NON-CHEMICAL WEED MANAGEMENT IN ANNUAL AND PERENNIAL ORGANIC CROPPING SYSTEMS

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MASTER OF SCIENCE

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ABSTRACT

Weedy pests, especially perennial weeds, are among the most challenging barriers to organic crop production. Improving non-chemical weed management tactics for established organic productions systems, like cool-season grains, and emerging crops like perennial flax could benefit producers. We compared three crop sequences for creeping perennial weed suppression in organic grains. Three years of alfalfa was associated with reduced densities and aboveground biomass of perennial weeds compared to sequences that alternated grain and cover crops. Interseeding cover crops with perennial flax for weed management was attempted, but neither flax nor cover established well. Flame weeding and cultivation in perennial flax were assessed in response to the failure of these cover crops. Greenhouse trial results suggested flaming could eliminate weeds without damaging shallowly planted flax seed, but emerged flax seedlings suffered greater mortality. Massive perennial flax mortality in subsequent field trials suggested flaming is a risky weed management tactic for the crop.

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CHAPTER 1: REVIEW OF LITERATURE

Introduction

The Northern Great Plains (NGP) is a key region for cool-season grain production in the United States. The NGP is known for productive farmland and convenient proximity to market centers. A few of the greatest challenges that both organic and conventional producers face in the NGP are creeping perennial weeds, droughts, persistent wet periods, and temperature extremes (Padbury et al., 2002). Improving approaches to cope with these obstacles is critical to continue the development of sustainable agriculture in the NGP region.

Despite advances in annual weed management, organic producers continue to struggle with creeping perennial weeds (Favrelière et al., 2020; Lukashyk et al., 2007; Orloff et al., 2017). Canada thistle (*Cirsium arvense* L. Scop.) and field bindweed (*Convolvulus arvensis* L.) are recognized as two of the most problematic perennial weed species in organic grain cropping systems (Hodges, 2003; Lukashyk et al., 2007; Tautges et al., 2016). Limited research is available regarding suppression of these perennial weed species in NGP organic grain production systems. Refining perennial weed suppression methodologies, such as diversifying crop sequences, could benefit organic producers throughout the NGP.

Seasonal soil moisture content extremes complicate agricultural operations by impeding producers' ability to operate heavy equipment in the field, often preventing timely field operations such as seedbed preparation, planting, and cultivation. NGP producers struggle considerably with these conditions, which are compounded by dynamic droughts and persistent wet periods (Padbury et al., 2002). Incorporating perennial crops into crop rotations may help address some of these problems.

Perennial crops may mitigate soil moisture issues by improving water infiltration, water storage, reducing surface run-off, and utilizing excess spring precipitation (Crews et al., 2018; Glover & Reganold, 2010). Perennial crops also offer operational flexibility, as such crops do not require yearly planting and soil preparation once established (DeHaan et al., 2020). Mutualistic relationships with arbuscular mycorrhizal fungi in the soil often formed by longer lived species like perennial crops may further benefit producers by improving crop nutrient uptake, thereby enhancing sustainability compared to annual crops (Baker, 2017). Greater carbon sequestration by perennial crops compared to annual crops may also allow farmers to capitalize on carbon trading markets in the near future (Baker, 2017; Glover & Reganold, 2010; McKenna et al., 2020).

Similar to annual flax (*Linum usitatissimum* L.), perennial Lewis flax (*Linum lewisii* Pursh) is a potential candidate as an oilseed crop suitable for NGP environmental conditions and cropping systems (Johnston et al., 2002). Flax is often grown on the same land that produces productive wheat stands, and can quickly mature in the cool, short growing season of the NGP (Ehrensing, 2008; Kandel & Keene, 2020). Further research is required to assess the agronomic, environmental, and economic benefits of Lewis flax for the NGP. Non-chemical weed management tactics for Lewis flax should be investigated, as no herbicides are labeled for use in perennial flax, herbicide costs are rising, and consumers are increasingly concerned about potential human health impacts of herbicides (Crews et al., 2018; Pimental et al., 2005; Van der Weide et al., 2008). Demonstrating effective weed management in Lewis flax through multiple methods could help producers design improved integrated weed management plans for the crop.

Perennial Weeds in Organic Systems

Consumer preference for environmentally conscious commodity production and the existence of lucrative niche markets are driving the growth of organic agricultural production (Dmitri & Baron, 2020; Greene et al., 2017; McErlich & Boydston, 2013; Pimental et al., 2005). The organic agriculture industry in the United States is rapidly expanding, surpassing $63 billion in sales between 2020 and 2021 (Organic Trade Association, 2022). Despite this promising outlook, weedy pests can cause 20% yield loss in organic systems compared to 10% in conventional counterparts (Chauhan, 2020; Kniss et al., 2016). Limited access to synthetic herbicides hinders organic producers' ability to combat weeds, while simultaneous advances in conventional pest management continue to widen the yield gap between the systems (de Ponti et al., 2012; Kniss et al., 2016).

Diverse crop sequencing in organic systems as part of an integrated weed management (IWM) program may be an effective way to combat perennial weeds. Multiple authors state that further research addressing IWM tactics with a focus on perennial weed suppression should be conducted (Favrelière et al., 2020; Meiss et al., 2010; Orloff et al., 2017; Tautges et al., 2016). Further research into the benefit of diverse crop sequencing as an IWM tactic could prove beneficial for organic producers (Bastiaans et al., 2008).

Perennial Weeds

Two perennial weed species identified as major limiters of organic crops are Canada thistle (*Cirsium arvense* L. Scop.) and field bindweed (*Convolvulus arvensis* L.) (Orloff et al., 2017; Tautges et al., 2016). Vegetative organs of these perennial weeds can survive harsh conditions and store considerable energy for generating new roots and shoots. Resilience of and vegetative spread by perennial weeds can lead to their persistence in agricultural systems

(Håkansson, 1982; Hodges, 2003; Lukashyk et al., 2007). For example, uncontrolled infestations of field bindweed can spread rapidly, adding an estimated 4-11 tons/ha of root mass per year (Hodges, 2003).

The presence of Canada thistle and field bindweed can reduce crop yields. Densities as low as 10 Canada thistle shoots m^{-2} can result in 10% yield loss in spring wheat (Donald & Khan, 1992). Yield further decreases as Canada thistle density increases (Donald & Khan, 1992; O'Sullivan et al., 1982). Similar yield impacts have been reported with field bindweed; yield declines in wheat (*Triticum aestivum* L.), pea (*Pisum sativum* L.), and barley (*Hordeum vulgare* L.) of 16%, 69% and 31%, respectively, resulted at 30 shoots m^{-2}, with further decreases at greater bindweed density (Black et al., 1994). Canada thistle may also impact grain crops through the release of allelopathic phytotoxins. Tissue extracts of Canada thistle have been reported to hinder germination and growth of crops and other weeds (Tiley, 2010). Without effective management, perennial weeds such as Canada thistle and field bindweed may spread and persist for several years (Favrelière et al., 2020; Håkansson, 1982).

Mechanical Management of Perennial Weeds

Tillage is among the most prevalent direct methods for perennial weed management in organic systems (McErlich & Boydston, 2013; Turner et al., 2007). Tillage weed control efficacy is determined by the ability of implements to bury, dismember, and/or uproot weeds. Consequently, weed control efficacy by tillage varies by implement type, biology of target species, and application timing (Melander et al., 2012; Mohler, 2001). Creeping perennial weeds are more susceptible to tillage actions that frequently sever roots and fragment rhizomatic structures (Mohler, 2001). Moldboard plows are best at uprooting weeds due to soil inversion, but do not effectively fragment weed subsurface rhizomatic structures without extensive repetition (Brandsæter et al., 2020; Mohler, 2001). Large soil clods containing intact weeds often remain after moldboard plowing, requiring sequential discing or harrowing for maximum fragmentation of perennial roots (Mohler, 2001). Selecting an implement with wide chisel sweeps can effectively sever creeping perennial vegetative organs while reducing soil structure damage (Hodges, 2003; Mohler, 2001).

Perennial weeds are most susceptible to mechanical control when they are in the cotyledon stage or initiating growth of new tillers, rhizomes, and reproductive organs (Hodges, 2003; Mohler, 2001). Perennating organs reach a critical minimum mass in the spring when new growth initiates, leaving them susceptible to damage at this time (Mohler, 2001). Canada thistle in particular is most prone to tillage when it is utilizing energy reserves to develop reproductive structures (Lukashyk et al., 2007). When Canada thistle begins flowering, carbohydrate reserves in its roots are reduced, creating an optimum window for tillage (Lukashyk et al., 2007).

Frequency is the most critical aspect when using tillage alone to manage perennial weeds. Hodgson (1958) found that Canada thistle can be up to 99% eliminated when cultivated every 21 days throughout the growing season. More recently, Mohler et al. (2021) suggested that repeated cultivations and dense planting of cereal grains can reduce Canada thistle density. Similar work conducted by Nikurunziza and Streibig (2011) found that destroying above-ground vegetative structure of Canada thistle every 500-600 growing degree days °C can further deplete carbohydrate stores and prevent population increase. Field bindweed must also be cultivated frequently to prevent infestation. Hodges (2003) concluded that cultivating field bindweed every 2-3 weeks can help reduce its presence.

When conducted improperly, tillage regimes can contribute to the proliferation of creeping perennials, as they can multiply vegetatively when roots are severed at the wrong time or frequency (Gruber & Claupein, 2009; Liebman & Dyck, 1993). Although regular tillage can suppress or even eradicate perennial weeds, it can also negatively affect soil health because of the high frequency and intensity of disturbance required for control (Brandsæter et al., 2020; Mohler, 2001; Orloff et al., 2017). Excessive tillage can reduce soil aggregate stability, water infiltration, and erosion resistance (Karlen et al., 1994; Liebig et al., 2004). Melander et al. (2016) also noted that in organic systems with cover crops, successfully timing cultivation of perennial weeds like Canada thistle can be extremely difficult as they go dormant before post-harvest cultivation. Given these risks, organic producers should not rely solely on tillage for creeping perennial weed suppression. A sustainable organic weed management plan for reducing creeping perennial weeds should combine tillage with other tactics (Brandsæter et al., 2020).

Crop Sequencing for Perennial Weed Management

Incorporating strategic crop sequencing into an integrated weed management plan can help reduce the density of problem weeds through greater diversity of crop-weed competitive interactions (Clements et al., 1994). Weed suppression by crop sequencing is further enhanced when selected crops vary in phenology, resource competition, allelopathic interaction, and management related disturbance regimes (du Croix Sissons et al., 2000; Liebman & Dyck, 1993). Diverse cropping sequences also provide opportunities to apply multiple forms of mechanical management such as tillage, mowing, or haying. This variation in crop management applies multiple stresses to the weed community, thus increasing mortality risk and altering the timing of weed germination cues (Liebman & Staver, 2001).

Organic producers often include a multi-year alfalfa (*Medicago sativa* L.) crop phase in crop rotations to combat perennial weeds. Alfalfa is effective because it is highly competitive and is frequently disturbed by cutting intervals for haying (Ominski et al., 1999). Cutting alfalfa or similarly managed cover crops is particularly effective for depleting energy reserves of perennial weeds like Canada thistle and field bindweed (Anderson, 2015; Derscheid, 1961; Hodges, 2003; Melander et al., 2016; Tautges et al., 2015). When vegetative shoots of creeping rhizomatic perennial weeds are dismembered by cutting, carbohydrate reserves are used for regeneration, thereby reducing their persistence over time (Graglia et al., 2006). Alfalfa recovers from cutting faster than many weed species, outcompeting them for light resources (Meiss et al., 2010; Tiley, 2010). The aggressive resource competition and regeneration by alfalfa is noted to be especially effective for field bindweed suppression and may be further enhanced by exudation of allelopathic compounds (Hodges, 2003; Khanh et al., 2004; Stahler, 1948). An additional benefit of alfalfa is its ability to build soil fertility through nitrogen fixation (Harris & Hesterman, 1990). Nitrogen fixation occurs through a symbiotic relationship between rhizobia bacteria and legumes like alfalfa. Rhizobia bacteria convert atmospheric N_2 into NH_3, which is subsequently converted to plant usable NO_3 by soil bacteria (Flynn & Idowu, 2015). However, fixed nitrogen from alfalfa is often not sufficient for subsequent crops, especially when biomass is removed from the field as hay (Tautges et al., 2018). Incorporating alfalfa residues into the soil may improve soil nitrogen content (Flynn & Idowu, 2015).

Including alfalfa in an organic cropping sequence presents several management challenges. Establishing alfalfa in fields with perennial weed issues may be difficult and can potentially lead to reduced yields and hay quality (Fuerst et al., 2009). Producers in dryland systems can also typically expect a net economic loss during the first year of growing alfalfa (Fuerst et al., 2009). Excessive water use by alfalfa can cause yield depression in subsequent cash crop sequences in drought prone regions like the NGP (Austenson et al., 1970; Blanco-Canqui et al., 2015; Bourgault et al., 2022; Carr et al., 2011; Entz et al., 2002). Furthermore, alfalfa phases tend to extend beyond their opportune time for termination and economic returns (Mohr et al., 1999). Alfalfa termination becomes increasingly difficult the longer the crop is in place, eventually requiring extremely aggressive tillage to terminate stands organically (Bullied & Entz, 1999; Mohr et al., 1999). Although alfalfa can reduce the vigor of perennial weeds, it is noted to cause an overall shift from annual to perennial and biennial weed dominated systems due to a lack of soil disturbance associated with managing the crop (Bàrberi et al., 2002; Meiss et al., 2010; Melander et al., 2016). Cover crop monocultures that fix nitrogen may also promote increases in perennial weed biomass compared to cover crop mixtures, while simultaneously not supplying enough nitrogen for subsequent crops (Melander et al., 2016; Tautges et al., 2018).

Perhaps the most significant alfalfa related management challenge in an organic system is stand termination. Alfalfa is a persistent, deep-rooting perennial crop that can be difficult to terminate without access to herbicides. Organic producers must rely on intensive tillage to terminate alfalfa, risking soil erosion, loss of stored soil moisture, loss of soil organic carbon, increased CO_2 emissions, and encouragement of annual weed germination (Entz, 2002; Ledo et al., 2020; Mohr et al., 1999; Fuerst et al., 2009; Toderi et al., 2021). Small-seeded annual weeds such as green foxtail (*Setaria viridis* (L.) P. Beauv.) and redroot pigweed (*Amaranthus retroflexus* L.) may increase following alfalfa stand termination by tillage, as consequent soil disturbance increases weed seed recruitment and creates favorable micro-topographies for germination (du Croix Sissons et al., 2000; Ominski & Entz, 2001). Research by Moyer et al. (2003) supports this idea, as they found that redroot pigweed densities were higher following alfalfa in conventional tillage vs. no-till. Furthermore, tillage can be an expensive endeavor for producers at approximately $12-$24 per acre, often requiring multiple passes with various implements (Malhi et al., 2007; Plastina & Johanns, 2019). Carr et al. (2005) compared wheat yields following several forage legumes and found that yield after alfalfa was 1248 kg ha^{-1} versus wheat that followed sweet clover, which yielded 4102 kg ha^{-1}. The impact to wheat yield noted by Carr et al. (2005) demonstrates the need to thoroughly terminate alfalfa stands. Depleted stands of alfalfa can also be difficult to re-sow with more alfalfa due to disease risk and autotoxicity (Tesar, 1993). Alfalfa releases intraspecific allelochemicals that prevent germination of new alfalfa plants, thereby necessitating rotation into a different crop after 2-3 years (Seguin et al., 2002). The limitations of alfalfa suggest a need to explore alternative options for perennial weed suppressing crop rotations.

