1, 34.7	2.64	0.11	1, 37.5	2.14	0.15	1, 37.1	0.92	0.34
Y × H × S	2, 32.3	2.86	0.07	2, 35.6	0.28	0.76	2, 35.5	0.25	0.8

Table 3. Effects of spring wheat height and seeding rate on spring wheat tiller density (mean ± standard errors of the mean) under weed-free conditions in 2017, 2018, and 2019.

Factor	Spring wheat tiller density (tillers m^{-2})		
	2017	2018	2019
Height (H)			
Short wheat	224 ± 16.1a	458 ± 25.3a	272 ± 15.4a
Tall wheat	195 ± 15.8a	369 ± 25.3b	255 ± 15.4a
p-value	0.2	**< 0.01**	0.43
Seeding rate (S)			
67 kg ha^{-1}	211 ± 16.1a	360 ± 25.3a	207 ± 15.4b
101 kg ha^{-1}	208 ± 15.8a	467 ± 25.3b	320 ± 15.4a
p-value	0.99	**< 0.01**	**< 0.01**
H × S			
Short & 67 kg ha^{-1}	228 ± 23a	366 ± 35.7b	206 ± 21.8b
Short & 101 kg ha^{-1}	220 ± 24.1a	550 ± 35.7a	338 ± 21.8a
Tall & 67 kg ha^{-1}	188 ± 23.2a	355 ± 35.7b	207 ± 21.8b
Tall & 101 kg ha^{-1}	201 ± 23.1a	383 ± 35.7b	302 ± 21.8a
p-value	0.67	**0.05**	0.41

Note. Tiller counts were taken in the end of growing seasons. Significant ($p \leq 0.05$) values are highlighted in bold. Different letters indicate significant differences in the same column within each factor ($\alpha \leq 0.05$, Tukey-adjusted).

Spring Wheat Biomass and Grain Yield

The interactions between wheat height and seeding rate for wheat biomass and grain yield were not significnt across three years (Table 2). Wheat height and seeding rate did not affect spring wheat biomass and grain yield across years. Spring wheat biomass was observed the highest in 2018 and the lowest in 2019 (Table 4). Grain yield was not different between 2017 and 2018, while the yield was the lowest in 2019.

Table 4. Spring wheat biomass and grain yield under weed-free conditions in 2017, 2018, and 2019.

Factor	Spring wheat variables	
Year	Biomass	Grain yield
	g m^{-2}	kg ha^{-1}
2017	418 ± 20.4b	1706 ± 105.8a
2018	578 ± 29.8a	1428 ± 93.7a
2019	258 ± 12.8c	874 ± 55.2b

Note. Data were pooled across seeding rates and heights within each year. Back-transformed means ± standard errors of the means. Different letters indicate significant differences in the same column ($\alpha \leq 0.05$, Tukey-adjusted).

Wild Oat Tiller Density, Biomass, and Seed Production

The effect of year was significant for wild oat tiller density, biomass, and seed production, and the interaction between year and seeding rate was significant on the wild oat seed production (Table 5); therefore, data are presented for each year separately (Table 6). A wheat height by seeding rate interaction was not detected for wild oat tiller density, biomass, and seed production ($p > 0.05$; Table 5).

Wheat height did not affect wild oat tiller density, biomass, and seed production ($p > 0.05$; Table 5). No differences in wild oat tiller density, biomass, and seed production were observed between seeding rates in 2017 and 2018, except in 2019 (Table 6). The seeding rate effect was significant on wild oat biomass and seed production in 2019, but not on wheat tiller density (Table 6). The high seeding rate had about 28% less wild oat biomass than the low treatment. The results of wild oat seed production follow similar pattern as wild oat biomass. The high seeding rate had 22% less wild oat seeds produced than in the low seeding rate in 2019.

Table 5. Type III test of fixed effects of year, spring wheat height, spring wheat seeding rate, and their interactions on wild oat tiller density, biomass, and seed production. F values with degree of freedom (numerator, denominator) are shown and significant ($p \leq 0.05$) values are highlighted in bold.

	Wild oat variables								
Factor	Wild oat tiller density (tillers m^{-2})			Biomass[a] (g m^{-2})			Seed production[a] (seeds 0.25 m^{-2})		
	DF	F value	*p*-value	DF	F value	*p*-value	DF	F value	*p*-value
Year (Y)	2, 42	14.9	< **0.01**	2, 47	18.5	< **0.01**	2, 45.1	59	< **0.01**
Height (H)	1, 41.8	1.62	0.21	1, 40.8	0.81	0.37	1, 41.3	0.62	0.43
Seeding rate (S)	1, 41.8	0.04	0.85	1, 40.3	6.7	**0.01**	1, 41	1.8	0.19
Wild oat tiller density				1, 170	31.3	< **0.01**	1, 182	420	< **0.01**
Y × H	2, 37.3	1.99	0.16	2, 38.3	1.68	0.2	2, 36.5	2.28	0.12
Y × S	2, 37.3	0.25	0.78	2, 37.7	0.93	0.4	2, 36	6	< **0.01**
H × S	1, 37	0.01	0.92	1, 37	0.35	0.6	1, 35.7	0.8	0.38
Y × H × S	2, 35.4	2.23	0.12	2, 36.6	0.37	0.69	2, 34.7	0.05	0.95

[a] Wild oat tiller density was included as a covariate.

Table 6. Effects of spring wheat height and seeding rate on wild oat tiller density, biomass, and seed production (mean ± standard errors of the mean) in 2017, 2018, and 2019. Significant ($p \leq 0.05$) values are highlighted in bold. Different letters indicate significant differences in the same column ($\alpha \leq 0.05$, Tukey-adjusted).

Factor	Wild oat variables								
	Wild oat density (tillers m^{-2})			Biomass[a] (g m^{-2})			Seed production[a] (seeds 0.25 m^{-2})		
	2017	2018	2019	2017	2018	2019	2017	2018	2019
Seeding rate[b]									
67 kg ha^{-1}	447± 34a	425 ± 49a	234 ± 40a	235 ± 21a	93 ± 8a	93 ± 7a	824 ± 51a	1134 ± 34a	1200 ± 72a
101 kg ha^{-1}	408 ± 34a	440 ± 49a	241 ± 40a	174 ± 22a	86 ± 9a	67 ± 7b	765 ± 51a	1187 ± 33a	940 ± 72b
p-value	0.43	0.82	0.91	0.07	0.58	**0.02**	0.43	0.27	**0.03**

[a] Wild oat tiller density was included as a covariate.

[b] Data were pooled across heights at each seeding rate.

Relative Yield Loss

Relative spring wheat yield loss (%) in response to wild oat biomass was fitted for each year (Figure 2a-c; Table 7). All three years, wild oat biomass increases resulted in greater wheat yield losses. The results from the 2017 model indicated that yield losses in the presence of wild oat differed between seeding rates ($p < 0.02$; Figure 2a). When wild oat biomass was below 350 g m^{-2}, a lower yield reduction was predicted under the high seeding rate of 101 kg ha^{-1}, compared to the low seeding rate of 67 kg ha^{-1}. The predicted yield loss was about 15%, 30%, and 40%, due to 50, 100, and 150 g m^{-2} of wild oat biomass respectively. On the other hand, the predicted yield loss was about 56%, 62%, and 65% due to 50, 100, and 150 g m^{-2} of wild oat biomass respectively under the low seeding rate (Figure 2a). The initial yield loss parameter i was not significant for both seeding rates. The maximum potential spring wheat yield loss due to the presence of wild oat, estimated by parameter a, was 69% at the low seeding rate ($p < 0.001$). It is possible that the maximum potential yield loss caused by wild oat at the high seeding rate (146%) was overestimated because there are few observations that had wild oat biomass above 350 g m^{-2}.

There were no differences of the relative yield loss among treatments in 2018 and 2019; therefore, the yield loss function to wild oat biomass was fitted to the combined data (Figure 2b & c). For 2018, about 42%, 50%, and 53% of yield loss predicted due to 50, 100, and 150 g m^{-2} of wild oat biomass, respectively. The maximum potential yield loss was 61%. For 2019, wild oat biomass at 50, 100, and 150 g m^{-2} would cause yield loss of 48%, 50%, and 52%, respectively. The maximum potential yield loss was estimated to be 53%. However, the initial wheat yield loss was not significant ($p > 0.05$) in 2018 and 2019.

Table 7. Estimates of parameters of the rectangular hyperbolic curve model fitted to spring wheat yield loss data in relation to wild oat biomass for all three years. Significant ($p \leq 0.05$) values are highlighted in bold.

	Year	Seeding rate (kg ha^{-1})	Parameter	Estimate	SE	*p*-value
Wild oat biomass	2017	67	*i*	6.2	5.8	0.32
			a	69.1	4.8	**< 0.01**
		101	*i*	0.36	0.08	0.07
			a	145.58	50	**< 0.01**
Wild oat biomass	2018	-	*i*	2.73	1.47	0.07
		-	*a*	61.02	9.22	**< 0.01**
Wild oat biomass	2019	-	*i*	11.74	14.33	0.42
		-	*a*	52.68	5.47	**< 0.01**

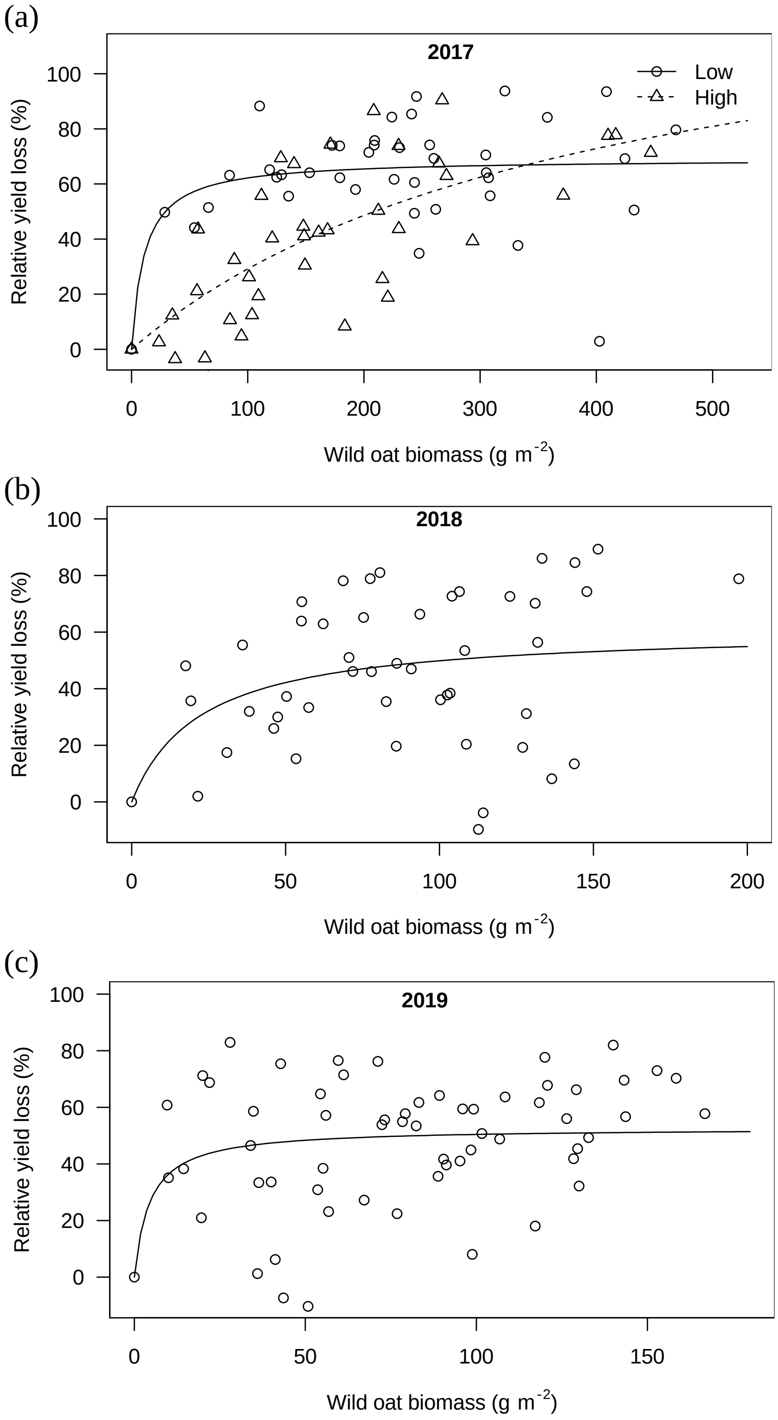

Figure 2. Relative spring wheat yield loss (%) in response to wild oat biomass (g m^{-2}) in (a) 2017, (b) 2018, and (c) 2019. Separate curves were fitted for different spring wheat seeding rates (low and high) in 2017.