Diversifying Cover Crops and Crop Sequencing

Cover crop mixtures containing different functional groups of crops in sequences may be an alternative to forage monocultures like alfalfa, potentially increasing profitability, soil physical quality, and weed suppression benefits (McCollough et al., 2020; Weisberger et al., 2019; Williams et al., 2017). Enhancing rotation diversity could improve economic outcomes for producers by reducing input costs, improving land productivity, and creating opportunities to include high value crops (Anderson, 1999; Anderson, 2005; Zentner, et al., 2002). Capitalizing on crop phenological variation can lead to positive weed management outcomes. Sequencing two cool season crops followed by two warm season crops or crops with varying planting dates can disrupt crop-weed competitive interference (Anderson, 2015; Nichols et al., 2015). Switching between different crop types in a long-term rotation can increase weed-weed competition as each crop type (i.e., warm vs. cool season, or summer annual vs. winter annual) favors a different weed community (Garrison et al., 2014). Finney and Kaye (2016) found that as cover crop diversity increased to include a greater variety of plant functional groups, weed suppression, soil nitrogen retention, and crop biomass improved. A meta-analysis by Weisberger et al. (2019)

found that diverse crop rotations greatly reduced weed pressure compared to simple rotations. The authors found that between diverse and simple systems, more diverse systems were associated with significantly better weed control, reducing weed density by 49% on average. This meta-analysis also suggested that more diverse crop rotations are best for reducing weed establishment. Diversifying rotations can be an important foundation for creating a holistic Integrated Weed Management (IWM) plan that incorporates several approaches to weed suppression (Weisberger et al., 2019).

Perennial Crops

Intensively managed annual grain cropping systems have become dominant in modern agriculture, spanning 70% of global cropland (DeHaan & Ismail, 2017; Glover & Reganold, 2010; Vico & Brunsell, 2017). The popularity of annual systems may be due to their typically higher yields and economic flexibility (Glover & Reganold, 2010; Kantar et al., 2016). Although annual cropping systems are crucial for meeting global food demand, they have been associated with reduced ecosystem services compared to perennial systems (Asbjornsen et al., 2013). Fisher et al. (2009) have defined ecosystem services as "…aspects of ecosystems utilized (actively or passively) to produce human well-being". Indeed, annual systems do provide some ecosystem services, including pollinator support, soil stabilization, and soil fertility regulation, but can lack long term sustainability due to the greater need for external inputs and management (Power, 2010; Tilman et al., 2002; Zhang et al., 2007).

Ecosystem disservices associated with annual systems include increased erosion risk, reduced soil nitrogen and carbon stores, reduced water quality, non-target insect mortality, and potential damage to soil microbial communities (Culman et al., 2010; Glover & Reganold, 2010; Hart & Trevors, 2005; Pinto et al., 2021; Tilman et al., 2002; Zhang et al., 2007). Cropping systems centered on annual production are also a driver of global climate change. These systems produce around 11% of the world's greenhouse gas emissions, despite the carbon sequestering potential of agricultural land (Hunter et al., 2017; Ledo et al., 2020; Schipanski et al., 2016; United States Environmental Protection Agency [EPA], 2020). Adapting agriculture to include multifunctional systems that both maintain yields and deliver valuable ecosystem services is a critical challenge for long term sustainability (Asbjornsen et al., 2013; Glover et al., 2010).

Perennial grain systems offer a potential solution to improving agroecosystem sustainability by simultaneously meeting conservation, ecosystem service provisioning, and commodity production goals (Baker, 2017; Glover et al., 2010a; Glover et al., 2010b; Pinto et al., 2021; Ryan et al., 2018). The basis of benefits associated with perennial crops is their long-lived, deep rooting nature (Baker, 2017; Glover et al., 2010b; Kantar et al., 2016; Vico et al., 2018). Perennials allocate more carbon to their root structures, potentially generating greater root biomass than annual crops. Kantar et al. (2016) reported that perennials can produce up to 10 Mg ha^{-1} of root biomass compared to 6 Mg ha^{-1} produced by annual crops. Greater production of root biomass in perennials benefit soils by improving aggregate stability, reducing erosion risk, increasing soil organic matter, and forming mutualistic relationships with arbuscular mycorrhizal fungi (Baker, 2017; Crews et al., 2018; DeHaan & Ismail, 2017; Ledo et al., 2020). Water resources can benefit from perennial cropping systems as well. Perennials emerge earlier in the spring than many annual grain crops, protecting soil during the time of the year when the majority of precipitation and fertilizer addition occurs (Kantar et al., 2016). This results in reduced sediment and nutrient loading into streams from field runoff, lessening the impact of agricultural lands on aquatic ecosystems (Asbjornsen et al., 2013; DeHaan & Ismail, 2017; Glover et al., 2010b).

Incorporating perennial crops into an agricultural production system may have several benefits for producers. Perennials offer stability, as their deep root systems allow them to be more tolerant of environmental disruptions like droughts (Glover & Reganold, 2010; Marquardt et al., 2016; Vico & Brunsell, 2017). Spring regrowth is typically more vigorous in perennials as well, allowing these plants to take advantage of more light and water resources throughout the growing season (Cox et al., 2006; DeHaan & Ismail, 2017; Kantar et al., 2016). Perennials are more efficient utilizers of nutrients than annuals, potentially saving input expenses for producers (Cox et al., 2006; Vico & Brunsell, 2017; DeHaan et al., 2020). Producers could also save time by growing perennials, as these crops would not have to be replanted each spring (DeHaan et al., 2020; Ryan et al., 2018). The use of perennial grains in cropping systems could be tailored to the management needs of producers. Perennial crops can be intercropped with annual grain or legume crops to provide greater productivity and yields per unit area (Mckenna et al., 2020; Ryan et al., 2018). Sediment and nutrient loss from agricultural fields can be reduced by planting perennial crops as long-lived buffer crops on marginal or sloped lands (Ryan et al., 2018; Tork et al., 2019). Vegetative biomass of perennial crops can also be utilized as forage, feed, biofuel, mulch or bedding after harvest, thereby providing a secondary revenue stream that may compensate for lower yields (Lanker et al., 2019; Ryan et al., 2018).

Despite the many benefits of perennial crops, several barriers to widespread adoption exist. Perennial grain crops are relatively novel and need to be further developed to producer similar yields to their annual counterparts (Pugliese et al., 2019; Ryan et al., 2018). Given the novel nature of many perennial grain crops, access to herbicides labeled for weed management are scant, and many producers may face excessive weed pressure when establishing stands (Lanker et al., 2020). Developing weed management tactics for perennial crops should also be investigated to facilitate their utilization (Marquardt et al., 2016). Producers must also have confidence that perennial grains can be marketed and have access to information regarding the value of these commodities (Marquardt et al., 2016). Addressing these management and economic issues could greatly bolster the adoption of perennial grain and oilseed crops.

Lewis Flax

Lewis flax (*Linum lewisii* Pursh) is a potential perennial oilseed crop that may be adapted to the variable climate of the U.S. NGP. Lewis flax is native to North America, occurring in the United States from California to eastern Minnesota in a variety of habitats (Ogle et al., 2006). Like other perennial crops, Lewis flax may be a beneficial alternative to annual crops due to it’s deeper root systems and ecosystem service provisioning (Baker, 2017; Brown et al., 2012; Tork et al., 2019). Lewis flax is also noted to form mutualistic relationships with arbuscular mycorrhizal fungi (AMF). Analyses of native plant species’ associations with AMF by Jordan et al. (2012) found that Lewis flax root rhizosphere samples had greater AMF species richness than several other species. These relationships with AMF may improve the ability of Lewis flax to take up essential nutrients like phosphorus and nitrogen (Baker, 2017). Improved nutrient uptake from AMF relationships are due to extensive hyphal networks that act as an extension of the root system, increasing its reach and absorptive area (Hart & Trevors, 2005).

Marketability

Flax provides the opportunity to market food, feed, and fiber. Over 2.6 million ha are sown with flax worldwide (Singh et al., 2011). The prairies of Canada and the NGP comprise an important region for flax production (Dean, 2003; Kandel & Keene 2020; Singh et al., 2011).The health benefits of omega-3 fatty acids in annual flaxseed oil have been well-documented, and perennial Lewis flax seed contains the same omega-3 rich oil as annual cultivated flax varieties

(Singh et al., 2011; Tork et al., 2019; Innes et al., 2022). Large corporations and small-scale bakeries alike have expressed interest in using perennial crops for their products to meet sustainability goals (Baker, 2017; Lanker et al., 2019). For example, Kernza©, a perennial variety of intermediate wheatgrass (*Thinopyrum intermedium* Barkworth & D.R. Dewey), has been used for brewing beer by Patagonia Provisions and making cereal by General Mills (Lanker et al., 2019). Perennial flax could have a similar appeal to food processing companies, potentially boosting its market value.

Perennial flax seed could also be used for animal feeds. Flax based feeds are reported to improve the quality and market value of eggs and meat (Kandel and Keene 2020; Scheideler, 2003; Singh et al., 2011). Flaxseed based feeds are also a good option to supplement the diets of cattle grazing native pasture (Scholljegerdes & Kronberg, 2007).

Lewis Flax Establishment and Management

Limited information exists about managing weeds in organic flax crops (Wiedenhoeft et al., 2007). Annual flax is known to be weakly competitive against weeds, necessitating the use of integrated weed management approaches in the crop (Flax Council of Canada, 2022). Additional research is needed to understand how to establish Lewis flax, and approach the challenge of weed management.

Lewis flax is a perennial subshrub that is a larger plant than annual flax (*Linum usitatissimum* L.) when mature, having several branches that originate from a woody base (Ogle et al., 2006; Reeves, 2006). Producers may need to use different seeding rates and spacings when cultivating Lewis flax versus annual flax due to these physiological differences. Furthermore, Lewis flax may establish best when seeded in late fall, whereas annual flax in North Dakota is typically planted in late April or early May (Kandel & Keene, 2020; Ogle et al., 2006; Reeves, 2006). Defining best practices (e.g., planting timing, seeding rate, and row spacing) for establishing perennial flax is crucial to facilitate its adoption in the NGP.

Like annual flax, Lewis flax is likely a weak competitor against weeds, and both seed quality and yield may suffer under weed pressure (Bilalis et al., 2012; Ehrensing, 2008; Flax Council of Canada, 2022; McCollough et al., 2020). A meta-analysis of organic-conventional yield gaps by de Ponti et al. (2012) found that organic flax yields are on average only 65% of typical conventional yield. Lewis flax may struggle even more to compete against weeds during the establishment year than annual flax, as it requires up to 30 days to germinate, providing annual weeds a substantial time advantage for establishing (Reeves, 2006). Annual flax growers can compensate for weak flax competition with herbicides, but none are currently labeled for use in perennial flax. Organic production systems would likely require frequent weed control to aid in the establishment of Lewis flax. Once established, Lewis flax would occupy a large space as it has several branches that can reach up to 75 cm in height (Addicott, 1977; Reeves, 2006). This shrub-like nature may help Lewis flax outcompete weeds for light resources, but weed management will likely still be necessary to establish and maintain strong stands.

Flame Weeding Potential in Perennial Flax

Flame weeding or flaming is the process of heating, but not burning, plant tissues to disrupt cell function (Leroux et al., 2001; Stepanovic et al., 2016a). Plants are destroyed by flame weeding when temperatures of 55°C or higher cause cell membranes rupture (Bajwa et al., 2015). The leaf tissue of many weed species can be destroyed by flame exposure times as short as 0.065 to 0.13 seconds (Ascard, 1998). Flame weeding is non-selective, making it a good pre-emergence weed control method (Steponovic et al., 2016a). Ideal application of flame weeding occurs when weeds are just emerging, as older plants are less thermally sensitive due to their thicker cuticles and greater regrowth potential (Ascard, 1994; Baker & Mohler, 2015). Plants with thinner leaves and unprotected growing points are generally more easily killed by flame weeding. Grasses such as annual bluegrass (*Poa annua* L.) are more resistant to flaming because their meristems lie close to the soil surface and are thus protected from heating (Ascard, 1995). Although flame weeding does not always provide complete control for grassy weed species, it can set back their development and provide a competitive edge for crops (Knezevic & Ulloa, 2007). In the field, applicators can tailor flame weeding to their needs by adjusting dosage and utilizing physical thermal shielding. Flame weeding doses are often reported in kg propane/ha as a function of application speed and pressure. Broadleaf weeds are typically susceptible to doses of approximately 50 kg/ha, whereas grasses usually require higher doses of around 180 kg/ha (Knezevic & Ulloa, 2007). Physical shielding, which is typically part of the flaming implement, can be used once crops are emerged to provide more targeted inter-row weed control (Bond & Grundy, 2001).

Organic producers can utilize flaming as part of an integrated plan to reduce tillage, which often does not remove in-row weeds and produces deleterious effects on soil health (Knezevic, 2017; Stepanovic et al., 2016). Flaming provides further flexibility for producers as it can be conducted when soil is too wet for tillage (Bond & Grundy, 2001). Flame weeding has been shown to be an effective part of an integrated weed management plan in corn (*Zea mays* L.), sorghum (*Sorghum bicolor* (L.) Moench.), soybean (*Glycine max*), and sunflower (*Helianthus annuus* L.) when applied at intervals that minimize risk of injury to crops (Knezevic, 2017). Farmer surveys have indicated interest in research demonstrating the use of flame weeding in additional agronomic crops (Baker & Mohler, 2014). No previous research documenting the use of flame weeding in Lewis flax stands exists. Determining safe use intervals and dosages for flaming in Lewis flax would help producers develop integrated weed management plans for the crop. However, selection pressure from weed management techniques often shift weed community composition (Zimbric et al., 2019). Therefore, documenting weed communities in Lewis flax stands and their response to flame weeding would also provide useful information for producers.

We identified flame weeding as a potentially effective weed control method for perennial Lewis flax stands. Wild Lewis flax has been reported to not easily burn in wildfires, and quickly reestablishes after high intensity fires. The foliage of Lewis flax may perish in fire, but the plant readily sprouts from its caudex (Reeves, 2006). The fire-resistant nature of Lewis flax suggests that flame weeding applications could potentially be conducted in stands both inter and intra-row.

Due to the novelty of cultivating Lewis flax in a traditional agricultural context, we approached the task of creating an IWM plan through the lens of adaptive management. We evaluated the efficacy of tillage, competitive intercrops, and thermal weed control to begin creating an integrated weed management plan for perennial flax. Fall and spring cultivation with herbicide application during the growing season is typically used for weed management in annual flax, while organic flax systems may rely on more aggressive mechanical weeding through use of tine-harrows (Kandel and Keene, 2020; McCollough et al., 2020) Combining various weed management tactics may help negate the limitations of cultivation alone such as limited operability in wet soil (McCollough et al., 2020). Interseeding cover crops with flax has also been noted to reduce weed pressure by increasing resource competition (Sánchez Vallduví & Sarandón, 2011). Thermal weed control (i.e., propane flaming) results in less soil disturbance and annual weed emergence stimulation than inter-row tillage, and thus may also be an effective tactic for weed control in Lewis flax stands (Stepanovic et al., 2015; Knezevic, 2017). Timing and intensity of flame application must be tested to prove its efficacy for weed management while minimizing crop damage. Demonstrating effective non-chemical weed management through flame weeding in Lewis flax could provide benefit for producers, especially considering the projected growth in popularity of perennial crops due to the recognition of their associated ecosystem services (Ryan et al., 2018).

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CHAPTER 2: DIVERSIFIED CROP SEQUENCING FOR SUPPRESSION OF CREEPING PERENNIAL WEEDS IN ORGANIC SYSTEMS

Abstract

Multi-year cropping sequences of alfalfa are typically utilized by organic producers to suppress perennial weed growth. Although this approach is often effective, producers in the precipitation-limited Northern Great Plains (NGP) of the United States may benefit from alternative crop sequences that provide market flexibility and reduce risks to soil moisture depletion and stability. We compared the perennial weed suppressive ability of three cropping sequences: (i) three years of alfalfa (ALF), (ii) lentil/sweet clover + hard red spring wheat (HRSW)/sweet clover (LENCL), and (iii) alternating years of a nine species polyculture and HRSW (CCPLY). Consistently lower mean densities of perennial weeds were associated with ALF compared to LENCL and CCPLY. Mean biomass production of Canada thistle and perennial sow thistle was greatest in LENCL versus ALF and CCPLY. Greatest mean densities of field bindweed biomass were associated with CCPLY. The highly competitive nature and associated management regimes of alfalfa make it especially effective for weed management. The ease of managing single species cover crops over polycultures also makes alfalfa a superior choice for perennial weed suppression in many situations. Despite some of the drawbacks to cultivating alfalfa in the NGP, it remains among the most viable management options for creeping perennial weed suppression in organic systems.

Introduction

Perennial weeds Canada thistle (*Cirsium arvense* L. Scop.) and field bindweed (*Convolvulus arvensis* L.) have long been considered among the worst pests in organic agricultural systems due to their resilience, rapid proliferation, and detrimental impact to yields

(Favrelière et al., 2020; Kniss et al., 2016; Orloff et al., 2018; Ringselle et al., 2021; Tautges et al., 2016). The extensive subsurface rhizomatous structures of these species store considerable amounts of energy as carbohydrates, allowing them to resist many organic management actions and environmental disturbances (Håkansson, 1982; Ringselle et al., 2021). Without intervention, these rhizomatous structures rapidly spread, adding 4-11 tons ha^{-1} of root mass per year, and potentially generating numerous new aerial shoots and buds (Håkansson, 1982; Hodges, 2003; Lukashyk et al., 2007; Mohler, 2001; Mohler et al., 2021; Ringselle et al., 2021). The tendency for these weeds to spread throughout croplands has led to their designation as “wandering” or “creeping” perennials (Håkansson, 1982). Ultimately, infestations of creeping perennial weeds can result in substantial grain yield losses. Densities as low as 10 Canada thistle shoots m^{-2} can result in 10% yield loss in spring wheat (Donald & Khan, 1992). Yields can further decline as Canada thistle density increases (Donald & Khan, 1992; O’Sullivan et al., 1985). Similar yield impacts have been reported resulting from field bindweed infestations; yield declines in wheat (*Triticum aestivum* L.), pea (*Pisum sativum* L.), and barley (*Hordeum vulgare* L.) of 16%, 69% and 31% respectively at 30 bindweed shoots m^{-2}, further declining as bindweed density increases (Black et al., 1994).

Frequent deep tillage and establishment of competitive cover crop sequences are two of the most common management tactics employed by organic farmers to reduce creeping perennial weed pressure (McErlich & Boydston, 2013; Ominski et al., 1999; Turner et al., 2007). When tilling to manage creeping perennial weeds, timing, implement choice, and repetition are paramount to success. Perennial weeds tend to be most vulnerable to mechanical damage when carbohydrate reserves in their root structure are being mobilized to develop new tillers or reproductive structures (Hodges, 2003; Lukashyk et al., 2007; Mohler, 2001). Targeting perennial weeds during this time with an implement that can sever their root structure, such as a chisel plow with wide sweeps, can significantly reduce their vigor (Mohler, 2001). Mechanical management of perennial weeds is further improved when it is conducted often. Hodgson (1958) found that Canada thistle can be up to 99% eliminated when cultivated every 21 days throughout the growing season. Similar work conducted by Nkurunziza and Streibig (2011) suggested that destroying above-ground vegetative structure of Canada thistle every 500-600 °C growing degree days can further deplete carbohydrate stores and prevent population increase. More recently, Mohler et al. (2021) suggested that repeated cultivations and dense planting of cereal grains can reduce Canada thistle density.

Alfalfa (*Medicago sativa* L.) is one of the most common cover crop choices for perennial weed management in organic systems. Phases of alfalfa placed within a larger crop rotation design are effective at suppressing perennial weeds because they are highly competitive, and frequently disturbed by cutting intervals for haying (Anderson, 2010; Ominski et al., 1999). Cutting alfalfa or similarly managed cover crops can deplete energy reserves of perennial weeds like Canada thistle and field bindweed while simultaneously disrupting annual weed seed production (Anderson, 2015; Derscheid, 1961; Hodges, 2003; Tautges et al., 2015). When aerial shoots of creeping perennial weeds are fragmented by cutting, carbohydrate reserves fuel regeneration, thereby reducing stored carbohydrates and their persistence over time (Graglia et al., 2006). Furthermore, alfalfa recovers from cutting faster than many weed species, outcompeting them for light resources (Meiss et al., 2010; Tiley, 2010).

The use of frequent tillage and alfalfa sequencing are good options for perennial weed management in many scenarios, but can be problematic to implement in the Northern Great Plains (NGP) of the United States, where producers have cited these weedy pests as one of the largest obstacles to commodity production (Orloff et al., 2018; Padbury et al., 2002; Tautges et al. 2016). The extent of tillage required to reduce perennial weed pressure poses a threat to soil aggregate structure, critical soil moisture reserves, and soil erosion resistance (Brandsæter et al., 2020; Karlen et al., 1994; Liebig et al., 2004; Mohler, 2001). This risk to soil structure and stored moisture is problematic, especially considering limited precipitation in the NGP is one of the largest impediments to agricultural production in the region (Bourgault et al., 2022; Carr et al., 2011). Properly timing tillage in organic systems can also be a challenge, as weather conditions can prevent producers from conducting field operations (Mirsky et al., 2010; Wortman et al., 2010). Additionally, improper tillage regimes can contribute to the proliferation of creeping perennials, as these weeds can multiply vegetatively when roots are severed at the wrong time or frequency (Gruber & Claupein, 2009; Liebman & Dyck, 1993).

Producers in dryland systems can typically expect little to no profit from first-year alfalfa and also risk depletion of stored soil moisture due to the high rate of water use by the crop (Entz et al., 2002; Fuerst et al., 2009). Excessive water utilization by cover crops like alfalfa can cause yield depression or reduced yields in sequential cash crop sequences in drought prone regions like the NGP (Austenson et al., 1970; Blanco-Canqui et al., 2015; Bourgault et al., 2022; Carr et al., 2011; Entz et al., 2002). Alfalfa can also cause a shift in the weed community from annual to perennial weed dominated systems due to lack of soil disturbance by tillage, protecting perennial weed rhizomes and potentially allowing creeping perennial weed spread (Bàrberi et al., 2002; Meiss et al., 2010; Melander et al., 2016). Perhaps the most detrimental aspect of utilizing alfalfa to suppress perennial weeds is the extent of tillage necessary to terminate stands in organic systems when rotating into the next phase of a cropping sequence. Organic producers must rely on aggressive tillage instead of herbicides to terminate alfalfa, risking associated soil erosion, loss of stored soil moisture, loss of soil organic carbon, and increased CO_2 emissions (Creech et al., 2020; Fuerst et al., 2009; Mohr et al., 1999; Toderi et al., 2021). Alfalfa termination can also be difficult, and incomplete stand termination can impact yields in subsequent crops (Carr et al., 2005; Creech et al., 2019; Tautges et al., 2015).

For these reasons, crop and cover crop alternatives to alfalfa and tillage for perennial weed management in the NGP could benefit producers. One such solution for creeping perennial management could be increasing the complexity of cropping sequences by diversifying crop phenology and management regimes (Schoofs and Entz, 2002). Continuous cropping systems incorporating rotations of alternating cool and warm-season species have already been shown to foster effective weed management compared to the traditional wheat-fallow rotation typically used in the NGP (Anderson, 2005; Anderson, 2010; Liebig et al., 2004). Diversified systems tend to require fewer external inputs while maintaining weed suppression and yield benefits, potentially offering a more sustainable approach to long term perennial weed management (Clements et al., 1994; Davis et al., 2012; Weisberger et al., 2019).

Cover crop sequences that produce large quantities of biomass have been shown to reduce weed pressure in organic systems (Florence et al., 2019; Wittwer et al., 2017). Increasing the diversity of cover crops by mixing species from different functional groups has been suggested to improve their performance by optimizing niche differentiation (Florence et al., 2019; Khan and McVay, 2019; Schoofs and Entz, 2002; Wortman et al., 2012). Reports regarding efficacy of cover crop polycultures vary, however, and further work should be conducted to assess these phases in long-term crop sequences (Blanco-Canqui et al., 2015). Inclusion of a green manure phase in rotation with cash crops could be another useful approach for managing creeping perennial weeds over time. Use of biennial cover crops, such as yellow sweet clover (*Melilotus officinalis* (L.) Lam.), can reduce the need for spring and fall tillage, while providing weed suppression, especially when used as a green manure (Blackshaw et al., 2001; Moyer et al., 2007).

The benefits of diversified crop sequences for creeping perennial weed suppression have not been assessed to our knowledge. We compared the weed suppressive ability of three four-year crop sequences including polycultures and sweet clover green manure phases: (i) three years of alfalfa followed by a year of hard red spring wheat (HRSW, *Triticum aestivum* L); (ii) lentil (*Lens culinaris* Medik.) / HRSW + yellow sweet clover / yellow sweet clover green manure / HRSW; (iii) nine species cover crop (CC) polyculture / HRSW / CC / HRSW. Three years of hayed alfalfa is a common tactic used to manage weeds in organic systems. Three grain crops within a four-year rotation represented by the second sequence is a common production system utilized in the NGP, and represents a “business as usual approach”. Lentil is cultivated first as a high-value crop, but is noted to be weakly competitive with weeds (McDonald et al., 2007). Sweet clover is included later within the four-year grain crop rotation to help build soil health and reduce weed pressure. Rotating a cover crop polyculture with HRSW in the third sequence provides the most opportunity to apply tillage, and could potentially increase soil nitrogen as legumes are included within the polyculture. Furthermore, HRSW provides the benefit of being both common and marketable in the NGP while maintaining competitiveness against weeds (Padbury et al., 2002; Weiner et al., 2001). Evaluating the efficacy of these crop sequences may demonstrate an optimal cropping sequence that organic producers could implement for perennial weed suppression.

Materials and Methods

Site Description

Field studies evaluating crop sequences were conducted at two certified organic sites, beginning in 2019. The first field site was located at the Dale E. Herman Research Arboretum near Absaraka, ND (Lat. 46.988319, Long. -97.352284. Elev. 314 m). The second field site was located at an organic producer's farm near Turtle Lake, ND (47.401058, -100.879758). Each study site was established on certified organic land, but varied environmentally, with differing soils and average annual precipitation (Figure 1). The Absaraka site is on a Warsing sandy loam complex (Fine-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Oxyaquic Hapludolls) (Natural Resource Conservation Service). Soil texture at the Absaraka, ND site based on mechanical analysis of soil samples taken at a depth of 30.5 cm was 58% sand, 28.8% loam, and 13.2% clay. Soil samples were also taken to evaluate organic matter and plant available nitrogen at the Absaraka, ND site in November of 2020. Samples taken at a depth of 30.5 cm had 2.8% organic matter and 14.5 kg/ha available nitrogen. The Turtle Lake site is on a Williams-Bowbells loam complex (Fine-loamy, mixed, superactive, frigid Typic Argiustolls).

The Absaraka site was located on part of a field that had been fallow since 2017; the Turtle Lake site was located in a field that was previously sown to a variety of organic crops. The field at Turtle Lake was rye (*Secale cereale* L.) in 2016, a barley (*Hordeum vulgare* L.)-radish (*Raphanus sativus* L.)-turnip (*Brassica rapa* subsp. *rapa*)-vetch (*Vicia villosa* Roth) forage mix in 2017, manure-fallow in 2018 (11.85 kg mt^{-1} N, 5.3 kg mt^{-1} P, 15.58 kg mt^{-1} K, 2.2 kg mt^{-1} S manure applied at a rate of 45 kg N ha^{-1}), and teff (*Eragrostis tef* (Zuccagni) Trotter) production in 2019. Both sites were infested with creeping perennial weeds. Canada thistle and perennial sow thistle were dominant at the Absaraka site, whereas Canada thistle and field bindweed were dominant at the Turtle Lake site. Field studies were conducted through August 2022 (i.e., four field seasons).

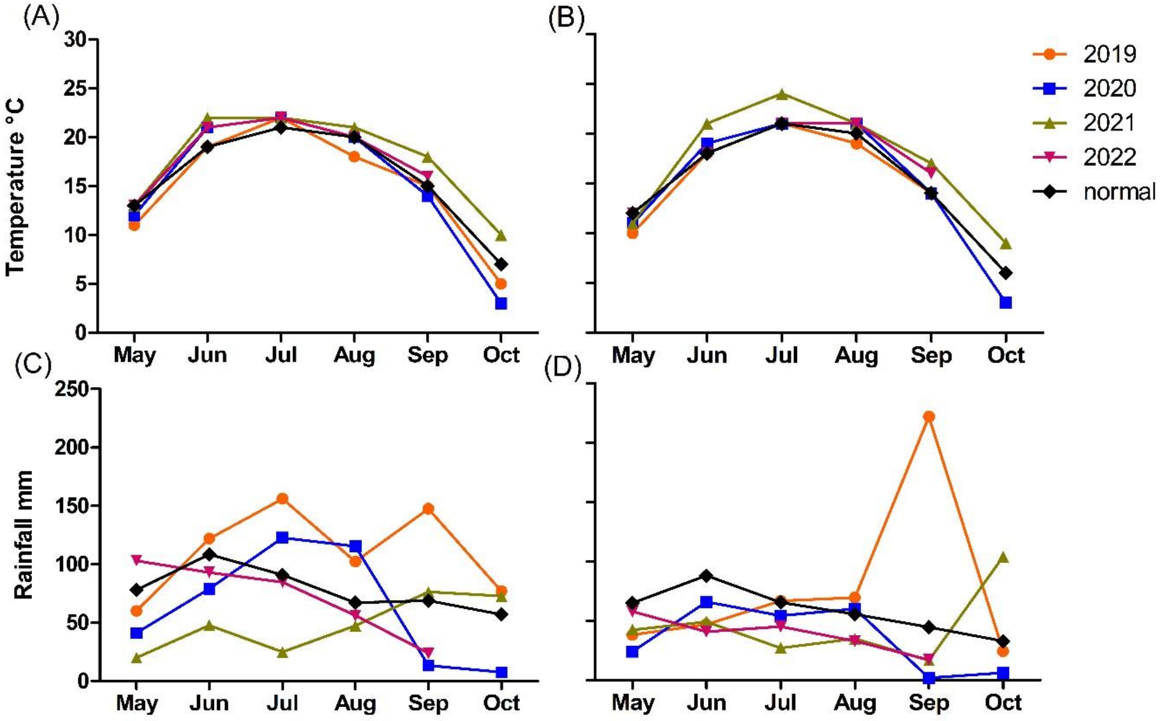

Figure 1. Mean monthly temperature for (A) Prosper, ND; and (B) Turtle Lake, ND and total monthly precipitation for (C) Prosper, ND; and (D) Turtle Lake, ND sites from 2019 to 2022 during the growing season. Prosper, ND was used as a proxy site for Absaraka, ND as it is the closest weather station to this field site. Weather data was obtained from the North Dakota Agricultural Weather Network (NDAWN).

Site Preparation

Prior to planting in 2019, the Absaraka site was prepared using a combination of moldboard plowing and rototilling. Plowing was conducted using a John Deere 5105 tractor and a two-bottom moldboard plow. Following plowing, a John Deere 655 rotary hoe was used to level the seed bed (Deere & Company, Moline, IL). Rotary hoeing was applied three times across the study area in alternating directions. The Turtle Lake site was prepped using a 20’ Rol-

O-Flex cultivator with 16” wide sweeps attached to a Case 1270 tractor (CNH Industrial N.V., Amsterdam, Netherlands).

Experimental Design

Three four-year crop sequences were grown at two sites to evaluate their weed suppressive ability (Table 1). Crop varieties and respective seeding rates used for each treatment are listed in Table 2. The nine-species cover crop polyculture incorporated three species each from the broad functional groups of cool-season grasses, legumes, and brassicas as demonstrated by Florence et al. (2019). Due to poor emergence and establishment of sweet clover at the Turtle Lake, ND site in 2020, field pea was planted in 2021 to provide some of the same benefits and green manuring potential that the sweet clover phase would have provided. Treatments were arranged in a randomized complete block (RCBD) at both sites. The total experimental area was 51 m x 41 m at Absaraka and 83 m x 29 m at Turtle Lake. Treatments were applied to 5.5 m x 15 m and 9.75 m x 9.75 m plots at Absaraka and Turtle Lake, respectively. Each treatment was replicated four times at each site. Three-meter alleys between plots were maintained by mowing at Absaraka; Turtle Lake had five-meter alleys between plots, also maintained by mowing.

Each treatment was managed with a standard (i.e., not reduced) tillage regime. This tillage regime included a rotary hoe and disc combination prior to planting each year. Disc tillage was applied using a Ford 3600 tractor with a 1.8-meter-wide disc implement (Ford Motor Company, Dearborn, MI). Pre-planting rotary hoeing was again conducted using the John Deere 655 rotary hoe. The Absaraka site was planted using a Great Plains 3P600 1.8 m double-disk press compact drill with 19 cm row spacing (Great Plains Ag, Salina, KS). The Turtle Lake site was prepped using a chisel plow and was planted using a John Deere LLA press drill with 19 cm row spacing (Deere & Company, Moline, IL). Study site dimensions were adjusted based on available space at each site, and sizes of planting and tillage implements available, but the goal was to apply similar amounts and types of soil disturbance at each site.