Discussion

This study indicated that there were no interaction effects of crop height and seeding rate on crop productivity in the absence of wild oat. Spring wheat biomass and grain yield were comparable between the two tested near-isogenic wheat lines and between seeding rates. These findings were consistent for all three years. Despite crop height historically being negatively correlated with yield potential (Ogg & Seefeldt, 1999), previous studies that compared near-isogenic wheat lines showed that tall near-isogenic lines can produce yields equal or greater than short near-isogenic lines (Zerner et al., 2008; Lanning et al., 2012). Our results also support the idea that it is possible to obtain higher crop competitiveness without compromised grain yield through crop breeding programs.

In agreement with previous findings, our study shows that increasing spring wheat seeding rate to a higher than recommended rate does not necessarily result in a yield benefit under weed-free conditions (Blackshaw et al., 2000; Walsh & Walsh, 2020), even though there was a greater number of average final tiller density in the seeding rate of 101 kg ha^{-1} than the 67 kg ha^{-1} seeding rate treatments in 2018 and 2019. As the crop density increases, intraspecific competition among crops increases and could result in a decreased number of kernels per tiller. However, a grain yield reduction was not observed under the higher seeding rate in this study. It is possible that in this study, the greater number of plants per unit area in the higher seeding rate compensated for an equivalent total kernels per unit area to the lower seeding rate (Champion et al., 1998; Watson et al., 2006; Li et al., 2018).

The tall and the short near-isogenic lines did not differ in weed suppression (the ability to suppress weeds) and weed tolerance (the ability to resist crop yield losses due to weeds), contrary to many studies (Seefeldt et al., 1999; Mason et al., 2007; Harker et al. 2009; Beres et al., 2010). Our result suggests that other plant traits (e.g., early plant vigor and photosynthetically active radiation) may contribute more to weed suppression than the final crop height. Ogg & Seefeldt (1999) noticed that the height growth rate and soil moisture availability related to winter wheat competitiveness, rather than the crop height at maturity. Similarly, O'Donovan et al. (2005) suggested that crop competitiveness with wild oat was associated with differences in seedling establishment among the varieties instead of plant height or light interception.

Taller varieties tended to have greater early vigor compared with short varieties (Richards, 1992); however, we did not evaluate the emergence, seedling establishment time, or the relative growth rates of wild oat and the two near-isogenic lines in this experiment. Further study should examine how these early vigor traits could affect crop competitivness against weeds using near-isogenic lines. Taller canopy of spring wheat may still be a valuable tool in reducing wild oat persistence, although the suppressive ability of the tall near-isogenic line was not greater than the short line. Lehnhoff et al (2013) demonstrated that wild oat seeds grown below crop canopy will be 10% to 30% less viable than the seeds grown above, and wild oat populations can decline in the following years.

Previous research concluded that taller crop varieties decreased yield loss due to the presence of weeds compared to short varieties (Zerner et al., 2008; Fradgley et al., 2017). In those studies, the height of the tall near-isogenic lines exceeded the height of the weeds, while the height of short near-isogenic lines was similar. In this study, based on our field observations, the tall isogenic line had a similar or shorter average height than wild oat. The lack of height advantage in the tested near-isogenic wheat lines to wild oat could explain why we found little to no correlation between crop height and yield losses in this study. We suspect that the advantage of crop height to crop tolerance may not be important in competition with taller-growing wild oat, as this was also suggested by others (Cousens et al., 2003; Fradgley et al., 2017).

This study showed inconsistent results of seeding rate effect on spring wheat competitiveness in the presence of wild oat across the three years. In 2017, the use of the higher seeding rate did not suppress wild oat biomass but reduced wheat yield loss compared to the low seeding rate. In 2018, the effect of seeding rate was not different on yield loss and wild oat suppression. In 2019, yield loss response to wild oat did not differ between seeding rates, but wild oat biomass and seed production were reduced at the high seeding rate. It is not clear why distinct patterns were shown among three years. Our results contradict many previous studies which showed that increased crop density suppressed weeds and maintained yield in the presence of weeds (Evans et al., 1991; Champion et al., 1998; Olsen et al., 2005; Mason et al., 2007; Kristensen et al., 2008; Harker et al., 2009; Kolb et al., 2012; Li et al., 2018).

Interestingly, previous studies assessing the crop seeding rate effect on crop competitiveness documented that the cereal crops were sown at rows spaced less than 30 cm apart (Evans et al., 1991; Champion et al., 1998; Olsen et al., 2005; Mason et al., 2007; Kristensen et al., 2008; Harker et al., 2009; Kolb et al., 2012; Li et al., 2018). Row spacing is usually dependent on what seeders farmers have. Reduced row spacing with higher seeding rate can possibly augment crop competitiveness (Thill et al., 1994), allowing less room and fewer resources for weed growth and greater interspecific competition between crops and weeds (Weiner et al., 2010). We speculate that the weed suppressive impact of a higher crop seeding rate may be less apparent with 30 cm rows apart in our study. Besides the potential for enhancing crop competitiveness, narrower row spacings with increasing seeding rate could provide crop yield advantage (Chen et al., 2008). However, the manipulation of the crop sowing patterns and seeding rates together on crop performance was outside the scope of this study. This study suggests a need to improve our understanding of interaction between crop seeding rates and row spacings on crop competitiveness and productivity based on weed pressure.

Noticeably, wild oat biomass was almost double in 2017 compared to the other two years. We broadcasted nitrogen fertilizer in 2017 (112 kg ha^{-1}) and 2019 (56 kg ha^{-1}), but not in 2018. Nitrogen rates and placement methods have significant influences on crop-weed competition (Thill et al., 1994; O’Donovan et., 2007). In accordance with a review of strategic fertilization application, broadcasting is more favorable for wild oat growth than side-banding and point-injection methods (O’Donovan et al., 2007). In addition, most agricultural weeds, including wild oat, acquire nitrogen more than wheat (Blackshaw et al., 2003; O’Donovan et al., 2007). Thus, it is not surprising that wild oat benefited from the higher nitrogen application in 2017. Although wild oat can preempt the applied nitrogen, Burns et al. (2018b) showed that the combination of a higher nitrogen rate with a higher spring wheat seeding rate can reduce wild oat biomass and wild oat populations. This finding would explain why crop competitive ability was improved with a higher seeding rate in 2017 and 2019 as nitrogen fertilization may have been attributed to the competitiveness of spring wheat at the higher seeding rate in those two years. Given that soil nitrogen content was unknown throughout the three years, the results could be confounded with different applied nitrogen rates.

Our results concur with previous studies indicate that wheat yield loss is correlated with weed biomass (Lemerle et al., 1996; Kristensen et al., 2008). If wild oat is not controlled, our yield loss models estimated that wild oat could cause nearly up to 70%, 60%, and 50% yield reduction in 2017, 2018, and 2019, respectively. The predicted results from the 2017 model indicated the extent of yield losses in the presence of wild oat differed between seeding rates.

Taken together, our results did not support our hypothesis, as the joint use of tall near-isogenic line and a higher seeding rate did not show a greater suppression against wild oat. In contrast with our results, O'Donovan et al. (2000) demonstrated that the competitiveness of barley against wild oat was enhanced by the combination of taller varieties with higher seeding densities. Perhaps the lack of consistency between our study and O'Donovan et al. (2000) may be due to the fact that spring wheat is less competitive with wild oat than barley (Lanning et al., 1997; Mason et al., 2007).

Conclusion

This study highlights that compared to the use of taller crop height, increasing crop seeding rate is a more reliable tool to suppress wild oat and reduce yield losses caused by wild oat competition. It is possible that other agronomic practices are needed in order to enhance crop performance against weeds, such as nitrogen application and row spacing. These two factors combined with a higher seeding rate could augment spring wheat competitive ability over wild oat. The principles of the "many little hammers" strategy is not just simply to use many "little hammers", but also to understand the interactions among these "little hammers", and ways to manipulate them to better improve crop performance. Further research should strengthen the use of enhanced crop competitiveness strategy by adjusting nitrogen rate and row spacing together with crop varieties and seeding rates. In addition, it is important to examine how the interactions of tools and environmental factors like soil nitrogen and moisture, could influence crop yield and competitiveness in the Northern Great Plains.

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CHAPTER THREE

INTEGRATED WILD OAT (*AVENA FATUA* L.) MANAGEMENT UNDER DIVERSIFIED CROPPING SYSTEMS

Introduction

Diversified cropping systems can create opportunities to manage troublesome weeds such as *Avena fatua* L. (wild oat), which has widespread biotypes with herbicide resistance in the Norther Great Plains (Beckie, 2006; Harker et al, 2009; Harker et al., 2016; Heap, 2021). Spring wheat (*Triticum aestivum* L.)-summer fallow cropping was once a dominant crop rotation used to minimize crop failure due to drought and to stabilize crop yield in semiarid regions (Farahani et al., 1998). However, wild oat has prevailed under this simplified rotation system because of its similar life cycle to spring wheat (Beckie et al., 2012). Over the last three decades, weed management efforts in spring wheat cropping systems have largely focused on alternating two herbicide modes of action: Acetyl-CoA carboxylase (ACCase) inhibiting (Group 1) and acetolactate synthase (ALS) inhibiting (Group 2) herbicides. The repeated use of the same herbicide groups has led to the evolution of herbicide resistance and multiple herbicide resistance, leaving few herbicide options to control wild oat in spring wheat and other cereal crops (Beckie et al., 2020; Heap, 2021). Therefore, replacing spring wheat-only cropping systems with more diversified systems is essential to limit wild oat population growth and spread (Beckie, 2006; Beckie & Harker, 2017; Harker et al, 2009; Harker et al., 2016).

Weed management is a long-term process and systematic planning should be prioritized (Bagavathiannan & Davis, 2018; MacLaren et al., 2020). Global agriculture has been heavily dependent on herbicides for weed control since the 1950s (Owen, 2016). While effective in terms of securing yields and increasing farm-labor efficiency, the over-reliance on herbicides has resulted in an increase in the number of herbicide resistant weed biotypes (Heap, 2021). It is possible that the selection of herbicide resistance could outpace human innovation to replace outmoded chemicals (Gould et al., 2018) and that the current herbicides may become ineffective by 2050 (Duke, 2012; Westwood et al., 2018). As a result, it is necessary to develop alternative management tactics as herbicides alone will not be effective in long-term weed management (Blackshaw et al., 2008; Menalled et al., 2016; Owen et al., 2015). Integrated weed management (IWM) has been highlighted as a system level approach for combating difficult-to-control weeds such as herbicide resistant biotypes (Liebman et al., 2001, 2016; Bagavathiannan & Davis, 2018). This approach combines multiple tactics instead of relying on only one to break the life cycle of any predominant weed species (Anderson, 2005, 2008).

Crop diversification is a strong foundation of IWM (Anderson, 2005; Beckie, 2007; Beckie & Harker, 2017; Davis et al., 2012). Continuous cropping with diverse crops became feasible due to the innovation of no-till farming which resulted in greater soil water retention (Carr et al., 2012; Peterson & Westfall, 2004). Currently, pulse and forage crops are grown as popular alternative crops in the Northern Great Plains (Carr et al., 2020; Gan et al., 2015; P. R. Miller et al., 2018; Smith et al., 2017). Rotating diverse crops is a multi-year tactic that hinders the ability of weed species from proliferating (MacLaren et al., 2020). This tactic exposes weeds to different growing conditions resulting from changes in fertilizer, planting times, canopy development, and herbicide applications, creating a wide range of selective pressures (Beckie, 2007; Beckie et al., 2004; Derksen et al., 2002; Weisberger et al., 2019).

Enhancing crop competitiveness against weeds to better acquire light, water, and nutrients is an important component of an IWM program (Andrew et al., 2015). Planting crops and cultivars that have early seedling vigor, tall stature, and increased crop density are strategies to improve crop suppression of weeds and to withstand crop yield in the presence of weeds. Early vigor and rapid growth crop species can uptake resources faster than weeds (Bertholdsson, 2005). For example, winter cereals are perceived to be more competitive with summer annual weeds than spring cereals because of the early spring growth (Beres et al., 2010; Harker et al., 2011). On the other hand, crops that are slow in development (e.g., lentil) are less competitive with weeds (Jha & Kumar, 2017; Thill et al., 1994).

Taller crop cultivars intercept more light from weeds than short crop cultivars (Andrew et al., 2015; Champion et al., 1998). Most studies that quantified the effect of height on crop competitiveness have been confounded when using tall and short cultivars with different genetic backgrounds; variation in other traits (e.g., morphology and phenology) could contribute to competitive ability (Cousens et al., 2003; Seefeldt et al., 1999; Zerner et al., 2008). To assess how the height effect alone alters spring wheat competitiveness, near-isogenic lines that differ in height genes should be compared.

Increasing the crop seeding rate could increase the proportional resources used by crops rather than weeds (Evans et al., 1991; O’Donovan et al., 1999). Research has shown that increasing the seeding rate with taller barley varieties had greater suppression of wild oat compared to the standard seeding rate (Harker et al., 2009; O’Donovan et al., 2000). Recent work has demonstrated that planting spring wheat at a higher than recommended rate (101 kg ha^{-1}) combined with increasing nitrogen rates could decrease multiple herbicide resistant wild oat populations (Burns et al., 2018). Based on the wild oat suppression found in these studies, similar tactics could be used to enhance the competitiveness of spring wheat. To our knowledge, the individual and joint effects of height and seeding rate have not yet been well addressed in spring wheat competitiveness against wild oat.

Integrating livestock into cropping systems has potential to control weeds (Kumar et al., 2019; MacLaren et al., 2019). Previous studies showed that grazed sheep (*Ovis aries*) on fallow fields reduced weed density and biomass (Goosey et al., 2005; Hatfield et al., 2007), and could be as effective as tillage to control weeds (Hatfield et al., 2007). However, a few studies showed sheep grazing could increase weed biomass (Larson et al., 2021; Miller et al., 2015), so additional research is needed to understand how targeted sheep grazing in annual forage crops could affect wild oat growth.

The aim of this study was to assess integrated strategies to mitigate multiple herbicide resistant wild oat populations. We investigated the effects on wild oat density, biomass, and seed production on the following treatments:1) spring wheat height (short and tall), 2) spring wheat seeding rate (67 and 101 kg ha^{-1}), 3) crop identity (lentil, and fall and spring forages), 4) forage crop termination (grazing and haying), and 5) tillage in fallow. In addition, the impact of wild oat on crop biomass and yield was examined. We hypothesized that a taller wheat sown at a higher density would reduce wild oat biomass and seed production without compromising yield. Due to the timing of crop harvest, we also hypothesized forage crops would suppress wild oat better than lentil and spring wheat, and tillage would result in the greatest wild oat suppression compared to all other treatments. Our study serves as a prelude to understand how these practices may change wild oat population dynamics and as a base to design diversified crop rotations.

Materials and Methods

Experimental Site

Two trials were conducted in separate fields and years at the Montana State University Central Agricultural Research Center (CARC) located in Moccasin, Montana (47° 03´ N 109° 57´ W, 4300 m). Trial 1 was from October 2017 to September 2018, and trial 2 from October 2018 to September 2019. The soil at CARC was Judith clay loam (fine-loamy, carbonatic, frigid Typic Calciustolls) with limited water holding capacity due to gravel (Web Soil Survey of NRCS, 2021). From 1909 to 2016, the average annual precipitation at CARC was 388 mm, and the mean annual temperature was 6.5°C (PRISM Climate Group, 2021). During the study period, the mean annual rainfall was 540 mm and the mean annual temperature was 4.1 °C (PRISM Climate Group, 2021; Figure 1).

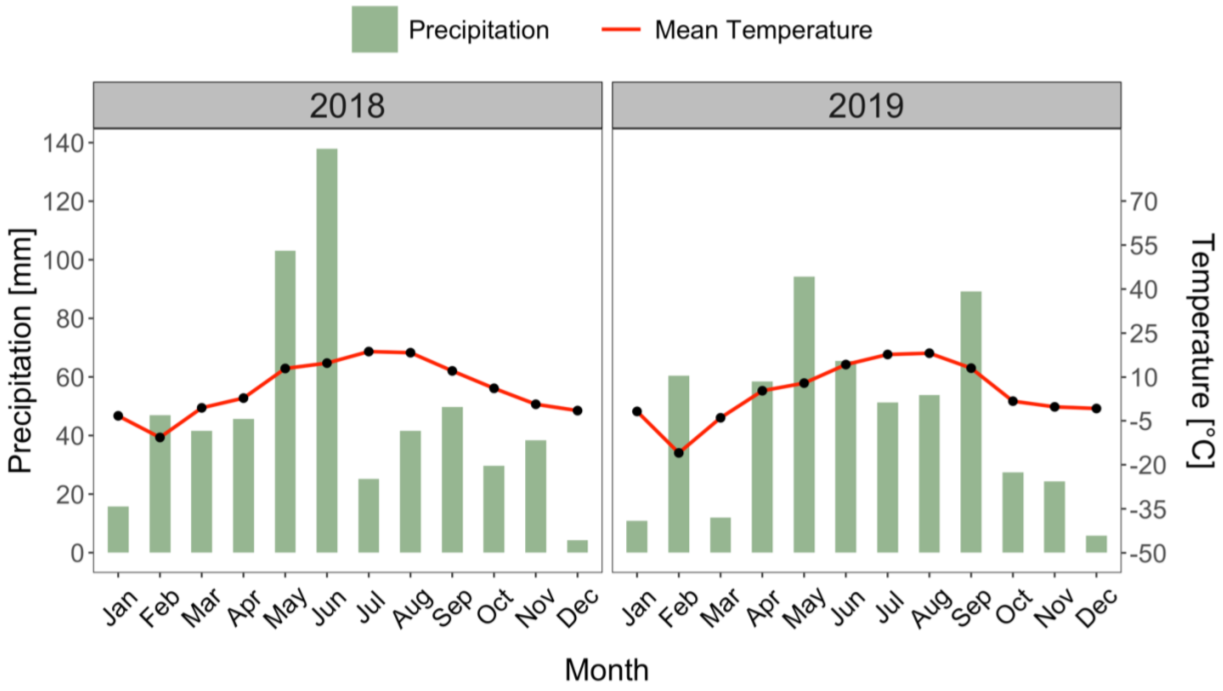

Figure 1. Monthly total precipitation (mm) and monthly mean temperature (°C) in 2018 and 2019 at the Central Agricultural Research Center (CARC) in Moccasin, Montana.

Experimental Design and Treatments

In each trial, a split-plot randomized complete block design with four replications was used. Each replication had ten plots for a total of 40 plots. Each year, plots were arranged in an area that was 40 m wide and 120 m long. Each plot measured 5 m wide and 10 m long. Each plot was divided into two 5 m wide and 5 m long split plots, with a 0.5 m buffer separating split plots.

Each of the ten treatments was randomly assigned to a main plot in each replication. There were four spring wheat treatments with two near-isogenic lines (short and tall) seeded at either 67 or 101 kg ha^{-1}. Four of the treatments were two different forage crop mixtures; each mixture was either terminated by sheep-grazing or haying. The two forage crops mixtures were a fall-seeded winter triticale (×*Triticosecale* Wittm.) with Austrian winter pea (*Pisum sativum* L.) (hereafter, fall forage mixture), and a spring-seeded mixture of spring barley (*Hordeum vulgare* L.) with spring pea (*Pisum sativum* L.) (hereafter, spring forage mixture). Sheep were enclosed using portable fencing during grazing. Five sheep were placed on grazed forage crop treatments for approximately 72 hours and were removed after consuming approximately 90% of the above ground crop and weed biomass. In hayed treatments, forage crops were cut to an 8-cm stubble height using a sickle to simulate the height of stubble that would be left by a hay mower. The remaining two treatments included lentil (*Lens culinaris* Medik.) and a tilled-fallow that was cultivated by a chisel plough. Crops were sown at a row spacing of 30 cm. Planting was done directly into a no-till seedbed. Field management operations followed farmers' practices in the region (Table 1). No fertilizers or fungicides were applied in both trials. Glyphosate (900 g ai ha^{-1}) was applied to the entire plot area prior to crop seeding to kill early emerged weeds. Postemergence herbicides were applied in trial 1 during 2018 and resulted in lentil damage (Table 2). No postemergence herbicide applications were made in trial 2 during 2019 to minimize the risk of herbicide damage on crops, and weeds were managed through routine hand weeding.

Table 1. Crop seeding rates, planting and termination dates, and crop termination methods used to manage wild oat during 2018 and 2019 at the Central Agricultural Research Center (CARC) in Moccasin, Montana.

Crop treatment (Cultivar)	Seeding rate	Date			
	live seeds m^{-2}	Planting		Harvest	
		2018	2019	2018	2019
Spring wheat (Amidon)					
Tall isogenic line	101 (kg ha^{-1})	4/26	5/7	8/13	9/14
	67 (kg ha^{-1})	4/26	5/7	8/13	9/14
Short isogenic line	101 (kg ha^{-1})	4/26	5/7	8/13	9/14
	67 (kg ha^{-1})	4/26	5/7	8/13	9/14
Spring lentil (Richlea)	215	4/26	5/7	8/13	8/12
Spring forage mixture[a]					
Spring barley (Lavina)	118	4/26	5/7	7/10	7/15
Spring pea (4152)	53				
Fall forage mixture[b]					
Winter triticale	96	10/11/ 2017	10/24/ 2018	Grazed 6/25 Hayed 7/10	7/15
Austrian winter pea	64				
Tilled fallow[c]	-	-	-	7/10	7/11

[a] Grazed and hayed spring forage mixtures were terminated on the same date.

[b] Grazed fall forage mixture was terminated two weeks earlier than the hayed fall forage mixture in 2018. Grazing and haying took place on the same date in 2019.

[c] Fallow was tilled in July of 2018 and 2019.

Table 2. Herbicides and application rates used following crop emergence at Central Agricultural Research Center (CARC) in Moccasin, Montana, in 2018.

Weed treatment	Crop treatment	Herbicide	Field rate
			g ai or ae ha^{-1}
Weed-free	Spring wheat and fallow	Pinoxaden[a]	60
		Bromoxynil	280
		Clopyralid	180
	Lentil	Quizalofop-p-ethyl	36
		Metribuzin	560
Wild oat	Spring wheat and fallow	Bromoxynil	280
		Clopyralid	180
	Lentil	Metribuzin	560

[a] 1% v/v of adjuvant added per application.