Alfalfa was mowed and biomass was removed at each site each year of the study that it was present. Alfalfa was cut at the late flowering stage prior to seed pod set. Fertility building measures were also taken during spring and fall of 2021. The nine-species polyculture plots (treatment 3) at the Absaraka, ND site received 34 kg each of certified organic granular composted poultry manure (CPM) in spring of 2021, resulting in an application rate of 84 kg N/ha (2-4-3, Chick ‘n’ Poo, Pearl Valley Farms, Inc., Pearl City, Il). We fertilized the Absaraka, ND site as soil tests revealed insufficient nitrogen and phosphorus for cover crop growth (10.6 kg/ha N, 7.25 ppm P, 247.5 ppm K). Granular CPM was not added at the Turtle Lake, ND site as soil sampling showed sufficient fertility for cover crop production (78 kg/ha N, 35.5 ppm P, 31.25 ppm K).

All plots at the Absaraka, ND site received 27.2 kg each of certified organic pelletized CPM in fall of 2021, resulting in an application rate of 136 kg N/ha (4-5-3, Ag Resource Inc., Detroit Lakes, MN). Following fertilization in fall of 2021, the entire study area was tilled using a Case-IH 310 Magnum tractor with a 4.26 m Case-IH disk-ripper implement to incorporate CPM and terminate remaining alfalfa within treatment ALF (CNH Industrial N.V., Amsterdam, Netherlands). Secondary tillage was then conducted using the Ford 3600 tractor with a 1.8-meter-wide disc implement. An oat (*Avena sativa* L.) and pea (*Pisum sativum* L.) cover crop was planted following secondary tillage at Absaraka across the entire study area to prevent soil erosion and water saturated soil. Oat was planted at a rate of 100 kg ha^{-1} and pea was planted at a rate of 112 kg ha^{-1}. The entire study area at Turtle Lake was fertilized with composted cow manure at a rate of 45 kg N/ha in fall of 2021 (manure 23.69% N by weight). Manure was then worked into the soil using a Roll-O-Flex cultivator at Turtle Lake (Roll-O-Flex Company, Regina, SK). Following fertility amendment at Turtle Lake, a cover crop of pea was planted across the entire study area at a rate of 112 kg ha^{-1}.

Table 1. Three crop sequences compared across four years for their weed suppressive ability at Turtle Lake, ND and Absaraka, ND.

	Year			
Treatment	2019	2020	2021	2022
ALF	Forage barley and alfalfa. Awnless barley planted as a nurse crop with alfalfa.	Alfalfa	Alfalfa	Hard red spring wheat (HRSW)
LENCL	Lentil for grain harvested in August	HRSW + yellow sweet clover	Yellow sweet clover or pea¥. Tilled under in May. Tilled at 21-28-day intervals subsequently.	HRSW
CCPLY	Nine species cool season polyculture	HRSW	Nine species mixed season polyculture	HRSW

¥ Pea was planted instead of sweet clover at the Turtle Lake, ND site as minimal clover reemerged after winter.

Table 2. Crop species, scientific names, varieties, and associated planting rates used in a multi-year crop sequencing study.

Crop species	Scientific name	Variety	Rate (Kg ha^{-1})
Alfalfa	*Medicago sativa*	'Golden Acres'	15
Barley	*Hordeum vulgare*	'Hays'	25
Green lentil	*Lens culinaris*	None specified	64
Barley§¥	*Hordeum vulgare*	'Haymaker'	6
Emmer wheat§	*Triticum dicoccon*	None specified	11
Oat§¥	*Avena sativa*	'Monida'	1
Yellow Pea§	*Lathyrus aphaca*	'Montech 4152'	39, 168¢
Faba Bean§	*Vicia faba*	None specified	64
Black Lentil§	*Vigna mungo*	'Indianhead'	11
Radish§¥	*Raphanus sativus*	'Tapmaster'	5
Purple top turnip§	*Brassica rapa* subsp. *rapa*	None specified	0.5
Yellow Mustard§	*Sinapis alba*	None specified	1
Hard red spring wheat	*Triticum aestivum*	None specified	168
Yellow sweet clover	*Melilotus officinalis*	'Yellow Blossom'	6
Cowpea¥	*Vigna unguiculata*	'Iron and Clay'	6
Sunn hemp¥	*Crotalaria juncea*	N/A	5
Field pea¥	*Pisum sativum*	'4010'	18
German foxtail millet¥	*Setaria italica*	None specified	4
Ethiopian cabbage¥	*Brassica carinata*	None specified	0.6
Dwarf essex rape¥	*Brassica napus*	None specified	0.6

¢ Denotes seeding rate utilized for pea instead of sweet clover at Turtle Lake, ND in 2021.
§ Denotes species comprising the nine-species cover crop mix grown in 2019.
¥ Denotes species comprising the nine-species cover crop mix that will be grown in 2021.

Data Collection and Analysis

Collection

Data for each site was collected during three intervals: spring/crop and weed emergence (May or June), summer/crop and weed peak growth (July or August), and fall/post-harvest (September or October). Data collection during the final year of the study was coordinated with the same thermal timing (i.e., growing degree accumulation, GDD) as the first year of the study so that perennial weed development would be as similar as possible between these two sampling years (Table 3). To calculate GDD, mean hourly air temperature throughout the growing season was subtracted from a base temperature of 2°C to quantify cumulative GDD (Battel, 2017).

Perennial weed, adjacent weed (i.e., non-creeping perennial weeds or annual weeds) and crop densities were measured at all sampling intervals. Although the study focused on field bindweed and Canada thistle, at the Absaraka site, we also assessed perennial sow thistle (*Sonchus arvensis* L.) presence as there was no field bindweed present and perennial sow thistle behaves similarly to other creeping perennial weeds.

Weed density was counted by hand in three 1-m^2 quadrats per plot; these subplots occupied consistent geolocations and were measured each year of the study. Density was quantified by counting aerial shoots. Creeping perennial weeds were separated by species whereas adjacent weeds were pooled across species. Density for all species was counted at the initial count interval. Field bindweed density was not counted at the destructive harvest interval, as the vining nature of the plant made it too challenging to discern individual plants, or clones.

Biomass for perennial weeds, adjacent weeds, and crops were collected from three 1 m^2 quadrats in each plot when physiologically mature at the destructive harvest interval; these plots were the same as the established plots used for the density counts. Biomass was hand clipped, dried at 50°C until at a constant weight, and then weighed. Leaf area index (LAI) was measured for cropping sequence treatment ALF at peak growth using an AccuPAR LP-80 photosynthetically active radiation (PAR) ceptometer in 2019 and 2020 to estimate biomass production (Dong et al., 2020) (Meter Group, Inc., Pullman, WA). LAI was not assessed in other treatments as they had mixed canopies, while ALF was homogenously alfalfa.

Grain from crops was hand collected in three 1-m^2 quadrats in each plot where they are present. Quadrat location for grain harvest was adjacent to the quadrat location used for density and biomass collection as weeds typically reached physiological maturity before the wheat. Grain was hand threshed in 2020 and machine threshed in 2022 using a Hege 125B plot combine (Hege Maschinen, Niederlassung, Germany). Harvest index was calculated; per plot yield was calculated in grams m^{-2}. Following grain harvest each year a final ‘post-harvest’ weed count was conducted at both study sites. This sampling interval occurred one to two months after grain harvest, allowing time for perennial weeds to recover following any mechanical damage from the harvest. Density of perennial weeds was quantified again in three 1 m^2 quadrats per plot at the predetermined locations utilized in the initial and destructive harvest sampling intervals. Perennial weed biomass was harvested during the post-harvest sampling interval in 2022 only; biomass was hand clipped at the soil surface, bagged by species, and dried to a constant weight at 50°C.

Table 3. Thermal timing of first and final year data collection by growing degree day (GDD). Thermal units were calculated from mean hourly air temperature in degrees Fahrenheit throughout the growing season utilizing North Dakota Agricultural Weather Network (NDAWN) data.

	Absaraka, ND		Turtle Lake, ND	
Sampling interval	2019	2022	2019	2022
	----------------GDD----------------		----------------GDD----------------	
Initial	1645	1644	1285	1003
Destructive	2701	2650	2680	2821
Post-Harvest	4403	3946	4111	4080

Analysis

Analysis of Variance (ANOVA) was used to compare data by using the MIXED or GLMMIX procedures of SAS (SAS release 9.4, SAS Institute Inc., Cary, NC). Pairwise differences among means were compared using Tukey's Honest Significant Difference method. Significance was tested at α=0.05. Replication (or block) and year were considered random effects. Cropping sequence treatment and site were considered fixed effects. Prior to testing, assumptions of ANOVA (i.e., normality, homogeneity of variance) were assessed. If assumptions were significantly violated (as was often the case with count data), SAS PROC GLIMMIX was used instead of PROC MIXED, using the distribution that produced the best model fit statistics.

Some response variables that were measured each year in the same plots (or experimental units); therefore, these repeated measures were accounted for by using analysis techniques designed to account for potential covariance structure within the random effect 'year' (Kincaid, 2005). A covariance matrix was applied for measures that were repeated in the same space each year of the study, using the mixed model optimization technique 'QUANEW'. Covariance matrix structures were selected based on best model fit with the fewest iterations within the model optimization table of SAS. Simpler covariance matrices (e.g., compound-symmetry, Toeplitz, first-order auto regressive) were preferred over complex ones (e.g., heterogeneous compound-symmetry) (Kincaid, 2005).

Sites were analyzed separately if interactions between treatment and site were found. Count data were analyzed with either a negative binomial or Poisson distribution (Pedan, 2001). Biomass and yield data were analyzed with a normal distribution. Means for biomass data contained many zero values, which is problematic for analysis of continuous data. These zero skewed models were modified by adjusting zeroes to 0.0000001, and then taking the natural log of the means. This modification let the zero skewed data to better fit a normal distribution, allowing convergence of analysis models. All means are reported in their untransformed state.

Results and Discussion

Weed Responses

Initial count interval

Lower densities of all perennial weed species were associated with the multi-year alfalfa sequence (ALF) (Figure 2). The lentil/sweet clover/hard red spring wheat (LENCL) sequence was associated with greater densities for all perennial species compared to other sequences. In most cases, the polyculture/hard red spring wheat (CCPLY) sequence performed similarly to LENCL. Only in the case of Canada thistle density at the Turtle Lake, ND site did CCPLY not differ from ALF (5 vs. 9 shoots m^{-2} respectively) (Figure 2.A.).

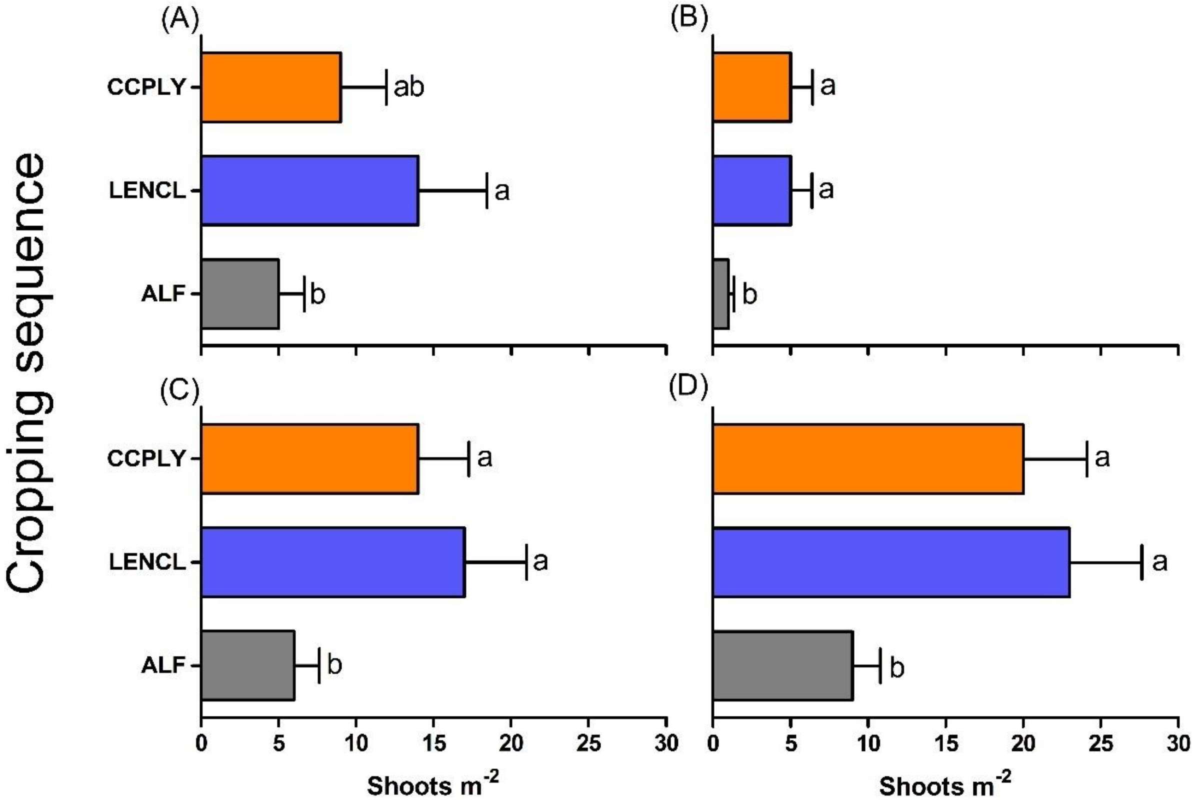

Figure 2. Mean plus standard error density (shoots m^{-2}) of (A) Canada thistle at Turtle Lake (P=0.0053); (B) Canada thistle at Absaraka (P=0.0052); (C) perennial sow thistle at Absaraka (P=0.0005); and (D) field bindweed at Turtle Lake (P=<.0001) from 2019-2022. Lower case letters denote differing means within a species among cropping sequence treatments according to Tukey's Honest Significant Difference test at α=0.05.

ALF was also associated with lower average densities of 'adjacent' or annual weeds compared to LENCL and CCPLY (9 vs. 23 vs. 20 individuals m^{-2}, respectively) (*P*<.0001). Treatments LENCL and CCPLY did not differ from each other regarding adjacent weed density (Figure 3).

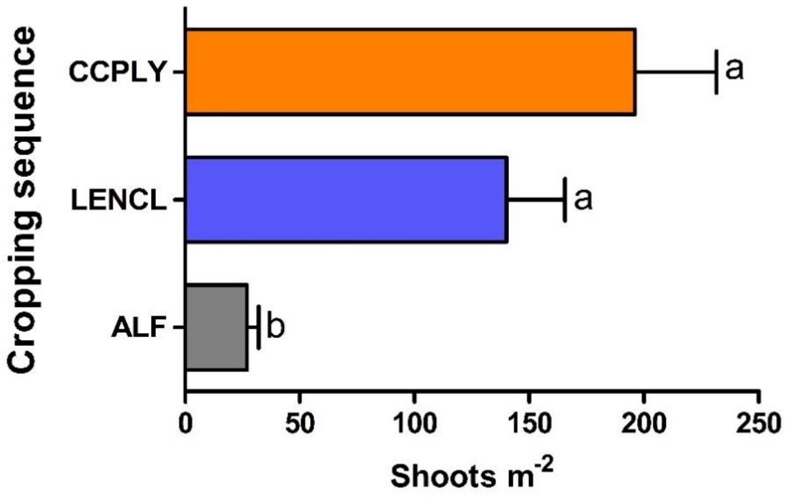

Figure 3. Mean plus standard error density (shoots m^{-2}) of adjacent weeds at the Absaraka and Turtle Lake, ND sites from 2019-2022. Lower case letters denote differing means of adjacent weeds among cropping sequence treatments according to Tukey's Honest Significant Difference test at α=0.05.

Destructive Harvest Interval

At the destructive harvest interval, density could only be quantified for Canada thistle and perennial sow thistle. Lower mean densities of both Canada thistle and perennial sow thistle were associated with the ALF treatment compared to LENCL and CCPLY (Figure 4).