The split plots were randomly assigned to have wild oat or be maintained weed-free through the growing season (hereafter, weed-free). Seeds of herbicide susceptible wild oat biotypes were planted in this study, since previous studies indicated that there were no differences in growth and competitiveness between susceptible and herbicide resistant populations (Lehnhoff et al., 2013a, 2013b). Wild oat seeds were planted at a rate of 1,000 seeds m^{-2} in parallel rows with crop treatments in the fall of 2017 (trial 1) where some wild oat and crop rows overlapped. However, wild oat was planted perpendicularly to crop treatments in the fall of 2018 (trial 2). Wild oat seeds were confirmed to have a germination rate >90% prior to planting. Germination rate of wild oat seeds was determined by placing seeds on Petri dishes with a moist filter paper. The germinated seeds were counted daily for 21 days. Seeds that did not germinate were further tested for viability with tetrazolium.

Data Collection

Early crop and wild oat seedling densities were counted three weeks after crop emergence within five 20 cm radius rings in each split-plot in trial 1. Five 0.5 by 0.5 m (0.25 m^2)

quadrats were used for sampling seedling densities at each split-plot in trial 2. The sampling locations were chosen in each split plot using a random number generator assuming uniform distribution. In the forage crop treatments, crops were harvested just before kernel development in cereals. Prior to grazing and haying forage crops, tillers and aboveground biomass of crops and weeds were collected in three 0.25 m^2 quadrats at each split-plot. In the spring wheat and lentil treatments, final tillers and aboveground biomass of crops and wild oat were sampled within three 0.25-m^2 quadrats at each split plot in trial 1 and within five 0.25-m^2 quadrats in trial 2. While the wheat height at maturity was not measured, the height differences were determined based on field observation. Wild oat was sampled on July 31, 2018 (trial 1) and 2019 (trial 2) in wheat and lentil treatments. Wild oat regrew after forage crops were harvested and fallow plots were tilled. The regrowth of wild oat in forage and tilled-fallow treatments was sampled within five 20 cm radius rings on August 30, 2018 (trial 1) and within five 0.25-m^2 quadrats on September 15, 2019 (trial 2). Final tiller number was counted for all plants, and plants were clipped at the ground surface. Each plant species was placed in a separate paper bag. Plant samples were dried at 40°C for at least 72 hours before weighing for total dry matter. Spring wheat and lentil seeds were threshed, cleaned, and weighed to determine grain yield.

In order to estimate wild oat seed production, a linear mixed effect model was fitted to estimate the number of pairs of glumes in response to wild oat biomass (g 0.25 m^{-2}) for trials 1 and 2 subsamples (Appendix B-Figure B1). The pairs of wild oat glumes were counted in each 0.25 m^2 quadrat for 102 subsamples (of 320 total) from trials 1 and 2, where subsamples were a random selection of plant samples with a biomass between 1 and 100 g 0.25 m^{-2}. The maximum wild oat seed production was determined by multiplying the number of pairs of glumes by three, as each pair of glumes usually enclose up to three viable wild oat florets (seeds).

Statistical Analyses

All analyses were performed using R software version 4.0.3 (R Core Team, 2021). Response variables were wild oat early seedling density (plant m^{-2}), wild oat tiller density (tillers m^{-2}), wild oat biomass (g m^{-2}), wild oat seed production (seeds 0.25 m^{-2}), crop tiller density (tillers m^{-2}), crop biomass (g m^{-2}), and crop yield (kg ha^{-1}). Response variables were analyzed by year, spilt plot, spring wheat near-isogenic line (height), spring wheat seeding rate, and crop treatment. Wild oat tiller and seed production were analyzed using generalized linear mixed models with a Poisson distribution to account for the presence of zero values (R package lme4; Bates et al., 2015). All other analyses used linear mixed-effects models (R package lme4; Bates et al., 2015). Each model tested interactions among predictors and used plot nested within block (replication) and year as random effects. Data from each year were analyzed separately if there was a significant year effect or a significant interaction between year and other predictors.

Type III analysis of variance (ANOVA) with Satterthwaite's method was used to assess if predictor variables accounted for variation in response variables. Analysis of covariance (ANCOVA) was used when covariates (i.e., wild oat tiller density and wild oat biomass) were included. We used backward stepwise model selection starting with a full model and based model selection on the p-value ($\alpha = 0.05$). Diagnostic plots of models were examined to ensure that normality and homogeneity of variance assumptions were satisfied. Log transformations were used when necessary, and the values were back-transformed to present the results.

Influential outliers were also checked for all models. Tukey’s honest significant difference was used for the post-hoc pairwise comparisons (R package *emmeans*; Lenth, 2020).

Assessment of Wild Oat Performance in Wild Oat Split Plots

To assess whether crop seedlings suppress wild oat seedling density, crop treatment and year were treated as fixed effects. Wild oat tiller density, biomass, and seed production at the end of growing seasons were analyzed as indicators of weed suppression. The data were first subset to the spring wheat treatments to assess the effects of spring wheat height and seeding rate on wild oat performance. The fixed effects were spring wheat height, seeding rate, and year. Wild oat tiller density was included as a covariate when analyzing wild oat biomass and seed production. If the effects of spring wheat height and seeding rate on wild oat performance were not different, wheat data from the wild oat split plots were pooled across wheat treatments.

Tiller density, biomass, and seed production of wild oat that had grown back after sheep grazing, haying, and tilling was compared to the wild oat in spring wheat and lentil treatments using the full dataset. Crop treatment and year were treated as fixed effects. Wild oat tiller density and seed production data were analyzed using generalized linear mixed models, and wild biomass data were analyzed with a linear mixed-effects model.

Assessment of Crop Performance in Weed-Free Split Plots

Linear mixed-effects models were used to assess how spring wheat tiller density, wheat biomass, and grain yield were affected by spring wheat height, seeding rate, and their interaction in weed-free split plots. The fixed effects were spring wheat height, seeding rate, and year. If the effects of spring wheat height and seeding rate on wheat performance did not differ among treatments in weed-free split plots, wheat data from the weed-free split plots were pooled across the wheat treatments. To compare grain yield and forage yield among crop treatments in the weed-free split plots, crop treatment and year were included as fixed effects. Grain yield was compared only between spring wheat and lentil treatments. There is no data on lentil yield for trial 1 in 2018 due to herbicide crop injury. Forage yield was compared between winter forage and spring forage treatments.

Relative Crop Yield Loss Due to Wild Oat Biomass

Split plot (weed-free vs. wild oat) and crop treatment were used as fixed effects to examine whether there was a reduction in crop yield due to the presence of wild oat for each crop treatment. Data from each year were analyzed separately using linear mixed-effects models because of the significant year by wild oat biomass interaction. If crop yields were significantly different between split plots, percentage crop yield loss (%) due to the presence of wild oat was calculated as the relative yield loss in wild oat split plots compared to weed-free split plots (Cousens, 1985):

$$\frac{Yield_{\ Weed\ free} - Yield_{\ Wild\ oat}}{Yield_{\ Weed\ free}} \times 100\ \%$$

where $Yield_{\ Weed\ free}$ was the grain or forage yield in the weed-free split plots and $Yield_{\ Wild\ oat}$ was the grain or forage yield in the wild oat split plots. Relative yield loss was used as an indicator of weed tolerance, which is the ability to resist yield loss due to weeds. Crop treatment and wild oat biomass were included as a fixed effect and covariate, respectively, when comparing percentage yield loss among crop treatments.

Results

Wild Oat Seedling Density

The average numbers of wild oat seedlings were not different among the ten treatments (ANOVA, $F_{9,69} = 1.22$, $p = 0.3$), but they were different between years (ANOVA, $F_{1,69} = 26.7$, $p < 0.01$). In trial 1, the early wild oat seedling density was 25 ± 1.8 plant m^{-2} (mean ± standard error of the mean) across ten treatments, and it was 42.3 ± 3.1 plant m^{-2} in trial 2.

Wild Oat Tiller Density, Biomass, and Seed Production

Spring Wheat Treatments. Wild oat tiller density did not differ between years, but wild oat biomass and seed production differed between years ($p < 0.01$; Appendix B-Table B1); data were analyzed by year (Table 3). There were no interactions between spring wheat height and seeding rate on wild oat tiller density within each year. In both trials, wild oat tiller density, wild oat biomass, and seed production did not not differ between spring wheat heights or seeding rates, thus data were pooled across four wheat treatments within each year (Figures 2, 3, and 4). Although wild oat biomass and seed production did not differ between near-isogenic wheat lines in trial 1, there were trends suggesting possible differences ($p = 0.06$; Table 3).

Table 3. Type III test of fixed effects of spring wheat height, spring wheat seeding rate, and their interactions on wild oat tiller density, biomass, and seed production in 2018 (trial 1) and 2019 (trial 2). F values with degree of freedom (numerator, denominator) are shown and significant ($p \leq 0.05$) values are highlighted in bold.

Factor	Wild oat variables								
	Wild oat tiller density (tillers m^{-2})			Biomass[a] (g m^{-2})			Seed production[a] (seeds 0.25 m^{-2})		
	DF	F value	*p*-value	DF	F value	*p*-value	DF	F value	*p*-value
2018 (trial 1)									
Height (H)	1, 13	0.06	0.8	1, 13	4.23	0.06	1, 13	4.1	0.06
Seeding rate (S)	1, 13	2.13	0.21	1, 13	2.49	0.14	1, 13	2.5	0.14
Wild oat tiller density	-	-	-	1, 31	60	**< 0.01**	1, 31	53	**< 0.01**
H × S	1,12	0.11	0.75	1, 12	2	0.19	1,12	1.9	0.19
2019 (trial 2)									
Height (H)	1, 13	0.07	0.80	1, 12	0.76	0.4	1, 12	0.45	0.52
Seeding rate (S)	1, 13	1.09	0.31	1, 12	0.02	0.88	1, 12	0.04	0.85
Wild oat tiller density	-	-	-	1, 57	121	**< 0.01**	1, 57	50	**< 0.01**
H × S	1, 12	0.17	0.69	1, 11	0.33	0.58	1, 11	0.22	0.65

[a] Wild oat tiller density was included as a covariate.

Crop Treatments. There were significant interactions between year and treatment on wild oat tiller density, biomass, and seed production ($p < 0.01$; Appendix B-Table B2). At the end of trial 1, wild oat tiller density was the lowest in the tilled fallow and the grazed spring forage mixture treatments (Figure 2 & Appendix B-Table B3). Wild oat tiller density was not different among other treatments. The tilled fallow treatment had the least number of wild oat tillers at the end of trial 2, followed by the grazed fall forage and spring forage mixture treatments (Figure 2). The wild oat tiller density of the grazed spring forage mixture treatment did not differ from the spring wheat, lentil, and both hayed forage mixture treatments.