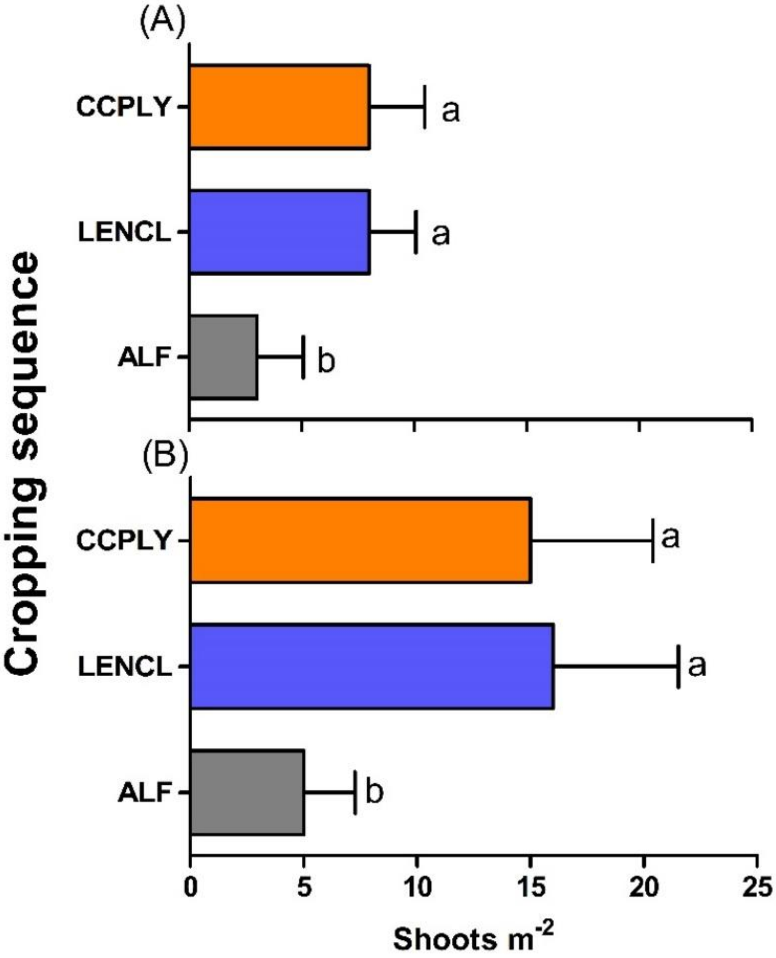

Figure 4. Mean plus standard error density (shoots m^{-2}) of (A) Canada thistle and (B) perennial sow thistle at the destructive harvest interval from 2019-2022. Canada thistle density was pooled for both the Absaraka and Turtle Lake, ND sites. Perennial sow thistle was only measured at the Absaraka, ND site. Lower case letters denote differing means within a species among cropping sequence treatments according to Tukey's Honest Significant Difference test at α=0.05.

Mean Canada thistle biomass was greater in LENCL than ALF at both sites (82 vs. 8 g m^{-2} respectively). Biomass of Canada thistle in CCPLY did not differ from ALF or LENCL (Figure 5). Greater mean perennial sow thistle biomass was associated with LENCL versus ALF and CCPLY (27 vs. 8. vs. 14 g m^{-2} respectively). Mean field bindweed biomass lower in ALF versus CCPLY, while LENCL did not differ from either of the other treatments (31 vs. 59 vs. 42 g m^{-2} respectively).

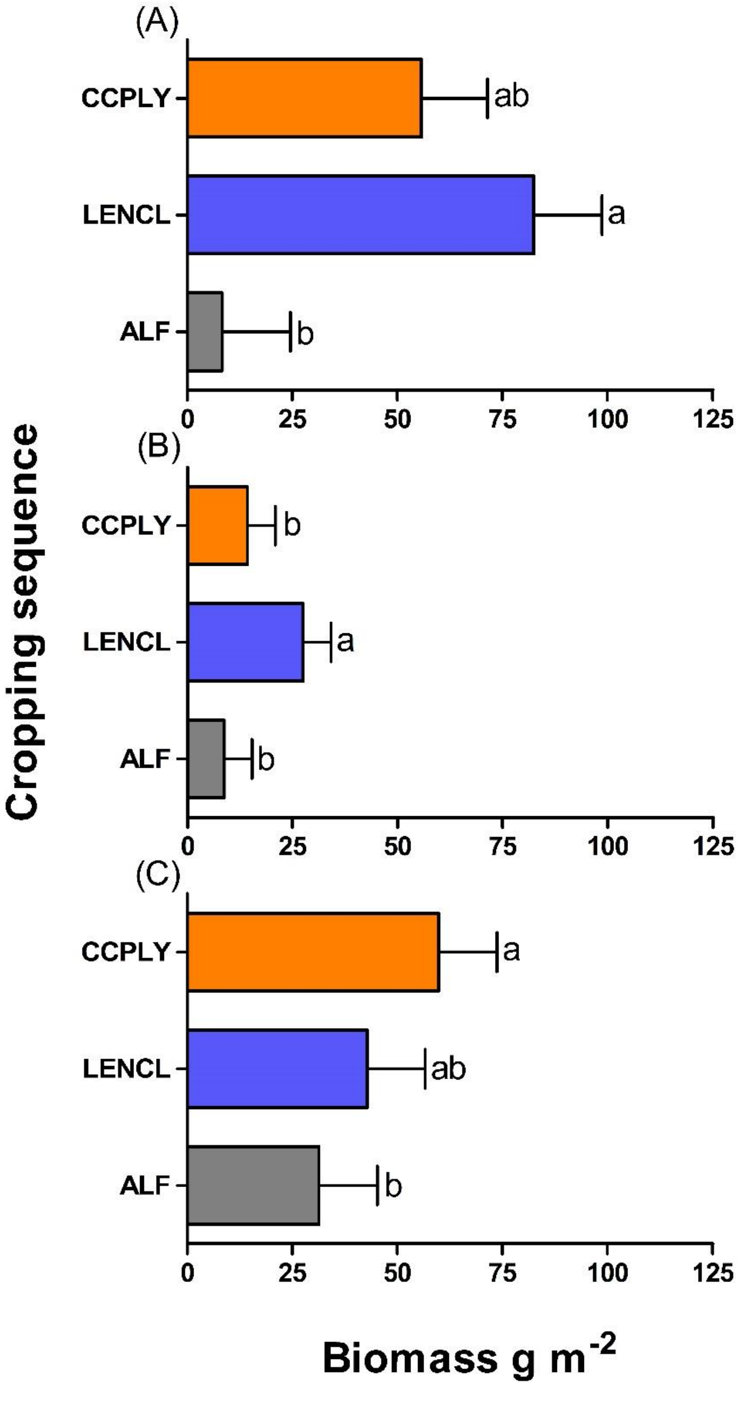

Figure 5. Mean plus standard error average dry biomass (grams m^{-2}) of (A) Canada thistle (pooled across sites); (B) perennial sow thistle; and (C) field bindweed from 2019-2022. Canada thistle was measured at both the Absaraka and Turtle Lake, ND sites. Perennial sow thistle was only measured at Absaraka, ND; field bindweed was only measured at Turtle Lake, ND. Lower case letters denote differing means within a species among cropping sequence treatments according to Tukey's Honest Significant Difference test at α=0.05.

Lower mean adjacent weed biomass was associated with ALF versus LENCL and CCPLY (83 vs. 235 vs. 208 g m^{-2} respectively) (*P*=0.0009) (Figure 6). Adjacent weed biomass did not differ between sites (*P*=0.1042).

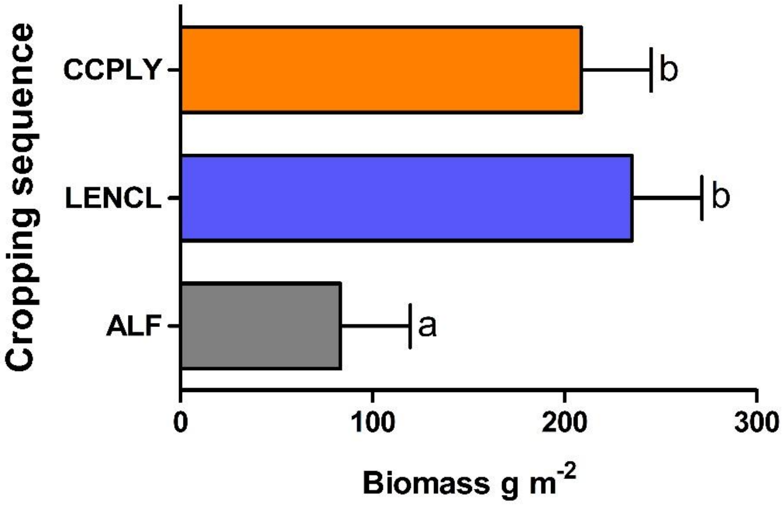

Figure 6. Mean plus standard error average dry biomass (grams m^{-2}) of adjacent weed species at both the Absaraka and Turtle Lake, ND sites from 2019-2022. Lower case letters denote differing biomass among cropping sequence treatments according to Tukey's Honest Significant Difference test at α=0.05.

Lentil yield was only quantified for the Absaraka site, because weed pressure caused 100% yield loss at Turtle Lake. Mean lentil yield at Absaraka in 2019 was 44.15 g m^{-2}. Lentil harvest index was 0.37. Mean hard red spring wheat (HRSW) yield did not differ between the cropping sequence treatments in 2020 (*P*=0.0693) nor in 2022 (*P*=0.3982). HRSW mean yield in 2020 was greater at the Absaraka site than the Turtle Lake site (146.65 vs. 15.14 g m^{-2} respectively. Greater mean HRSW yield was associated with the Turtle Lake site than the Absaraka site in 2022 (260.34 vs. 97.1 g m^{-2} respectively) (Figure 7). Mean harvest index for HRSW at Absaraka and Turtle Lake was 0.55 and 0.38 respectively. Mean harvest index for HRSW at Absaraka and Turtle Lake was 0.42 and 0.36 respectively in 2022. Alfalfa biomass was only quantified during the 2021 season. Mean alfalfa biomass was 294.8 g m^{-2} (2.94 mt ha^{-1}) and did not differ between Absaraka and Turtle Lake in 2021 (*P*=0.5394).

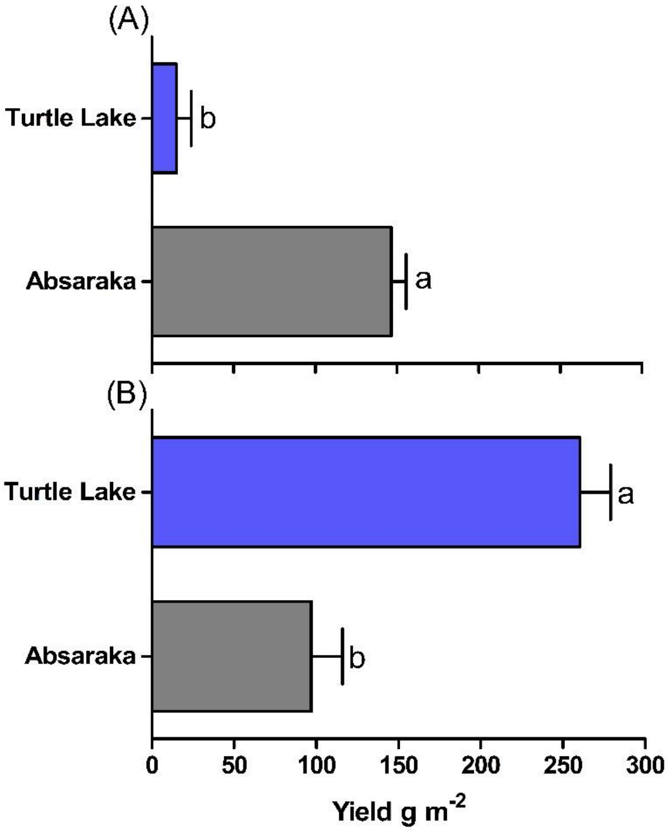

Figure 7. Mean plus standard error yield (grams m^{-2}) hard red spring wheat yield for the (A) 2020; and (B) 2022 seasons. Lower case letters denote differing yields according to Tukey's Honest Significant Difference test at α=0.05.

Leaf area index (LAI), measured via by intercepted photosynthetically active radiation, was only quantified in the ALF plots in 2019 and 2020 (Figure 8). Mean LAI for ALF in 2019 was 2.67 and 0.5 at Absaraka and Turtle Lake, respectively. Mean LAI for ALF in 2020 was 6.43 and 4.78 at Absaraka and Turtle Lake, respectively. Canopies of ALF plots were dominated by alfalfa (observation), so these values indicate the cover associated with the alfalfa stands.

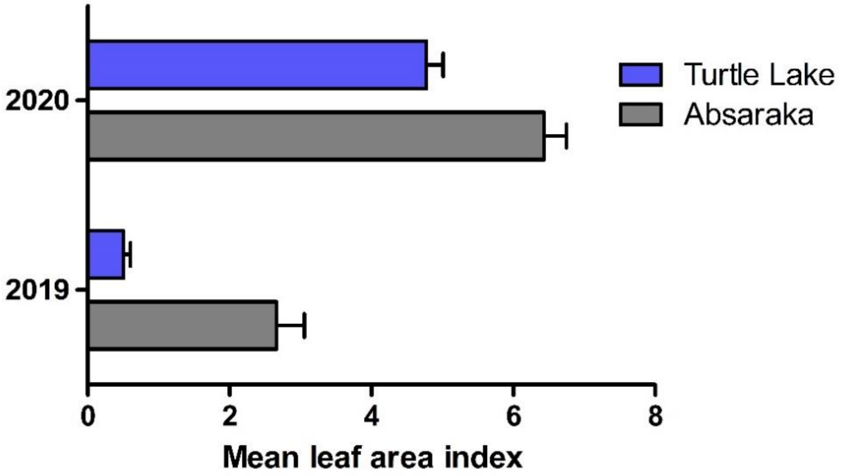

Figure 8. Mean plus standard error leaf area index m^{-2} in alfalfa plots at both the Turtle Lake and Absaraka, ND sites from 2019-2021.

Post-Harvest Interval

Mean Canada thistle density was lower in ALF compared to LENCL and CCPLY (1 vs. 5 vs. 4 shoots m^{-2} respectively). All crop sequencing treatments differed with respect to perennial sow thistle density. Lowest mean density of perennial sow thistle was associated with ALF, followed by CCPLY with both of these sequences having 1.0 shoots m^{-2}. Greatest mean density of perennial sow thistle was associated with LENCL at 2 shoots m^{-2}. Lowest mean density of field bindweed was associated with ALF compared to LENCL and CCPLY (4 vs. 11 vs. 11 shoots m^{-2} respectively) (Figure 9).

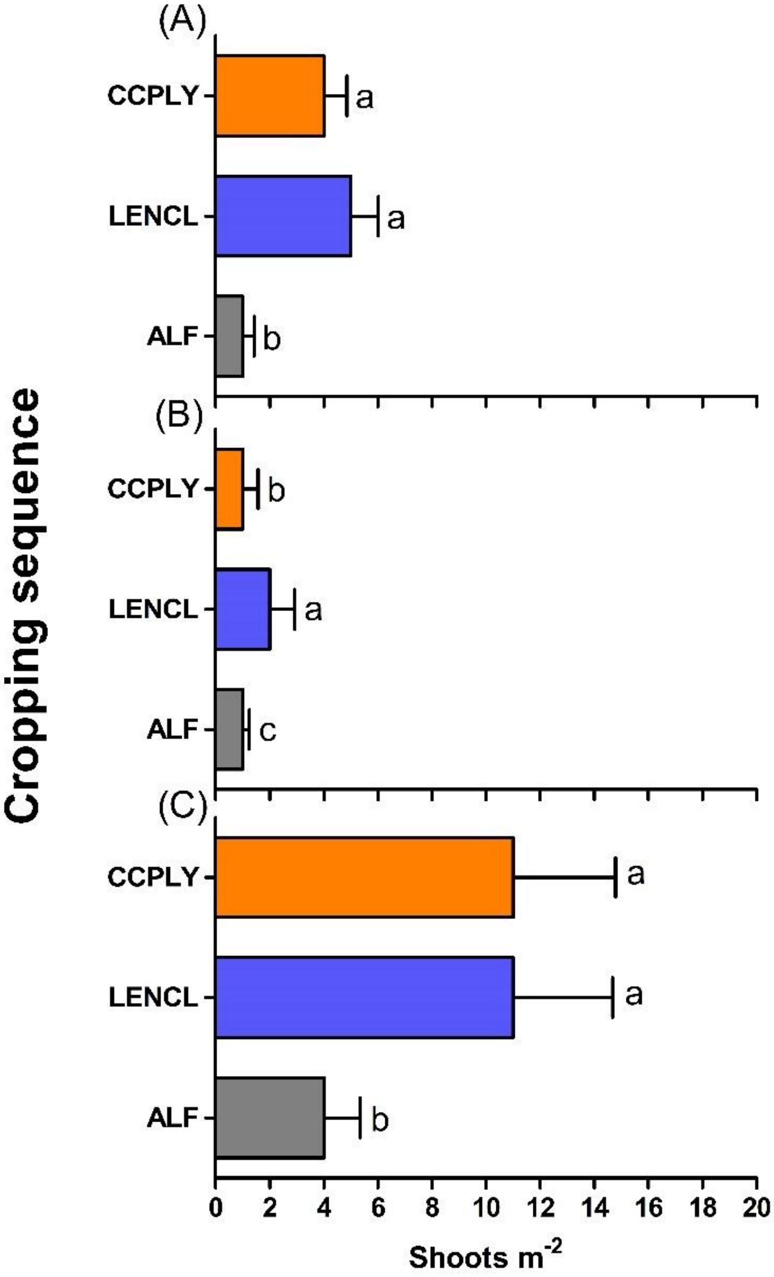

Figure 9. Mean plus standard error density of perennial weed aerial shoots m^{-2} for (A) Canada thistle at both the Absaraka and Turtle Lake, ND sites; (B) perennial sow thistle at the Absaraka, ND site; and (C) field bindweed at the Turtle Lake, ND site from 2019-2022. Lower case letters denote differing means within a species among cropping sequence treatments according to Tukey’s Honest Significant Difference test at α=0.05.

Discussion

Alternative crop sequences for suppression of perennial weeds did not perform better than the three-year alfalfa sequence. We observed that a sequence of three years of alfalfa (ALF) was associated with lower densities of all perennial weed species at both study sites. Only in the case of the initial count interval density for Canada thistle at the Turtle Lake, ND site did we see the hard red spring wheat (HRSW)/cover crop (CCPLY) sequence perform the same as ALF. The density of Canada thistle did ultimately differ between ALF and CCPLY by the destructive harvest and post-harvest intervals. This difference may be due to the in-season competitive effect of each treatment respectively. This result is consistent with Ominski et al. (1999) who observed that multiple years of alfalfa reduced Canada thistle and perennial sow thistle densities. Surprisingly, initial poor establishment of alfalfa at the Turtle Lake, ND site in 2019 did not lead to an associated increase of perennial weed pressure at that site.

Both the Absaraka and Turtle Lake sites had robust stands of alfalfa by the second year of the study, quantified by increases in mean LAI, which is positively correlated with biomass production (Dong et al., 2020). Tautges et al. (2015) reported a similar occurrence of poor alfalfa stand in the establishment year of their study becoming robust and suppressing weeds after multiple consecutive years. Alfalfa was able to outcompete perennial weeds for light, and also probably N, and mowing of the alfalfa stands likely further impacted perennial weeds by reducing their carbohydrate reserves (Graglia et al., 2006). The effect of mowing may also explain why ALF was associated with lower density of annual weeds compared to the lentil/HRSW+clover/clover or pea (LENCL) sequence and CCPLY as well. Mowing of alfalfa likely hindered production of seed by annual weeds, thereby reducing seedling recruitment throughout the study. Arlauskienė et al. (2021) similarly reported that mowing associated with alfalfa management reduced annual weed populations.

Annual tillage associated with the management schemes of LENCL and CCPLY may have led to higher weed densities, counterintuitively. Yearly cultivation and tillage within these treatments may have boosted perennial and annual weed density by increasing weed seedling recruitment and splitting perennial rhizomes into segments that could form new shoots (Bullied et al., 2003; Gruber & Claupein, 2009; Liebman & Dyck, 1993). This may partially explain why weed densities were often lowest in ALF, as this treatment did not receive tillage until fall of 2021.

Canada thistle biomass was lowest in ALF, and highest in LENCL. CCPLY was intermediate between ALF and LENCL. Canada thistle biomass accumulation may have benefitted from nitrogen input associated with N fixation resulting from legumes included in all cropping sequences, as each included at least two years of possible nitrogen fixation. Multiple authors have noted the tendency of Canada thistle to accumulate and benefit from soil nitrogen (Mamolos & Kalburtji, 2001; Nadeau & Vanden Born, 1990). However, the realized cover crop mixture in CCPLY was dominated by grasses and cereals (data not shown), with legumes making up a minimal percentage of the polyculture. We expect that the two consecutive years of sweet clover at Absaraka, ND and the sweet clover-pea phase from 2020 to 2021 at Turtle Lake, ND in the LENCL treatment would have made a more significant nitrogen contribution than CCPLY. We did not conduct frequent enough soil sampling throughout the study to understand exactly how soil nutrients may have changed year to year, however.

The dominance of grasses over legumes in cover crop polycultures has also been observed by Bourgault et al. (2021) and Florence et al. (2019). Finney and Kaye (2017) similarly reported that polycultures do not necessarily outperform single species cover crops for overall crop biomass production. Several other authors have published contradicting results however, with mixtures sometimes outperforming monocultures of legumes and brassica species in terms of overall crop biomass production (Baraibar et al., 2018; Khan and McVay, 2019; Wortman et al., 2012). A worthy consideration when debating whether or not to increase the number of species in a cover crop mix is the difficulty of obtaining an even stand due to variability in seed size and optimal planting depths. We experienced challenges when establishing cover crop polycultures in our study. Even when seed was hand mixed to ensure even distribution across plots, we observed larger seed falling to the bottom of the planter, sometimes resulting in uneven stands. The need to reduce seeding rates in polycultures also may detract from their efficacy for weed management. The Poaceae species likely would have performed better planted alone at a higher seeding rate in our study. The same observation likely applies to sweet clover establishment, which was also planted at a reduced rate when it was established as a dual crop with HRSW in 2020. Using a full rate of sweet clover could have helped to bolster its establishment vigor, and potential improve its efficacy for weed suppression.

Weakly competitive lentil stands in 2019 may have initiated the LENCL sequence with an established population of Canada thistle that was able to effectively compete and accumulate biomass throughout the study. Similarly, greater perennial sow thistle biomass was also associated with LENCL versus ALF and CCPLY. Strong competition and associated management of alfalfa likely explain why ALF suppressed perennial weeds effectively. The effect of CCPLY, in particular on perennial sow thistle, was likely due to alternating years of competitive HRSW and yearly tillage preventing biomass accumulation. Difficulties establishing a dual-crop phase of sweet clover and HRSW in 2020 likely worsened perennial sow thistle issues within LENCL plots.

Interestingly, the trend of ALF and CCPLY outperforming LENCL is upended when we look at field bindweed biomass. ALF again performed best, and this result is consistent with reports that alfalfa can compete especially well against vining weeds like field bindweed (Meiss et al., 2010). But additionally, we observed that field bindweed seemed to benefit from climbing on stems of cereal grains as though they were “trellises”. CCPLY was the only cropping sequence which included a cereal grain in all years, potentially allowing field bindweed to climb above the crop canopy and photosynthesize more efficiently. This trellising effect may have occurred to some degree in LENCL where HRSW was planted with sweet clover in 2020, however these stands tended to be uneven and weak when compared to years that HRSW alone was planted. The observation that field bindweed may have benefitted from vining on HRSW contradicts a prevalent belief that competitive cereals can suppress field bindweed populations (Weaver & Riley, 1982).

Low lentil yield in 2019 was unsurprising given the poor establishment of stands. Lentil yield was 441 kg ha^{-1} (6.56 bu ac^{-1}) in our study, whereas average lentil yield for North Dakota in 2019 was 1412 kg ha^{-1} (21.6 bu ac^{-1}) (USDA, National Agriculture Statistics Service). Alfalfa biomass yield in 2021 was typical for North Dakota at 2.94 mt ha^{-1}. Quantifying alfalfa biomass production yield in each year of the study would have provided more information about how the stands became more weed suppressive over time, although LAI measurements provided insight into how these stands performed in 2019 and 2020. Alfalfa LAI in 2019 was much lower than the suggested optimal range of 5.3-5.6 (Dincă & Dunea, 2018). Recorded LAI for alfalfa in 2020 was above this optimal range at Absaraka and just below at Turtle Lake. The variation in HRSW yield at both sites between 2020 and 2022 was likely due to variable sowing dates that occurred because of different weather patterns. Turtle Lake received below average precipitation in 2020, potentially explaining why HRSW yields were greater at Absaraka that year. Wheat stands did not establish well at Turtle Lake in 2020, possibly due to hot dry conditions, whereas Absaraka stands flourished under above average precipitation by mid-summer. Absaraka had above normal precipitation in spring of 2022 that prevented planting in a timely manner. Turtle Lake had ideal spring planting conditions and was planted at an optimum time.

Conclusion

When considering the long-term impacts of poor perennial weed management, producers should make decisions that continually reduce weed presence and competitive ability. Our study demonstrated that multiple years of alfalfa was the best option among the three analyzed cropping sequences for perennial weed suppression. The competitive ability of alfalfa and its associated management disturbances to weed communities makes it the optimal choice for reducing creeping perennial weeds. Cultivating three grain crops in four years as demonstrated by LENCL proved to be one of the worst scenarios for perennial weed management. Although cultivating grain crops for profit is an important consideration, the associated risk of encouraging perennial weed growth should not be ignored. Sequencing a polyculture with grain as demonstrated by CCPLY also performed poorly, especially for reducing biomass accumulation by field bindweed. Further reducing the appeal of CCPLY is the difficulty of planting several species simultaneously with each varying in seed size and optimal planting depth.

Further studies could be conducted to assess optimal placement of alfalfa sequences in a longer-term crop rotation. For example, multi-year alfalfa sequences could be utilized to either prepare for sequential grain crops or follow them in rotation to compensate for perennial weed biomass accumulation. Different arrangements of crop sequences for perennial weed suppression could be assessed as well. Sequencing two years of cool season followed by two years of warm season crops has been demonstrated to disrupt population increases in annual weeds (Anderson, 2004). Applying this concept within the lens of perennial weed management could provide additional insights for controlling these detrimental pests.

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CHAPTER 3: ADAPTIVE WEED MANAGEMENT IN A NOVEL PERENNIAL OILSEED CROP

Abstract

Perennial Lewis flax (*Linum lewisii* Pursh) is a potential new crop that could provide both high quality seed oil and a multitude of ecosystem services. Developing effective non-chemical weed management tactics is critical for the adoption of Lewis flax as a crop, as organic production is preferred, and no herbicides are currently labeled for use in the crop. We assessed sowing of competitive intercrops, thermal weed control via propane fueled flame, and cultivation as potential weed management tools for Lewis flax. A 2020 study establishing Lewis flax with competitive intercrops failed due to low flax and intercrop emergence, and excessive weed pressure. Subsequent greenhouse trials suggested that flame weeding could be a viable option for Lewis flax if conducted prior to seedling emergence. Additional field trials established indicated massive flax mortality as the crop emerged prior to weeds. The issues faced in these studies demonstrate the challenges of developing effective weed suppression strategies for a novel crop. Further exploration of agronomic and weed management best practices is necessary for the continued development of Lewis flax as a viable crop.

Introduction

Lewis flax (*Linum lewisii* Pursh) is an emerging perennial crop candidate native to a variety of ecosystems in North America (Ogle et al., 2006; Tork et al., 2019). Perennial crops like Lewis flax offer a potentially sustainable alternative to intensive annual cropping systems by simultaneously meeting conservation, ecosystem service provisioning, and commodity production goals (Glover et al., 2010a; Glover et al., 2010b; Baker, 2017; Ryan et al., 2018; Pinto et al., 2021). The basis of benefits associated with perennial crops is their long-lived, deep rooting nature (Baker, 2017; Glover et al., 2010b; Kantar et al., 2016; Vico et al., 2018). Perennials allocate more carbon to their root structures, potentially generating greater root biomass than annual crops. Kantar et al. (2016) reported that perennials can produce up to 10 Mg ha^{-1} of root biomass compared to 6 Mg ha^{-1} in annual crops. Greater production of root biomass in perennials benefits soils by improving aggregate stability, reducing erosion risk, increasing soil organic matter, and forming mutualistic relationships with arbuscular mycorrhizal fungi (Baker, 2017; Crews et al., 2018; DeHaan & Ismail, 2017; Ledo et al., 2020). Contrasting these benefits are annual cropping systems, which are associated with increased erosion risk, reduced soil nitrogen and carbon stores, reduced water quality, and damage to soil microbial communities (Culman et al., 2010; Glover & Reganold, 2010; Hart & Trevors, 2005; Pinto et al., 2021; Tilman et al., 2002; Zhang et al., 2007).

Producers may benefit from the multi-functionality and management flexibility offered by perennials. Perennials can save time and money as they do not need to be planted each year and can use light, water, and nutrient resources more efficiently than annuals, potentially saving on input costs (Cox et al., 2006; DeHaan et al., 2020; DeHaan & Ismail, 2017; Kantar et al., 2016; Ryan et al., 2018; Vico & Brunsell, 2017). Vegetative biomass of perennial crops can also be used as forage, feed, biofuel, mulch or bedding after harvest, thereby providing a secondary revenue stream (Lanker et al., 2019; Ryan et al., 2018).

Despite the numerous benefits associated with perennial grain crop cultivation, hesitation to adoption exists as these crops often do not match the yields of annual counterparts, marketability is sometimes unclear, agronomic best practices are not established, and limited weed management information exists (Marquardt et al., 2016; Pugliese et al., 2019; Ryan et al., 2018; Lanker et al., 2019). Lewis flax has the potential to be a high-value oilseed crop, especially if grown organically, but only if these production barriers are overcome. Lewis flax contains the same healthy omega-3 fatty acids as annual flax, and could be marketed to companies looking to meet sustainability goals (Baker, 2017; Lanker et al., 2019; Singh et al., 2011; Tork et al., 2019; Innes et al., 2022). Perennial flax may also have value as a feed, as flax-based feeds are reported to improve the quality and market value of eggs and meat (Kandel and Keene 2020; Scheideler, 2003; Singh et al., 2011).

Defining best practices (e.g., planting timing, weed management, seeding rate, and row spacing) for establishing perennial flax is crucial to facilitate the adoption of this novel crop. Compared to annual flax (*Linum usitatissum* L.), Lewis flax is a semi-evergreen perennial subshrub that is larger than annual flax when mature having several branches that sprout from a woody base (Ogle et al., 2006; Reeves, 2006). These physiological differences suggest that producers may need to use different seeding rates and spacings when cultivating Lewis flax versus annual flax. Optimal seeding date also differs between the two species. Lewis flax may establish best when seeded in late fall whereas annual flax typically is planted in late April through early May (Kandel & Keene, 2020; Ogle et al., 2006; Reeves, 2006). Like annual flax, Lewis flax is likely a weak competitor against weeds, and both seed quality and yield may be reduced because of competition from weeds (Bilalis et al., 2012; Ehrensing, 2008; Flax Council of Canada, 2022; McCollough et al., 2020). A meta-analysis of the organic:conventional yield gap by de Ponti et al. (2012) found that organic flax yields are on average only 65% of typical conventional yield. Lewis flax may struggle even more to compete against weeds than annual flax in the establishment year, as it requires up to 30 days to germinate, providing annual weeds a substantial time advantage for establishing (Reeves, 2006). Annual flax growers can compensate for weak flax competition with herbicide, but no herbicides are currently labeled for use in perennial flax systems.

Flame weeding may be an effective weed control method for perennial Lewis flax stands. Flame weeding or propane flaming is the process of heating weedy plant tissues to disrupt cell function (Leroux et al., 2001; Stepanovic et al., 2016). Plants are injured by flame weeding when temperatures of 55°C or higher cause cell wall damage, becoming more effective with repeated application (Bajwa et al., 2015). The leaf tissue of many weed species can be destroyed by flame exposure times as short as 0.065 to 0.13 seconds (Ascard, 1998). A major benefit of flame weeding is that it does not disturb the soil, thereby reducing annual weed seed germination (Knezevic, 2017; Stepanovic et al., 2015). Additionally, wild Lewis flax has been reported to not easily burn in wildfires, and quickly reestablishes after high intensity fires. The foliage of Lewis flax may perish in fire, but the plant readily sprouts from its caudex (Reeves, 2006). The fire-resistant nature of Lewis flax suggests that flame weeding applications could potentially be conducted in stands both inter- and intra-row. Determining safe use intervals and dosages for flaming in Lewis flax would help producers develop integrated weed management (IWM) plans for the crop. However, selection pressure from weed management techniques often shifts weed community composition (Zimbric et al., 2019). Therefore, documenting weed communities in Lewis flax stands and their response to flame weeding would also provide useful information for producers.