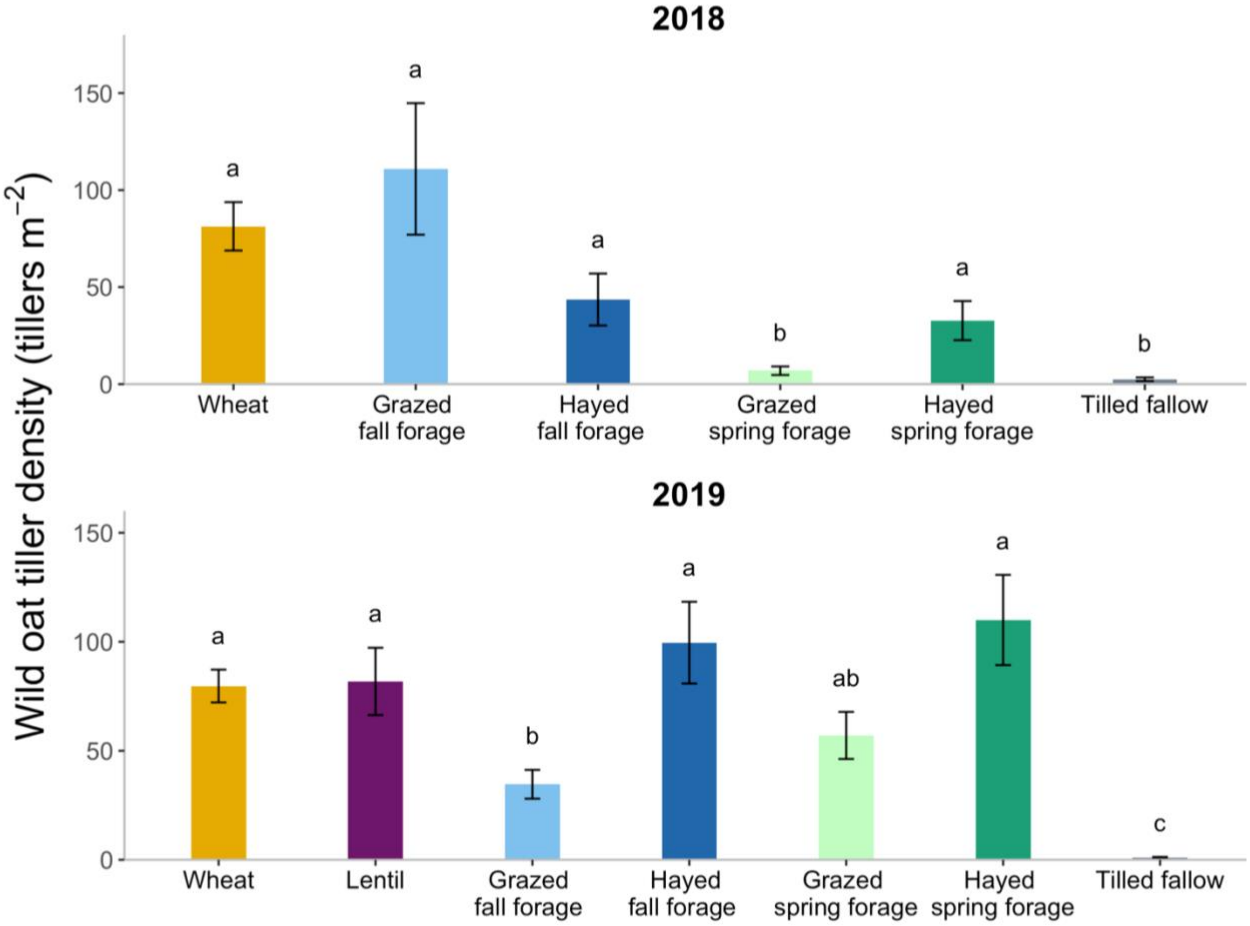

Figure 2. Mean wild oat tiller density (tillers m^{-2}) across crop treatments in the end of the 2018 and 2019 cropping years. Error bars represent standard errors of the means. Different letters indicate significant differences among treatments within year ($\alpha \leq 0.05$, Tukey-adjusted).

Wild oat biomass was the lowest in the tilled fallow and the grazed spring forage mixture treatments in trial 1 (Figure 3 & Appendix B-Table B3). The second lowest of wild oat biomass was observed in the hayed fall forage and spring forage mixture treatments. No significant differences were detected between the grazed fall forage mixture and spring wheat treatments. In trial 2, the tilled fallow treatment had the lowest wild oat biomass (Figure 3), followed by the grazed fall forage mixture treatment. The other three forage mixture treatments had similar wild oat biomass. Wild oat biomass was not different between the two hayed forage mixture and the spring wheat treatments. The largest wild oat biomass was observed in the lentil and the spring wheat treatments.

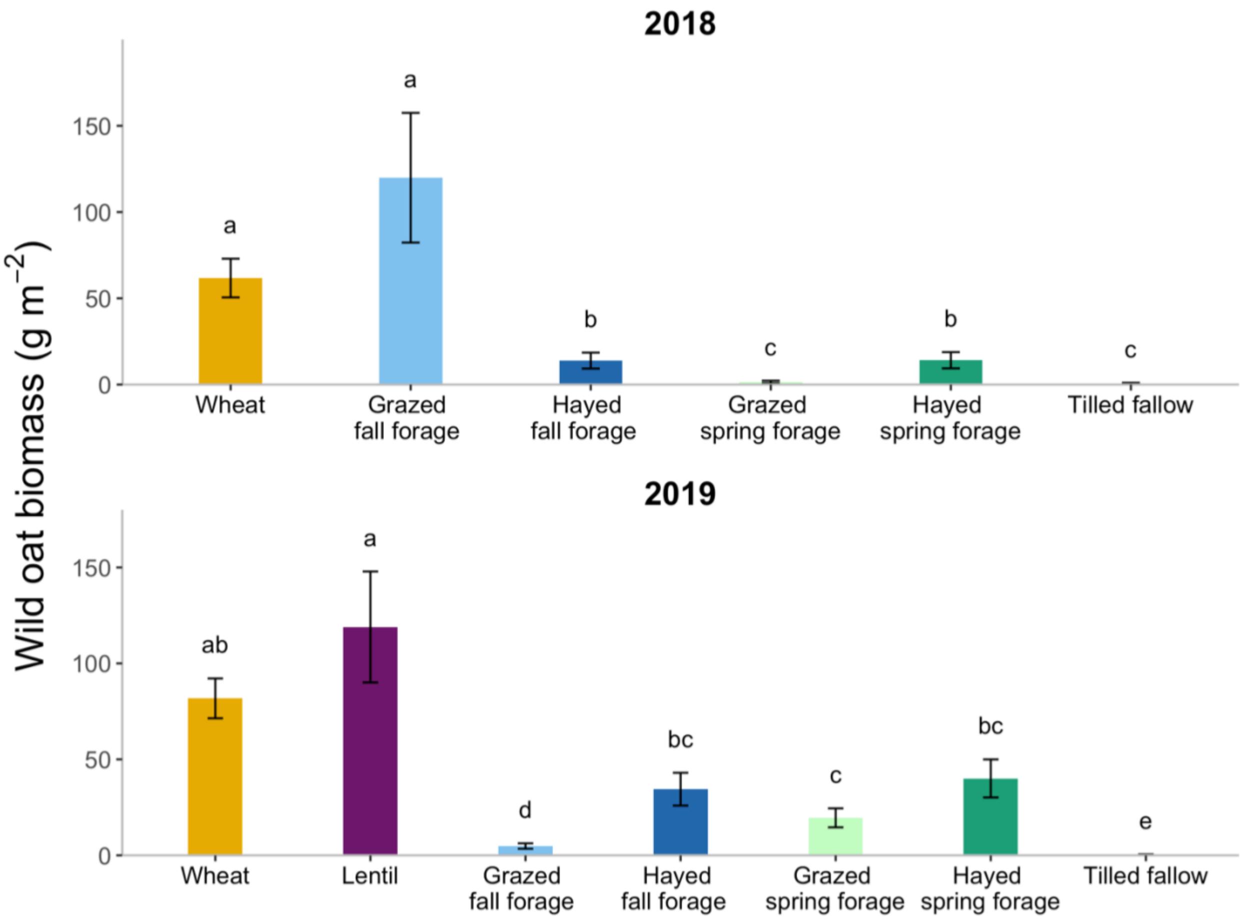

Figure 3. Mean wild oat biomass (g m^{-2}) across crop treatments in the end of the 2018 and 2019 cropping years. Error bars represent standard errors of the means. Different letters indicate significant differences among treatments within year ($\alpha \leq 0.05$, Tukey-adjusted).

Wild oat in the tilled fallow treatment produced the fewest seeds in trial 1 (Figure 4 & Appendix B-Table B3). The grazed spring forage mixture and the hayed fall forage mixture treatments had the second fewest wild oat seeds, followed by the hayed spring forage mixture treatment. Wild oat seed production was not different between the grazed fall forage mixture and the spring wheat treatments. The tilled fallow treatment had almost no wild oat seeds produced in trial 2 (Figure 4). The second lowest wild oat seed production was in the grazed fall forage and spring forage mixture treatments. Wild oat seed production did not differ among the other treatments.

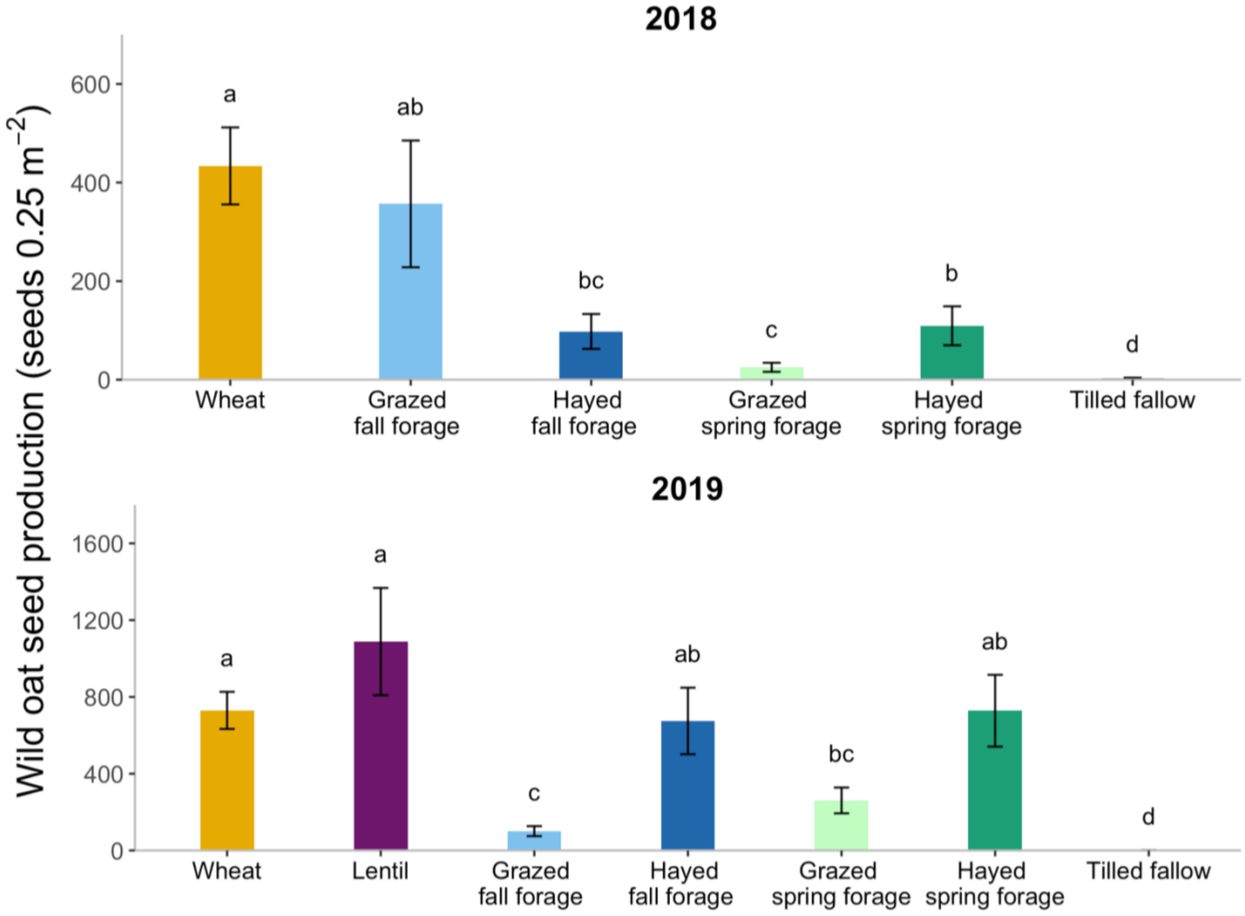

Figure 4. Mean wild oat seed production (seeds 0.25 m^{-2}) across crop treatments in the end of the 2018 and 2019 cropping years. Error bars represent standard errors of the means. Different letters indicate significant differences among treatments within year ($\alpha \leq 0.05$, Tukey-adjusted).

Crop Seedlings

Averaged across weed-free split plots, the number of crop seedlings (plant m^{-2}) was higher in trial 2 than in trial 1 for all crop treatments (Table 4). In both years, spring wheat seedling density was higher under the 101 kg ha^{-1} seeding rate than the 67 kg ha^{-1} treatments, averaged across near-isogenic wheat lines (Table 4). Winter triticale and Austrian winter pea seedling density in the fall forage mixture reached 67% and 47% targeted seeding rates, respectively, in trial 1.