Fall and spring cultivation with herbicide application during the growing season is typically used for weed management prior to planting flax, while organic flax systems may rely on mechanical weeding through use of tine-harrows before and after sowing (Kandel and Keene, 2020; McCollough et al., 2020) We decided to combine mechanical weeding with interseeding of cover crops as another non-chemical weed management tactic for Lewis flax. Combining these two weed management schemes may help negate the limitations of cultivation alone such as limited operability in wet soil (McCollough et al., 2020). Interseeding cover crops with flax has also been noted to reduce weed pressure by increasing resource competition, and is another option to be explored for efficacy in Lewis flax (Sánchez Vallduví & Sarandón, 2011).

Due to the novel nature of cultivating Lewis flax in a row cropping system, we approached the task of creating an IWM plan through the lens of adaptive management. Demonstrating effective non-chemical weed management through flame weeding in Lewis flax could provide benefit to producers, especially considering the projected growth in popularity of perennial crops due to the recognition of their associated ecosystem services (Ryan et al., 2018). We evaluated the efficacy of competitive intercrops, thermal weed control, and tillage to begin development of an integrated weed management plan for perennial flax. Thermal weed control by flame weeding was evaluated via greenhouse and field studies. Intercropping and tillage regimes were evaluated via field studies.

Materials and Methods

2020 Field study

An initial field scale study was attempted in 2020. The study objective was to determine the efficacy of various inter-seeded cover crops for reducing weed pressure in a first-year perennial flax stand (Table 6). Each treatment was replicated four times across two sites. Study sites were established at the Carrington Research Extension Center, Carrington, ND (lat. 47.506380, long. -99.123652, elev. 475.5 m) and the Askegaard Organic Farm near Comstock, MN (lat. 46.623927, long. -96.752881, elev. 281.33 m). Both sites were established on certified organic land. Soils at each site differed, with the Comstock site dominated by poorly drained

Fargo series fine, smectitic, frigid typic epiaquerts and the Carrington site dominated by well drained Heimdal-Emrick series coarse-loamy, mixed, superactive, frigid calcic hapludolls (United States Department of Agriculture – Natural Resource Conservation Service). Rotary hoeing was utilized at both sites for soil preparation.

All treatments were planted in the spring of 2020. Comstock, MN was planted on May 27th; Carrington, ND was planted on May 29th. Planting was conducted utilizing an ALMACO four row cone plot planter (ALMACO company, Nevada, Iowa). Particular difficulty was noted when planting the Comstock site. Variable winds of 8-12 kph caused the lightweight seed to blow out of the planter cones, thereby causing uneven stand sowing. We also noted that the inoculant used for leguminous cover crop species clogged the cone seeder at Comstock. The inoculant that was utilized was clay-based Pre-Vail™ pre-inoculant for alfalfa/true clovers (Verdesian Life Sciences, Cary, NC). We waited approximately 4 weeks to observe emergence of flax and cover crops, but ultimately planting issues noted above necessitated that the Comstock site be replanted; this replant occurred on June 24th.

Large rain events at Comstock immediately followed emergence of our second planting and resulted in a complete washout of that site. We assessed the Comstock site as a complete loss on July 27th. At the Carrington site, both flax and cover crop emergence were poor. The canopy of plots at the Carrington site were dominated by redroot pigweed (*Amaranthus retroflexus* L.) and yellow foxtail (*Setaria pumila* (Poir.) Roem. & Schult.), with these two species accounting for more than 90% of the canopy in all plots and treatments combined. Flax was almost completely absent at Carrington by mid-summer, and any remaining individuals had suffered from the heavy competition by annual weeds. We also assessed Carrington as a complete loss due to the combination of high weed pressure and low flax populations.

Table 4. Eight inter-crop systems to be assessed for weed management efficacy in perennial flax stands in 2020.

Treatment number	Flax row spacing (cm)	Flax rate (kg/ha)	Cover crop species	Cover crop rate (kg/ha)
1	30.48	4.25	n/a	n/a
2	76.2	6.37	n/a	n/a
3	60.96	4.25	red clover	13.45
4	60.96	4.25	white clover	8.97
5	60.96	4.25	crested wheatgrass	7.85
6	60.96	4.25	junegrass	1.12
7	60.96	4.25	berseem clover	16.81
8	60.96	4.25	faba bean	168.12

Experimental Design – Greenhouse Study

Following the failed field experiments in 2020 at both Comstock and Carrington, ND, we determined that more active weed control methods would need to be assessed in perennial flax. We conducted a greenhouse study to evaluate the efficacy of flame weeding as a potential solution for heavy weed pressure in Lewis flax stands. Flame weeding injury impacts across three stages of Lewis flax growth and two flaming doses were evaluated. Assessed growth stages of flax assessed include imbibed seed (i.e. flax seed initiating germination below the soil surface with no aerial shoots), cotyledon, and flax that had formed multiple true leaf pairs. We chose these growth stages as they represent similar growth stages that could align with the optimal flame weeding time of early spring when weeds are small (Ascard, 1994). Assessing imbibed seed was necessary to determine whether flaming would cause mortality among flax seeds germinating below the soil. Cotyledon stage flax is likely to be the highest mortality risk for exposed plants, while multiple true leaf flax should be the most resilient (Ascard, 1994; Ulloa et al., 2010). Additionally, control of kochia (*Bassia scoparia* (L.) A.J. Scott) and wild proso millet (*Panicum miliaceum* L.) by flaming were evaluated. These two weeds were selected as they represent the two broad functional groups of broadleaf and grass weeds. We hypothesized that imbibed seed would best withstand flame weeding as this seed would be protected by soil, despite the shallow planting depth required for perennial flax. We also predicted that the multiple true-leaf flax would better withstand flaming than the cotyledon stage flax, as they would have more time to develop roots and herbaceous structure. The 1x dose was predicted to reduce flax injury while providing acceptable weed control, while the 2x dose would provide better weed control with greater flax injury.

The greenhouse study was arranged in a 3x3x3 factorial, in a completely randomized design. Three growth stages of flax, three flaming doses (no flame control, single, and double dose), and three replications comprised the levels of the factorial arrangement. Standard greenhouse plastic flat trays (28 x 55 cm) were filled with 6 kg of mineral field soil sourced from the Dale E. Herman Research Arboretum, Absaraka, ND (lat. 46.988319, long. -97.352284, elev. 314.55 m), then sown with two flax rows per flat at a depth of 3 mm, with a spacing of 18 cm between each row. Seeds were spaced every 1.25 cm to achieve 40 seeds in each flax row. Flax seed was sourced from Southwest Seed Inc. Dolores, CO. A row of kochia and a row of wild Proso millet was sown between the flax rows following the same planting specifications as the flax. Weed seeds were field collected in Fargo, ND, and stored in a dry dark location at 5°C. The weed rows were spaced 5 cm apart. Planting of weed seed was staggered so that the weeds would be at the cotyledon to first true-leaf stage at the time of flame application. Germination tests of the field soil found that dominant weeds in the seedbank were field pennycress (*Thlaspi arvense* L.), common purslane (*Portulaca oleracea* L.), and curly dock (*Rumex crispus* L.). Field soil was hand weeded to remove weeds that were not planted.

Flame was applied using a Red Dragon Model VT 21/2-30SVC 400,000 BTU propane weeder (Flame Engineering, La Crosse, KS) with a 6.35 cm bell head. Soil moisture was kept constant among all flats by bringing each to half field capacity by weight before flame application. Field capacity was found by taking the difference between thoroughly watered soil and soil that was oven dried to a constant weight at 100°C. Oven dried soil weighed 5.74 kg, and field capacity soil weighed 8.06 kg. We added water to each flat prior to treatment so that the total weight of soil and water was 7 kg in each flat. Preliminary tests found that bringing flats to full field capacity made them challenging to work with and risked damaging plants given the amount of water needed. Furthermore, we assumed that field applications of flame would not be conducted if fields were at field capacity state.

The randomized layout for the experiment is shown below in Figure 8, with corresponding treatment combinations listed in Table 5. The three flax growth stage treatments were combined with three flame weeding dosages. Planting of flax was staggered to allow flame weeding application to be conducted across all stages in a single day. The treatment dosages included a 0x (control), 1x and 2x dose. Dosage rates were calibrated by measuring the heat from propane flaming applied to soil. We targeted a minimum temperature of 55°C for the 1x dose and attempted to double that for the 2x dose. The 1x rate was applied at a speed of 0.7 km/h, and the 2x rate at 0.4 km/h. Pressure of propane was constant at 45 kPa. The flaming implement was fixed at a constant height of 20 cm from the soil surface and held at a 45-degree angle. Flame was to mimic in-field application in which a tractor would pull a flame weeder, as demonstrated by Ascard (1995). Each treatment combination was replicated three times and assigned randomly to flats of soil. The entire experiment was repeated twice, with two separate runs conducted at different times. The first run occurred from January to February 2021, while the second run was occurred from February to March 2021.

20	24	27	6	16	22	26	15	5	12	1	4	10	21
null	14	8	18	23	25	7	19	11	13	17	3	9	2

Figure 10. A map of the greenhouse table with each treatment assigned a number and then randomly assigned to a flat.

Table 5. Treatment combinations for Lewis flax flame weeding trials.

Treatment Numbers	Growth Stage	Dosage
1, 10, 19	Imbibed seed	No flame (0x)
2, 11, 20	Imbibed seed	1x rate
3, 12, 21	Imbibed seed	2x rate
4, 13, 22	Cotyledon	0x rate
5, 14, 23	Cotyledon	1x rate
6, 15, 24	Cotyledon	2x rate
7, 16, 25	Multiple true leaf	0x rate
8, 17, 26	Multiple true leaf	1x rate
9, 18, 27	Multiple true leaf	2x rate

Data Collection and Analysis – Greenhouse Study

Collection

Prior to applying the flame weeding treatments, initial density counts of flax and weeds were taken. During the flame application, average maximum soil surface temperature was recorded for every experimental unit using Onset Type K 12” Probe Thermocouple sensors to test for differences between the two treatment doses (Onset Computer Corporation, Bourne, MA). Density counts were also conducted for both weeds and flax at 1,7, 14, 21, and 28 days after treatment (DAT). Final flax biomass was collected at 28 DAT by clipping plants at the soil surface. Flax clippings were then oven-dried at 60°C until reaching a constant weight. Biomass was recorded as total grams of dry matter per experimental unit (greenhouse flat).

Analyses

Flax responses to flame weeding dose were analyzed using the PROC GLIMMIX procedure of SAS (SAS release 9.4, SAS Institute Inc., Cary, N.C.). Analysis of variance

(ANOVA) was performed using PROC GLIMMIX to test for treatment effects (i.e., flax growth stage and propane dose) and their interactions for the following response variables: final density, final biomass counts, and maximum average soil temperature. Simple main treatments effects and interactions for all tests were considered significant at α=0.05. Distributional assumptions were adjusted to optimize model fit statistics. In general, a negative binomial distribution optimized the model fit for count data, whereas a normal distribution was optimal for continuous data like biomass and temperature. Model terms ‘run’ and ‘replication’ were considered random effects for all models.

Significant interactions between treatment effects were sliced using a Bonferonni correction within GLIMMIX. Means separation for significant treatment effects was performed utilizing Tukey’s honest significant differences method. Given that nearly all weeds were killed by flame weeding, it was not possible to perform ANOVA tests for treatment effects on weed density counts. The elimination of weeds resulted in nearly all count data being equivalent to zero. For this reason, we report the data regarding weed mortality observationally. Final biomass counts for each stage were analyzed separately with the slice function within SAS, as the plants did not all achieve a uniform growth point when harvested (i.e., thermal unit accumulation).

Results and Discussion – Greenhouse Study

Flax Responses

The final flax density count at 28 DAT for the imbibed (IMB) stage did not differ between the control (0x) or treatment doses (1x and 2x). The IMB stage flax was associated with greater final density than the cotyledon (COT) and multiple true-leaf (MTL) stage flax within each treatment dose (Figure 9). COT stage flax final density did not differ from MTL within the 1x dose (*P*=1.000). MTL stage flax was associated with lower final density than both COT and

IMB within the 2x dose (6 vs. 10 vs. 22 individuals tray^{-2}). Weeds of both the broadleaf and grass functional groups were 95-100% eliminated by both flame weeding treatment doses (observation).

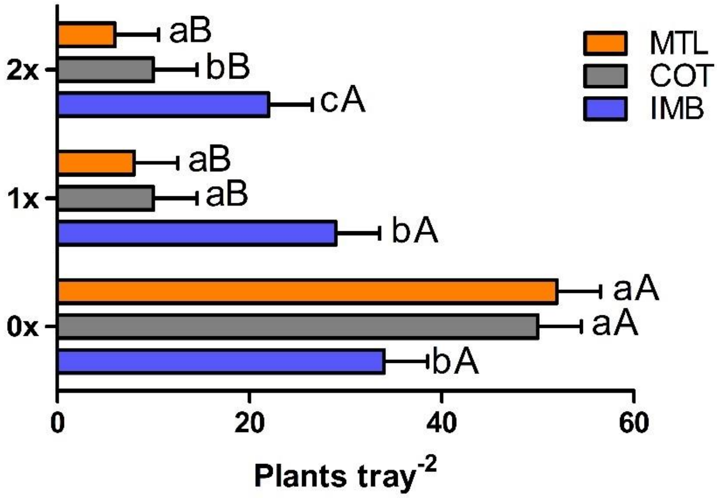

Figure 11. Final flax density count by dose and growth stage. Lowercase letters denote differing means among stages within a dose. Uppercase letters denote differing final densities among doses within a stage. Mean separation was determined according to Tukey's Honest Significant Difference test at α=0.05.

Final mean flax biomass did not differ for treatment doses (1x and 2x) across growth stage (*P*=1.000). IMB stage flax final mean biomass did not differ between the treatment doses and control dose (0x). The control dose was associated with greater mean flax biomass than the 1x and 2x doses for COT stage flax (1.75 vs. 0.32 vs. 0.36 g tray^{-2} respectively). The control dose was also associated with greater mean flax biomass for the MTL stage (3.61 vs. 0.63 vs. 0.38 g tray^{-2} respectively) (Figure 10).

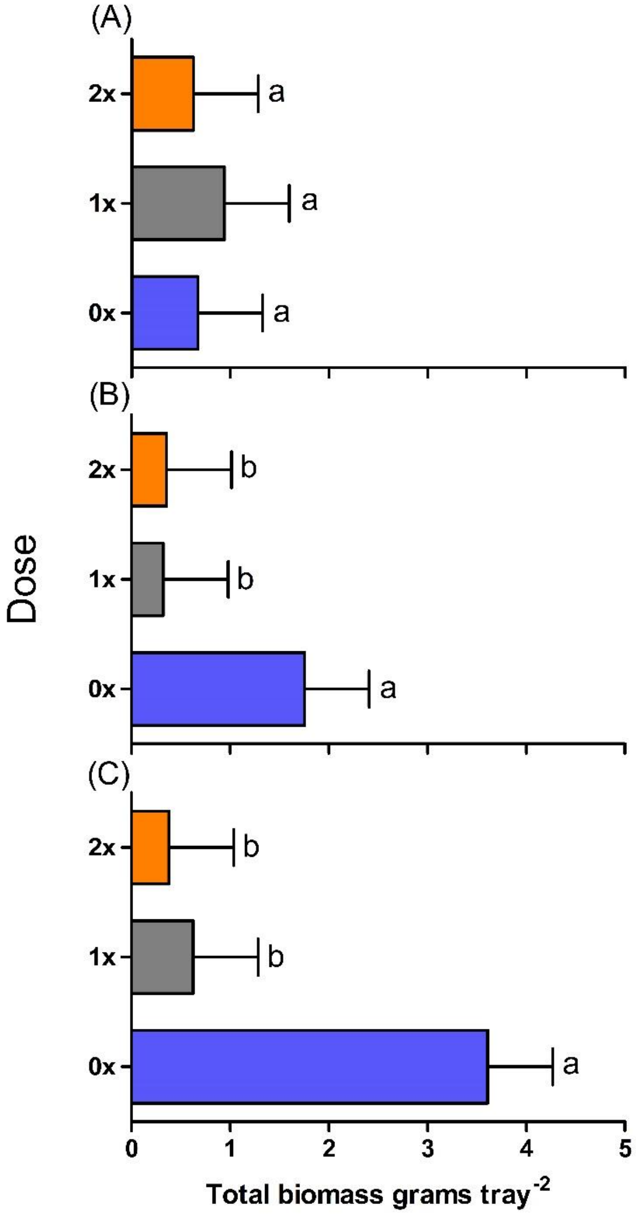

Figure 12. Mean plus standard error flax biomass of (A) IMB stage flax; (B) COT stage flax; and (C) MTL stage flax by dose. Lowercase letters denote differing biomass among doses within a growth stage according to Tukey's Honest Significant Difference test at α=0.05.

Mean maximum soil surface temperature achieved differed was greater in the 2x dose compared to the 1x dose (54.55 and 64.79°C respectively) (Figure 11).

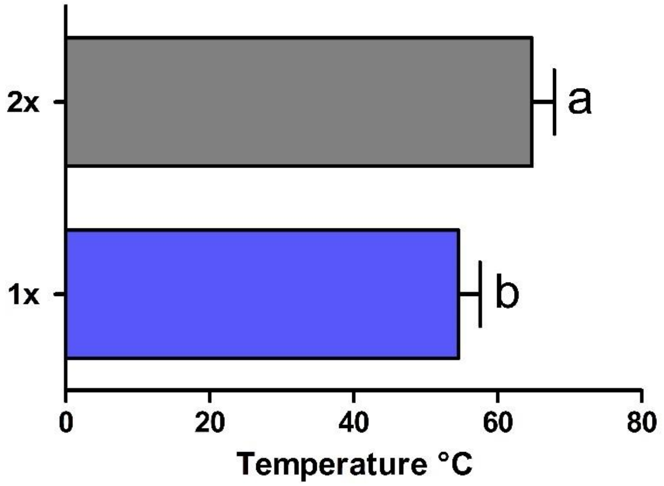

Figure 13. Mean maximum soil surface temperature by dose achieved by flame weeding. Lower case letters denote differing mean temperatures according to Tukey's Honest Significant Difference test at α=0.05.

Discussion – Greenhouse Study

Results support our hypothesis that imbibed flax seed (IMB) would better withstand flame weeding injury than cotyledon (COT) and multiple true leaf flax (MTL). Among both the 1x and 2x treatment doses, IMB was associated with greater final density than COT and MTL. Soil likely provided enough protection from flaming so that IMB flax was not damaged, while COT and MTL flax faced high mortality among both treatment doses. Within the 1x doses, final mean density of COT and MTL flax did not differ. Interestingly, within the 2x dose we found that COT flax was associated with greater final mean density than MTL flax (10 vs. 6 individuals tray^{1}). This contradicts our prediction that older MTL flax would be more resilient to flame weeding injury. Both Ascard (1994) and Ulloa et al. (2010) suggested that younger plants are more susceptible to flame weeding injury. Our results do not necessarily support these findings, however Lewis flax in our study may not have had sufficient time between the COT and MTL stage to develop root structure that would help them be resilient to injury. Soil depth in the greenhouse flats was only around 7 cm, likely limiting the growth of Lewis flax roots. The finding of lower mean density of IMB stage flax versus COT and MTL in the control treatment is challenging to explain. Increasing the number of replications could potentially reduce this difference among the growth stages within the control.

Both the grass and broadleaf weeds in the study appeared almost completely eliminated by both treatment doses. This result is noteworthy, as we would expect the grass weeds to be more resilient to flaming than the broadleaf weeds (Ulloa et al., 2010). The high mortality impact to the flax and weed species from both flaming treatment doses was not expected, as the temperatures achieved in our study were much lower than typical flame weeding temperatures. Leroux et al. (2001) and Knezevic (2017) both suggest that temperatures from 95-100°C are required to eliminate weeds. Our 1x dose achieved only 54.55°C and the 2x 64.79°C. We would not expect these reduced temperatures to have such a large impact on flax and weed density. We purposely calibrated our flamer to produce lower temperatures than necessary as we expected some risk to flax. One possibility is that the thermocouple we used could only sample every 1 second, potentially reducing the accuracy of our temperature measurements.

The mean biomass of IMB flax did not differ between the treatment doses, further suggesting that this growth stage was not impeded by flaming injury. Both MTL and COT stage flax mean biomass did not differ between the treatment doses. The control dose was associated with greater mean biomass than the treatment doses for COT and MTL. This is likely due simply to the reduction in density from flaming injury noticed in COT and MTL.

Conclusion – Greenhouse Study

Managing weeds in first year Lewis flax stands through the in-row application of propane fueled flame may only be appropriate prior to flax emergence. Flax faces a high mortality risk from flame weeding injury if treated after emergence, even at reduced flame weeding dosages. A scenario in which weeds emerge prior to Lewis flax would be ideal for apply flame weeding.

The potential for flax growing in field conditions in which rooting depth is not limited should be assessed. Emerged flax in the field that is exposed to flaming may be able to better recover given the lack of growth limitations. Fields often have unique micro-topographies as well that could affect the dispersal of heat from propane flaming, creating variable effects on flax and weed communities.

2021-2022 Field Study

Given the results of the greenhouse study, we determined that flame weeding of perennial flax should be tested with field scale equipment. We decided to explore the efficacy of flaming in the field combined with mechanical weed management (i.e., cultivation). These management tactics were applied to stands of flax that were planted at two intervals in fall of 2020: early fall and dormant seeding (i.e., following first frost). Field studies were conducted at two sites: Askegaard Organic Farm near Comstock, MN (lat. 46.623927, long. -96.752881, elev. 281.33), and the Dale E. Herman Research Arboretum near Absaraka, ND (lat. 46.987708, long. -97.352090, elev. 314.55 m). Both field sites were on certified organic land, differing in their soil structure and cropping history (Table 6; Table 7).

Prior to planting flax for the flame weeding study, the Comstock site was cultivated to terminate flax and inter-crops from the previous failed 2020 study. Following cultivation, a pea and oat cover crop was planted at the Comstock site in fall of 2020. The Absaraka site was cultivated multiple times to eliminate a previous winter rye cover crop utilizing a wide sweep chisel plow, disc, and rotary hoe in sequence.

Table 6. Dominant soil series and description of study sites located at Absaraka, ND and Comstock, MN (USDA-NRCS).

Site	Soil Series	Soil Texture	Soil Taxonomy	Slope (%)
Absaraka, ND	Warsing Loam	Sandy Loam	Fine-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Oxyaquic Hapludolls	0-3
Askegaard Farm, Comstock, MN	Fargo Silty Clay	Clay	Fine, smectitic, frigid Typic Epiaquerts	0-1

Table 7. Previous cropping history of the two perennial flax study locations from 2017-2020.

	Site	
Year	Comstock	Absaraka
2017	Summer fallow. Fall seeded oat cover crop.	Vegetable plots[§]
2018	Soybean	Carrot with mulches[‡], strawberry[¥]
2019	Hard red spring wheat under seeded with berseem clover	Alfalfa, strawberry
2020	Perennial flax and intercrop mixture	Alfalfa, strawberry, winter rye

§ - Vegetables included: onion, beet, pea, and squash with alfalfa hay mulch.
‡ - Mulches included: perennial ryegrass living mulch, white clover living mulch, red clover living mulch, and newsprint based hydromulch.
¥ - Strawberry patch made up ¼ of the study area.

Experimental Design – 2021-2022 Field Study

Treatments were designed to assess the efficacy of flame weeding combined with mechanical weeding for weed management at two management intervals (early and late season) in perennial flax (Table 9). Treatments were arranged in a randomized complete block with four replications per treatment at the two sites. Lewis flax was seeded into a pea and oat cover crop at Comstock and a cultivated/hand weeded area at Absaraka using an ALMACO 4-row cone seeder (ALMACO company, Nevada, IA). Individual plot dimensions were 3 by 6.1 m, with flax planted on 76-cm rows at a rate of 7.85 kg ha^{-1} (360 PLS m^{-2}). Flax seed was sourced from Southwest Seed Inc. Dolores, CO. Fall seeding was conducted on September 3rd of 2020 at both sites. Dormant seeding was conducted on November 4th of 2020 at both sites.

Flame weeding treatments were applied in spring of 2021. Flame was applied using an Agricultural Flaming Innovations 2-row propane flame weeder pulled by a John Deere 2155 utility tractor (Agricultural Flaming Innovations, Lincoln, NE; Deere & Company, Moline, IL). The flame weeding implement was configured for the 76-cm row spacing and calibrated differently for broadcast and inter-row flaming. Broadcast flaming was conducted with closed flaming hoods to concentrate heat, and a burner angle of 50°. Flamer hoods were opened for inter-row flaming to allow heat to escape around the flax rows, thereby concentrating heat in the inter-row space. Inter-row flaming was conducted using a burner angle of 30° (Ulloa et al., 2010). Both flaming configurations had a constant burner height of 20 cm from the ground. Flaming dose was also constant for both configurations at 93.5 L/ha. This dose was calculated based on application speed times and flaming pressure (3.22 kph x 241 kPa).

The Absaraka site was treated with flame weeding first on May 18th, 2021. We treated the plots in the evening to avoid morning dew, which decreases flaming efficacy. The bare soil temperature at the time of application was 17°C and the dew point was 11°C. Wind speed at the time of application was light and variable with infrequent 12 kph gusts. Flax was approximately 7-10 cm tall with multiple true leaves at the time of flaming.

Table 8. Flame weeding plus mechanical weed management treatments for perennial flax stands applied at Absaraka, ND and Comstock, MN in spring of 2021.

Treatment name	Early season action	Late season action
Control	n/a	Mowed as needed
Single broadcast	Broadcast flaming	n/a
Single inter-row	Inter-row flaming	n/a
Double inter-row	Inter-row flaming	Inter-row flaming
Inter-row + tine	Inter-row flaming	Tine weeding
Inter-row + Chisel plow	Inter-row flaming	Inter-row chisel plow application
Broadcast + inter-row	Broadcast flaming	Inter-row flaming

Data Collection – 2021-2022 Field Study

Flax and weed density were counted prior to the initial flame weeding application. Density was measured in four 0.25 m^2 quadrats per plot. Quadrats were placed with the center two rows of each four-row plot in a “V” pattern to capture spatial variation. Quadrat location was systematic, with each quadrat being placed at the same interval along transects spanning the inner two plot rows. Each quadrat was placed so that both inter and intra row space was measured as demonstrated by McCollough et al. (2020). Flax and weed density were then measured a second time following the initial flaming application. The second sampling interval occurred seven days after applying flame weeding to the plots.

Results and Adaptive Management

Following our initial flaming application at the Absaraka site, we observed 60 to 90% flax mortality among all flaming treatments (Data not shown). We detected little to no visible effect of flaming on weeds. Flax had emerged earlier than expected; we observed radicle and hypocotyl extension among excavated seeds as early as March 31st of 2021. Due to the early emergence of flax, we were forced to flame weed when it was at the multiple true-leaf stage. Flax at this growth stage displayed the greatest mortality in the greenhouse trials. Additionally, a miscommunication resulted in flax plots being hand weeded at Comstock, making replication of the treatments at our second site irrelevant to experimental objectives. We did not apply a second round of flame weeding that was planned as we assumed that additional flaming would totally eliminate any surviving flax from Absaraka.

Consequently, we shifted our weed management plan for plots that were not flame weeded to include mowing and interrow cultivation. Mowing was conducted using a Toro mower with a deck height of 35 cm to avoid damaging immature flax (The Toro Company, Bloomington, MN). Inter-row chisel plowing was conducted using an Unverferth Perfect II field cultivator configured for 76.2 cm row spacing with individual chisels set at a depth of 7 cm (Unverferth Manufacturing CO., Inc., Kalida, OH).

In the fall of 2021, we observed high densities of winter annual weeds, most notably field pennycress (*Thlaspi arvense* L.), emerging within the flax plots. Twelve plots at each site that had not been destroyed from the initial flame weeding treatments in spring of 2021 were selected to receive treatments targeting winter annual weeds. Flame weeding and mechanical cultivation were compared for their ability to reduce winter annual weed density. We applied flame weeding to these plots utilizing a small-scale hand flame weeder. We chose to use more controlled hand-flaming as the field-scale flaming equipment had proved to be difficult to adjust to shield flax plants from damage. Hand flaming was applied using a Red Dragon Model VT 21/2-30SVC 400,000 BTU propane weeder with a 6.35 cm bell head (Flame Engineering, La Crosse, KS). The hand flamer was set to a constant 45 kPa and applied in the inter-row space at a walking pace, approximately 10-12 cm above the soil surface. A Honda hand-held rotary hoe was utilized for mechanical cultivation. Again, we measured flax and weed density prior to treatment in fall of 2021, and then in spring of 2022 to assess the efficacy of our treatments. Reductions in winter annual weed density were not detected between the treatments (*P*=0.3132, data not shown).

Harvesting was attempted in July of 2022 at both study sites in additional flax plots that were not treated with flame weeding. Prior to harvest, flax was swathed and left to dry for approximately two weeks. Extensive boll shattering at the Absaraka site during swathing and drying made harvest impractical for that location; the Comstock site was successfully harvested. Flax was directly combined using a Hege 125B plot combine (Hege Maschinen, Niederlassung, Germany). Flax yielded 59.44 kg ha^{-1} at the Comstock site.

Discussion

The failures of the field scale flax studies demonstrate the need to have a better understanding of agronomic best practices for stand establishment of a novel crop prior to attempting complex weed management research. We faced several issues in 2020 while trying to establish study sites at Comstock, MN and Carrington, ND resulting from uncertainty around optimal planting date, extreme weather events, and difficulties establishing cover crops.

Although flame weeding in the greenhouse showed some promise as a potential tool to manage weeds prior to flax emergence, we faced difficulties with the subsequent field trials. The major problem with the field-scale flaming study was that the flax had emerged well before the weeds, making flame weeding extremely risky. Unsurprisingly, flame weeding in first year seedling perennial flax was devastating, with flax suffering high mortality. Repeating this study at Comstock could have further shown the risk of flame weeding, however this was not possible due to the site being unintentionally hand weeded. The removal of weeds at Comstock not only made it impossible to study the effect of flame weeding on weed populations, but created an environment in which the entire thermal energy produced by flaming would impact the flax crop.

Our attempt at reducing the winter annual weed species density by applying hand flaming and tillage in fall of 2021 was also ineffective.

Fortunately, we had established enough additional plots at Comstock and Absaraka to attempt a harvest in July of 2022. Flax at Absaraka suffered extensive boll shattering, however, leading to a stand which could not reasonably be harvested. Excessive weed pressure at Absaraka would have further complicated harvest. Even after swathing, large amounts of green weeds remained intermixed with the flax windrows and would have prevented successful combining of the crop. These issues stress the importance of developing an effective weed management plan and a need for perennial flax genetic improvement. Seeking ecotypes of perennial flax which have a more determinant growth pattern could prevent harvest delays and thereby reduce yield loss (Dribnenki, 2011). The Comstock site did not have as much of an issue with boll shattering as Absaraka, and was successfully harvested, providing a low baseline of possible yield. The yield recorded, however, was much lower than one would hope as we had harvested only 59 kg ha^{-1}, while the average annual flax (*Linum usitatissimum* L.) yield in nearby Canada is typically 1200 kg ha^{-1} (Rowland, 2006). We had also anticipated the potential for two harvest intervals in 2022 (i.e., July and September), but this did not occur. Flax was possibly limited by lack of moisture following the initial harvest, preventing a second harvest.

Conclusion

Perennial crops offer an attractive opportunity for producers to cultivate a crop that yields both grain and ecosystem services. Perennial flax is one such crop that may be profitable due to its high-quality oilseed, however much work remains to make it viable for production agriculture. Basic agronomic best practices for cultivating perennial flax could yet be refined, and weed management options are minimal. Extensive breeding efforts will also be necessary for perennial flax. A focus of breeding efforts should be increasing seed size, seed test weight, emergence vigor, and regrowth vigor.

Our work demonstrated that sowing of competitive intercrops and flame weeding may not be the best options for weed management in perennial flax. Interrow cultivation was the only method we noted to be viable for reducing some of the weed density within perennial flax stands. Much work remains as well for improving the yields of perennial flax. The studies we attempted between 2020 and 2022 on perennial flax represent the first steps of what is likely to be a long process in rounding out production guidelines and improved varieties for the novel crop.

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