Table 4. Mean (standard deviation) of crop stand density (plants m^{-2}) in 2018 and 2019.

Crop treatments	Crop plant stand density (plants m^{-2})	
	2018	2019
Spring wheat		
67 kg ha^{-1}	166 (65)	215 (50)
101 kg ha^{-1}	207 (76)	300 (64)
Lentil	166 (45)	265 (58)
Fall forage mixture		
Winter triticale	65 (46)	118 (35)
Austrian winter pea	25 (18)	42 (22)
Spring forage mixture		
Spring barley	123 (51)	125 (32)
Spring pea	30 (18)	52 (19)

Spring Wheat Tiller Density, Biomass, and Yield in the Weed-Free Split Plots

Spring wheat tiller density and grain yield were not different between years in the weed-free spilt plots; however, wheat biomass was higher in trial 1 than in trial 2 (ANOVA, $F_{1,27} = 43$, $p < 0.01$). No interactions were detected between spring wheat height and seeding rate across years (Appendix B-Table B4). Wheat tiller density did not differ between near-isogenic wheat lines but differed between seeding rates ($p < 0.01$; Appendix B-Table B4). The high seeding rate treatments resulted in a 23% greater wheat tiller density compared to the low seeding rate across trials and near-isogenic wheat lines (Figure 5). Moreover, the effects of wheat height and seeding rate were not significant on spring wheat biomass and grain yield across years (Appendix B-Table B4).

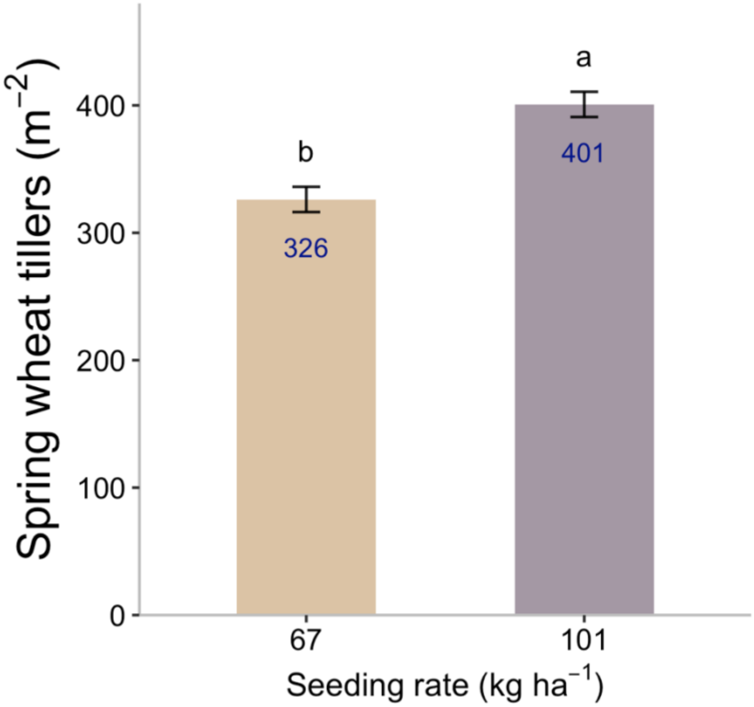

Figure 5. Effect of seeding rate on spring wheat tiller density (m^{-2}) under weed-free conditions, averaged across heights and years. Means are shown in the bar plot. Error bars represent standard errors of the means. Different letters indicate significant differences between seeding rates ($\alpha \leq 0.05$, Tukey-adjusted).

Crop Yield in the Weed-Free Split Plots

Lentil yield was comparable to spring wheat under weed-free conditions in trial 2 (Table 6). For the forage mixture yields, there was a significant interaction between treatment and year (ANOVA, $F_{1,18.2} = 6.13$, $p = 0.02$). In trial 1, the hayed fall forage mixture treatment that was harvested in July yielded nearly two-fold higher than the grazed fall forage mixture treatment that was harvested in June (Table 6). The fall and spring forage mixtures that were harvested on the same date had similar yields. However, the yield of the fall forage mixture was 81% more than the spring forage mixture in trial 2.

Relative Crop Yield Loss

Differences were detected in crop yield between weed-free and wild oat split plots for all crop treatments in both years (data not shown). The tall near-isogenic wheat line treatment had the highest yield loss compared to the short line and lentil treatments in trial 2, although the yield loss due to the presence of wild oat was not different between the two near-isogenic wheat lines in trial 1 (Table 6). The yield loss from wild oat competition did not differ for the fall and spring forage mixture treatments in both trials.

Table 5. Mean ± standard errors of crop yield, wild oat biomass, and percent crop yield loss for crop treatments in 2018 and 2019. Significant ($p \leq 0.05$) values are highlighted in bold. Different letters indicate significant differences in the same column within each year ($\alpha \leq 0.05$, Tukey-adjusted).

Year	Crop treatment	Crop yield[a]		Wild oat biomass	Yield loss
		Weed-free	Wild oat		
		kg ha^{-1}		g m^{-2}	%
2018	Short spring wheat[b]	1340 ± 173a	973 ± 80.1a	99 ± 9.4a	28a
	Tall spring wheat[b]	1521 ± 190a	726 ± 80.5a	82 ± 9.7a	33a
	p-value	0.5	0.07	0.22	0.48
	Fall forage (June)	2602 ± 646b	2562 ± 522b	112 ± 28.8a	14a
	Fall forage (July)	5394 ± 710a	4123 ± 477ab	103 ± 28.8a	29a
	Spring forage	5129 ± 479a	4209 ± 323a	99 ± 20.3a	10a
	p-value	**< 0.01**	**0.05**	0.9	0.55
2019	Short spring wheat[b]	1448 ± 253a	882 ± 121ab	110 ± 13.8a	37b
	Tall spring wheat[b]	1414 ± 180a	569 ± 122b	90 ± 14.8a	63a
	Lentil	1694 ± 195a	1240 ± 172a	139 ± 19.4a	17b
	p-value	0.65	**0.02**	0.17	**< 0.01**
	Fall forage[c]	3218 ± 255a	2664 ± 217a	32.9 ± 6.3a	21a
	Spring forage	1782 ± 141b	1475 ± 117b	49.2 ± 5.7a	12a
	p-value	**< 0.01**	**< 0.01**	0.08	0.26

[a] Crop yield in weed-free and wild oat split plots.
[b] Data were pooled across seeding rate at each near-isogenic wheat line.
[c] Grazed and hayed fall forage mixtures were terminated on the same date in 2019.

Discussion

Integrating diversified cropping systems and multiple management practices may help reduce wild oat populations. The objective of this study was to evaluate how wild oat responds under different crop treatments and to assess the relationship between wild oat competition and crop performance. Contrary to our hypothesis, the tall near-isogenic line and the higher seeding rate did not enhance spring wheat competitiveness against wild oat. In addition, wild oat biomass and seed production were not different between lentil and spring wheat treatments. However, we found evidence for our hypothesis that including forage crops with targeted sheep grazing could reduce the wild oat biomass and seed production. As expected, tillage was the most effective weed control practice.

Spring Wheat

Our study showed that wild oat suppression was not different between near-isogenic wheat lines, regardless of the seeding rates. However, there was a trend in trial 1 that the tall near-isogenic line could reduce wild oat biomass. In general, competition for light is greater when plants are in a limited space (Cousens, 2003; Weiner et al., 2010). Wild oat was planted in almost the same row as the crops in trial 1, where it grew in close proximity with spring wheat. Thus, this wild oat could have experienced a pronounced shading effect from the tall near-isogenic line compared to the wild oat that was sown at right angles to the crop rows in trial 2. In contrast with our results, previous studies observed that crop height was highly correlated to spring wheat competitive ability (Lemerle et al., 1996; Mason et al., 2007, 2008); however, the importance of plant height depends on the specific crop-weed interaction (O’Donovan et al., 2005). Two previous studies investigated different cereal varieties and concurred that little correlation existed between wheat height at maturity and wheat competitiveness against wild oat (Lanning et al.,1997; O'Donovan et al., 2005). These findings suggested that crop height may not be an important trait responsible for enhancing spring wheat competitive ability in relation to wild oat.

The results were inconsistent in terms of the tolerance of tall near-isogenic wheat line to wild oat. The cause of the anomaly is unclear in this study, but the effect of wheat height on crop tolerance was also inconsistent in previous studies as well (Seefeldt et al., 1999; Zerner et al., 2008). Zerner et al. (2008) demonstrated that the tall near-isogenic lines consistently decreased the yield loss from weeds compared to the short near-isogenic lines. On the contrary, Seefeldt et al. (1999) found that the tall isogenic lines did not necessarily produce higher yields than the short near-isogenic lines under weed competition, and they speculated that the cost of height competitiveness may be more apparent when competing against weeds.

Without competition from wild oat, spring wheat near-isogenic lines yielded equally in both trials. It is widely accepted that taller crop cultivars yield less than semi-dwarf cultivars because more resources are allocated for stem elongation rather than grain development (Mohler, 2001; Mason & Spaner, 2006). However, studies comparing the yield potentials among near-isogenic lines of the same cultivars observed that tall near-isogenic lines could yield similarily or greater than short near-isogenic lines depending on the cultivars (Zerner et al., 2008; Lanning et al., 2012). Competitive and yielding abilities of a taller near-isogenic line can affect whether or not farmers adopt it. This study did not show clear results about the superiority of the tall near-isogenic line over the short near-isogenic line, while environmental factors such as temperature, soil moisture and nitrogen contents could also influence crop competitive and yielding abilities

(Lanning et al., 2010, 2012). Further research could justify the advantage of using the tall near-isogenic line against wild oat under different environmental conditions.

Surprisingly, our study showed that the high crop seeding rate (101 kg ha^{-1}) had little effect on spring wheat competitiveness compared to the low seeding rate (67 kg ha^{-1}). This finding is contrary to numerous studies where increasing crop density improved crop suppression of and tolerance to weeds (Andrew et al., 2015; Burns et al., 2018; Evans et al., 1991; Harker et al., 2009; Mohler, 2001; O'Donovan et al., 2000, 2006). One possible explanation for the contradiction is that those studies applied fertilizers at planting according to the soil test recommendations, and crops were seeded at a row spacing that ranged from 9 to 25.4 cm (Burns et al., 2018; Evans et al., 1991; Harker et al., 2009; O'Donovan et al., 2000, 2006; Stougaard & Xue, 2004). We did not apply fertilizers, and no soil test was conducted. Additionally, we used a 30-cm row spacing which may have further contributed to little wild oat suppression as it could favor weed growth by allowing more space and resources (Weiner et al., 2010). Strategically incorporating fertilizer application and narrow spacing have been recommended to augment crop competitiveness over weeds (Thill et al., 1994).

Spring wheat grain yield was not different between the low and hight seeding rates under the weed-free conditions in both years. The results agree with Holman et al., (2021) that no yield penalty was observed when wheat was seeded at 101 kg ha^{-1} compared to the 67 kg ha^{-1}. Similarly, planting spring wheat at 135 kg ha^{-1} and 67 kg ha^{-1} yielded comparably (Walsh & Walsh, 2020). Since no yield reduction was observed at the 135 kg ha^{-1} seeding rate (Walsh & Walsh, 2020), further research could investigate whether seeding wheat between the 101 kg ha^{-1}

and 135 kg ha^{-1} would be an appropriate approach to enhance spring wheat competitiveness against weeds.

Lentil

Lentil had similar suppression of and tolerance to wild oat as spring wheat. In general, lentil does not compete as well as cereal crops because of its slow emergence, slow early growth, and short-stature (Beckie et al., 2012; Fedoruk et al., 2011; Jha & Kumar, 2017). However, lentil was planted at 215 seeds m^{-2} in this study which is higher than the recommended rate (130 seeds m^{-2}). Other research has demonstrated that increasing lentil density could decrease weed biomass and increase yield (Alba et al., 2020; Baird et al., 2009). We suggest that farmers can increase lentil seeding rate to reduce yield loss under wild oat competition. Including lentil in cropping systems may not inhibit wild oat population growth, but it would increase soil available nitrogen, a substitute for nitrogen fertilizers (Miller et al., 2003; Gan et al., 2015). In addition, lentil is a high economic value crop and makes the rotational systems more economically attractive to farmers.

Forage Crops

The fall forage mixture did not reduce the early wild oat seedling density in both trials, although they emerged earlier than wild oat and other spring crops. Other studies suggested that early vigor of winter cereals could suppress wild oat (Beres et al., 2010; Blackshaw et al., 2008; Schoofs & Entz, 2000). In our study, the suppressive effect on wild oat was probably minimized due to the fact that fall forage mixture had poor seedling establishment in trial 1. This is because crop competitive ability with weeds is reduced when crops are established at low plant density

(Beres et al., 2010; O'Donovan et al., 2005; Stougaard & Xue, 2004). In trial 2, however, the limited suppression may be related to the perpendicular sowing pattern of wild oat to crops.

Fall-seeded forages are often harvested earlier than spring-seeded forages because of their early establishment. Unintentionally, the hayed fall forage mixture treatment took place at the same time as the spring forage mixture termination in trial 1. The termination of fall forage mixture treatments was delayed in trial 2 due to the frequent precipitation.

Our findings in trial 1 agree with previous studies that early-cut forage crops can limit the number of weed seeds returning to the seedbank by impeding weed growth (Blackshaw et al., 2008; Harker et al., 2009); however, wild oat seedling regrowth and development maybe benefited under wet year conditions. Due the frequent precipitation in trial 2, the regrown wild oat tillers from haying reached the similar biomass and made as many seeds as the wild oat from the spring wheat treatments. We suggest that farmers can either lower the cutting height to 5 cm aboveground to disadvantage wild oat regrowth (Andreasen et al., 2002), or take a second cut in late fall to avoid wild oat seed dispersal if necessary.

We found lower wild oat tiller density after sheep grazing, which was responsible for substantially less biomass and seed production compared to other treatments. Moreover, the wild oat tiller density and biomass were reduced equally in the grazed spring forage mixture and tilled fallow treatments in trial 1. An exception was observed in the grazed fall forage mixture treatment in trial 1, where it was grazed two weeks earlier than other forage mixture treatments. This earlier termination allowed more time for wild oat tillers to regrow until the end of the growing season. Accordingly, the timing of forage termination appeared to be critical. Early harvest may lead to a higher weed pressure, while delayed harvest could result in over-mature forages with decreased forage nutritional quality (Miller et al., 2018). The termination window of annual forages should be determined by not only crop performance, but also weed management outcomes. Overall, our results confirm the findings from studies that livestock grazing can suppress weed growth (Hatfield et al., 2007; Sainju et al., 2011; Tracy & Davis, 2009). Although wild oat regrew and was able to form seeds after haying and grazing, those seeds may not have had enough time to reach maturity by the end of the growing season. Future research should verify this assumption by testing the viability of wild oat seeds from the regrowth.

Tilled-Fallow

Regrowth of wild oat tiller density was consistently the lowest after tilling compared with other treatments; thus, wild oat biomass and seed production were also the least. In agreement with other studies, tillage appears to be a successful strategy to manage weeds (Carr et al., 2012; Peterson & Westfall, 2004), and it is an integral component of IWM (Harker & O’Donovan, 2013). On the other hand, tilling can also facilitate the persistence of wild oat populations where the seedbank density is high (Beckie et al., 2012). Tillage alters the vertical placement of weed seeds in the soil, which affects seed survival, germinability, and emergence. In the cases where wild oat seeds are brought near to the soil surface through tilling, their mortality may increase due to predation, microbial decay, and desiccation (Anderson, 2008). Conversely, if wild oat seeds are buried in the soil, their viability would be higher than the seeds that are left on the ground surface (Gallandt et al., 2004). Wild oat seedling emergence may increase in the following years since wild oat seeds can stay dormant up to nine years in the seedbank (Beckie et al., 2012) and they are able to emerge from soil depths up to 20 cm (Gardarin et al., 2010).

Despite the effectiveness of tillage in wild oat control during fallowing, the adverse environmental effects of this practice represent major concerns (Peterson & Westfall, 2004). Implementing aggressive tillage in fallow could cause soil degradation and erosion while reducing water storage efficiency (Peterson & Westfall, 2004). Although more farmers have moved towards reduced tillage or no tillage practice in the last two decades, these practices required extensive herbicide application (Dang et al., 2020). The use of herbicides has not only put the health of non-targeted organisms (e.g., pollinators and human) at risk, but has also fostered herbicide resistant weed development (Liebman et al., 2016). Frequent use of herbicide or tillage are threatening agroecosystems.

Conclusion

In light of the growing concerns of multiple herbicide resistant wild oat, developing ecologically based weed management practices is urgently needed to reduce reliance on herbicides and impede the selection of herbicide resistance. This study strives to understand how to manipulate cropping system management practices to maximize wild oat suppression while maintaining yields.

Our results indicate that wild oat tillers are most vulnerable to mechanical damage when compared to other treatments. However, tillage should be prudently implemented to avoid the risk of excessive soil erosion. Planting fall and spring annual forage can decrease wild oat biomass and seed production, and sheep grazing of forages can further suppress the wild oat populations. Although many crop farmers do not raise sheep, they can partner with livestock producers to achieve “win-win” opportunities: saving feed costs for livestock farmers in exchange for pest control for crop farmers. The tall near-isogenic wheat line seeded at the higher seeding rate may not be sufficient to suppress wild oat as the extent of the wild oat suppression was similar to the short near-isogenic wheat line seeded at the lower seeding rate. Thus, we suggest that farmers should integrate appropriate fertilizer application and narrow row spacing to enhance spring wheat competitiveness against wild oat. Wild oat management will not succeed if practices are used as a stand-alone; therefore, integrating multiple tactics such as tillage, forage crops, and sheep grazing is necessary to reduce wild oat populations and deplete wild oat seedbank.

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CONCLUSION

Integrated Weed Management (IWM) as an ecologically based approach to reduce the reliance on off-farm synthetic inputs has been studied since the 1970s (Walker & Buchanan, 1982). However, the practice of IWM is still rarely adopted in the Northern Great Plains (Harker et al., 2016). This research contributes to the efforts in refining ecologically based weed management tools that could be integrated to reduce the spread and impact of multiple herbicide resistant wild oat biotypes in spring cereal cropping systems. We examined the use of a taller wheat canopy, increased wheat planting density, and the integration of lentil, fall and spring forage crop mixtures, haying, and sheep grazing as approaches to manage wild oat. These practices represented three essential components of IWM: enhancing crop competitiveness, increasing crop diversity, and livestock grazing.

To our knowledge, no previous studies have evaluated the potential of using tall near-isogenic lines of spring wheat in combination with higher seeding rates to suppress wild oat. We found no interaction between spring wheat height and seeding rate on wild oat biomass and seed production. Also, spring wheat height alone did not enhance the spring wheat competitive ability, as the tall and short near-isogenic lines performed similarly in competition with wild oat. Thus, we concluded that the height at maturity is not an important trait in suppressing wild oat.

Spring wheat seeded at a higher rate did not enhance its competitiveness against wild oat, in contrast to other studies (Andrew et al., 2015; Burns et al., 2018; Evans et al., 1991; Harker et al., 2009; Mohler, 2001; O’Donovan et al., 2000, 2006). Two studies we conducted in Bozeman and Moccasin, MT, showed that wild oat suppression and tolerance were similar between the low and high seeding rates when nitrogen fertilization was absent. It is possible that environmental (e.g., soil moisture and nitrogen content) and agronomic factors (row spacing and nitrogen fertilizers) not evaluated in this study played a significant role in determining the observed levels of spring wheat competitiveness. Hence, there is a need for further studies to address how to combine management variables to enhance crop competitiveness.

Our results suggest that integrating lentil, fall and spring forage mixtures, and tilled fallow in rotation with spring wheat could reduce wild oat populations. Although lentil is a worse weed competitor than spring wheat (Beckie et al., 2012; Fedoruk et al., 2011; Jha & Kumar, 2017), we observed that lentil seeded at a higher than recommended rate (215 seeds m^{-2}) resulted in a comparable wild oat suppression as the spring wheat seeded at 67 or 101 kg ha^{-1}. Furthermore, benefits of growing pulse crops (e.g., lentil, dry pea) in dryland cropping systems include improving water use efficiency (Lenssen et al., 2018; Miller et al., 2003; Gan et al., 2015) and increasing soil available nitrogen (Miller et al., 2003; Gan et al., 2015; Allen et al., 2011; Davis et al., 2012).

Growing fall and spring forage crops could lead to lower wild oat biomass and seed production due to earlier harvest than spring grain crops. Our results also showed that integrating targeted sheep grazing for forage crop termination can further reduce the regrowth of wild oat tillers, biomass, and seed production. The effectiveness of sheep grazing on wild oat suppression appeared to be similar as tillage in trial 1 of the Moccasin study. At the cropping system level, terminating forages earlier gives more time to replenish soil water (Miller et al., 2006; Miller et al., 2018; Carr et al., 2020), and mixtures of grass and legumes as forages can add value to forage quality and the subsequent crop yield (Carr et al., 2004; Entz et al., 2002; Miller et al., 2018).

Traditionally, tillage is used to manage weeds (Dang et al., 2020; Peterson & Westfall, 2004). Our results concur that tillage can successfully help farmers reduce weeds. Even though this research determined that tillage and sheep grazing can be employed to manage wild oat, their intensive use could lead to adverse environmental effects (e.g., soil erosion and compaction) (Dang et al., 2020; Peterson & Westfall, 2004).

Overall, this research elucidated the importance of understanding how management practices affect wild oat. Increasing crop diversity in rotation can hasten alternative weed management adoption without compromising crop yields and economic returns (Davis et al., 2012; Rosenzweig et al., 2018; Smith et al., 2018). Our findings could help future research to integrate strategic plans because the data could be used to construct wild oat population dynamics models under diverse cropping systems over longer periods of time. Demographic modeling can help guide weed management (Zimdahl, 2018), and identify the most vulnerable life-stage transitions of weed species (Burns et al., 2018; Davis et al., 2003; Davis & Liebman, 2003). Continuing to refine IWM tools focused on weed biology and ecology and put them into practice could bring agricultural sustainability to the community.

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APPENDICES

APPENDIX A

SUPPLEMENTAL INFORMATION FOR CHAPTER TWO

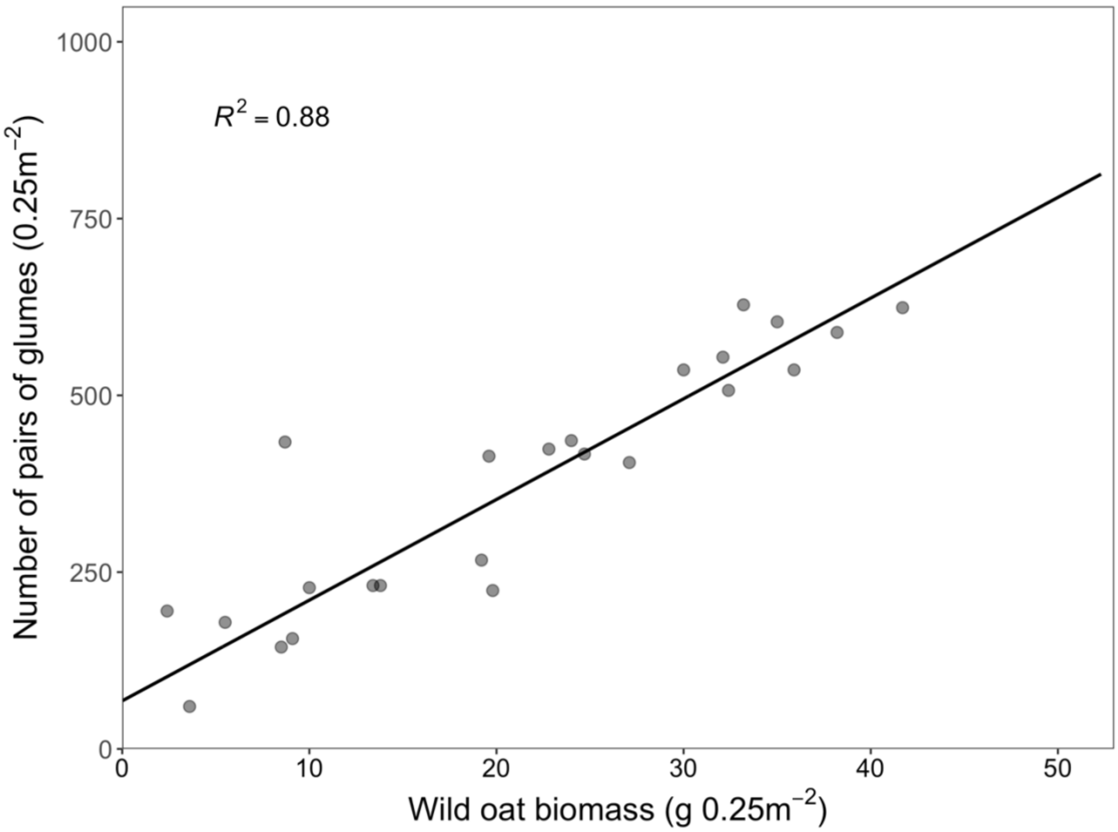

Figure A1. Relationship between wild oat biomass (g 0.25 m^{-2}) and the number of pairs of wild oat glumes (0.25 m^{-2}) across spring wheat treatments in 2019. Solid line represents the linear mixed-effects model regression line. Wild oat biomass and a random effect (plot) together explained 88% of the total variance (conditional *R*^{2}).

APPENDIX B

APPENDIX TITLE IN ALL CAPS (TRIPLE SPACE BELOW APPENDIX B)

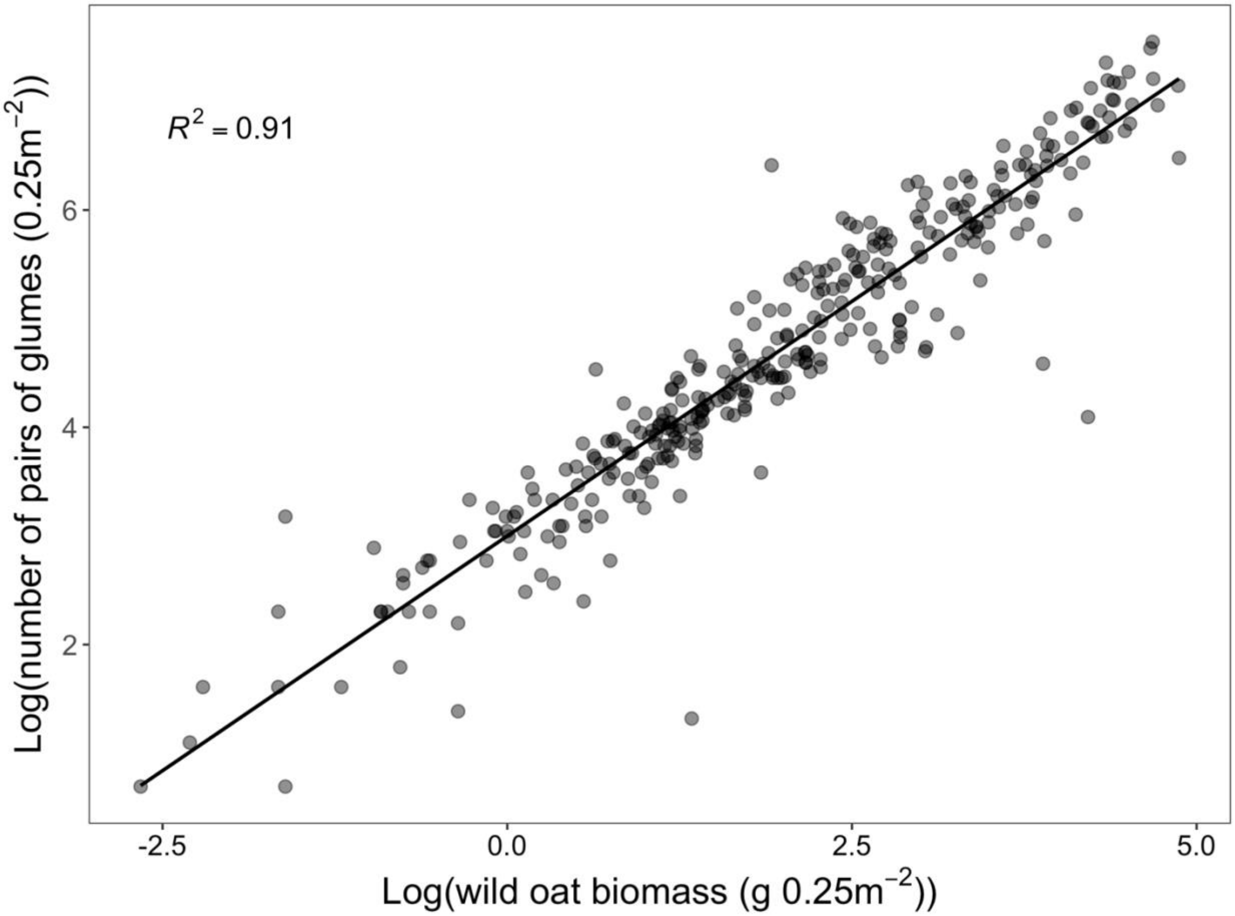

Figure B1. Relationship between wild oat biomass (g 0.25 m^{-2}) and the number of pairs of wild oat glumes (0.25 m^{-2}) across crop treatments in trials 1 and 2. Solid line represents the linear mixed-effects model regression line. Wild oat biomass and a random effect (plot) together explained 91% of the total variance (conditional R^2).

Table B1. Type III test of fixed effects of year, spring wheat height, spring wheat seeding rate, and their interactions on wild oat tiller density, biomass, and seed production under the spring wheat treatments. F values with degree of freedom (numerator, denominator) are shown and significant ($p \leq 0.05$) values are highlighted in bold.

Factor	Wild oat variables: Wild oat tiller density (tillers m^{-2})			Biomass[a] ($g\ m^{-2}$)			Seed production[a] (seeds $0.25m^{-2}$)		
	DF	F value	*p*-value	DF	F value	*p*-value	DF	F value	*p*-value
Year (Y)	1, 29.1	0.04	0.84	1, 27	13.9	**< 0.01**	1, 27	24	**< 0.01**
Height (H)	1, 28.8	0.01	0.91	1, 27	4.21	**0.05**	1, 27	2	0.17
Seeding rate (S)	1, 28.8	2.39	0.13	1, 27	0.75	0.4	1, 27	< 0.01	0.98
Wild oat tiller density	-	-	-	1, 89	178	**< 0.01**	1, 89	74.6	**< 0.01**
Y × H	1, 25.8	0.02	0.89	1, 24	0.59	0.45	1, 24	< 0.01	0.99
Y × S	1, 25.8	0.03	0.87	1, 24	0.27	0.61	1, 24	0.02	0.89
H × S	1, 25.6	< 0.01	0.95	1, 24	0.1	0.75	1, 24	< 0.01	0.94
Y × H × S	1, 24.7	0.22	0.64	1, 23	2.07	0.16	1, 23	0.84	0.37

[a] Wild oat tiller density was included as a covariate.

Table B2. Type III test of fixed effects of year, crop treatment and their interactions on wild oat tiller density, biomass, and seed production at the end of the growing seasons. F values with degree of freedom (numerator, denominator) are shown and significant ($p \leq 0.05$) values are highlighted in bold.

	Wild oat variables								
Factor	Wild oat tiller density (tillers m^{-2})			Biomass (g m^{-2})			Seed production (seeds $0.25m^{-2}$)		
	DF	F value	*p*-value	DF	F value	*p*-value	DF	F value	*p*-value
Year (Y)	1, 59.1	52.2	< **0.01**	1, 50.9	19	< **0.01**	1, 54.6	44.1	< **0.01**
Treatment (T)[a]	6, 62.6	46.3	< **0.01**	6, 61.7	21.2	< **0.01**	6, 68.7	27.9	< **0.01**
Y × T	5, 61.5	18.7	< **0.01**	5, 57.6	10.5	< **0.01**	5, 63.8	4.28	< **0.01**

[a] Data from wheat treatments were pooled across spring wheat heights and seeding rates.

Table B3. Effects of treatment on wild oat tiller density, biomass, and seed production (mean ± standard errors of the mean) at the end of the growing seasons in 2018 (trial 1) and 2019 (trial 2). Different letters are significantly different among years ($\alpha \leq 0.05$, Tukey-adjusted).

Factor	Wild oat variables					
	Wild oat density (tillers m^{-2})		Biomass (g m^{-2})		Seed production (seeds 0.25 m^{-2})	
	2018	2019	2018	2019	2018	2019
Treatment						
Spring wheat[a]	81 ± 12a	80 ± 7.5a	62 ± 11a	82 ± 10.4ab	433 ± 78a	730 ± 97a
Lentil	-	82 ± 15a	-	119 ± 29a	-	1088 ± 280a
Grazed fall forage	111 ± 34a	35 ± 6.6b	120 ± 38b	5 ± 1.4d	357 ± 129ab	101 ± 26c
Hayed fall forage	44 ± 13a	111 ± 34a	14 ± 4.6a	34 ± 8.5bc	98 ± 35bc	674 ± 173ab
Grazed spring forage	7 ± 2.2b	57 ± 11ab	2 ± 0.8c	20 ± 5c	25 ± 9.2c	261 ± 67bc
Hayed spring forage	33 ± 10a	110 ± 21a	14 ± 4.7b	40 ± 10bc	109 ± 39b	728 ± 187ab
Tilled-fallow	3 ± 0.9b	1 ± 0.3c	1 ± 0.5c	0.2 ± 0.3e	3 ± 1.2d	1 ± 0.3d

[a] Data were pooled across spring wheat heights and seeding rates.

Table B4. Type III test of fixed effects of year, spring wheat height, spring wheat seeding rate, and their interactions on spring wheat tiller density, biomass, and grain yield under weed-free conditions. F values with degree of freedom (numerator, denominator) are shown and significant ($p \leq 0.05$) values are highlighted in bold.

	Spring wheat variables								
Factor	Wheat tiller density (tillers m^{-2})			Biomass (g m^{-2})			Grain yield (kg ha^{-1})		
	DF	F value	*p*-value	DF	F value	*p*-value	DF	F value	*p*-value
Year (Y)	1, 24.6	3.96	0.06	1, 27	43	**< 0.01**	1, 29	< 0.01	0.98
Height (H)	1, 21.3	1.35	0.26	1, 26.3	0.44	0.51	1, 28.5	0.04	0.85
Seeding rate (S)	1, 21.3	29	**< 0.01**	1, 26.3	0.27	0.61	1, 28.5	0.22	0.64
Y × H	1, 21.2	3.17	0.09	1, 24.1	0.01	0.91	1, 25.9	0.03	0.88
Y × S	1, 21.2	2.53	0.13	1, 24.1	< 0.01	0.97	1, 25.9	0.59	0.45
H × S	1, 17.7	0.03	0.86	1, 23.6	0.82	0.38	1, 25.5	1.86	0.18
Y × H × S	1, 20.2	1.21	0.29	1, 23.2	< 0.01	0.93	1, 25	< 0.01	0.93