Integrating the organic arsenal for weed control in field pea and lentil

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ABSTRACT

Organic weed management in pulse crops is challenging due to their uncompetitive nature in the presence of weeds. Since the use of synthetic herbicides is prohibited in organic production, growers tend to rely heavily on mechanical and cultural weed control methods. To our knowledge, no previous research has directly compared the following in-crop mechanical weed control (MWC) methods: rotary hoe (RH), harrow (H) and inter-row cultivation (IT) combined with the cultural practice of increased crop seeding rate (SR) in organic pulse crops. The objective of this research was to determine the effect of mechanical weed control (RH, H and IT) and crop (SR) alone and in combination on weed suppression and yield in organically grown field pea (*Pisum sativum* L.) and lentil (*Lens culinaris* L.). The study was conducted in organically managed cropping systems in Saskatchewan, Canada in 2016 and 2017. Mechanical weed control methods including RH, H and IT were applied in a factorial arrangement with normal and increased SR in organically grown field pea (1 and 1.5X) and lentil (1 and 2X). Averaged over all site-years, all MWC treatments resulted in similar field pea yield increases ranging from 38% to 50%. Paired and multiple treatments reduced weed biomass in field pea by 73% to 86%. Increasing field pea SR 1.5X did not significantly improve weed control, but it did increase field pea yield by 13%. The combination of RH-IT resulted in 40% higher lentil grain yield. Increasing lentil SR to 2X the normal rate resulted in a 23% increase in yield, while weed biomass was reduced by 16%. Combinations of RH-IT and RH-H-IT in lentil resulted in a 76% and 79% decline in weed biomass, respectively. Treatments including RH, provided the greatest spectrum of weed control spectrum in both crops as on average they controlled more than 80% of the green foxtail (*Setaria viridis* L.), 60% of the wild mustard (*Sinapis arvense* L.), and 86% of the lambsquarters (*Chenopodium album* L.). Use of MWC did not provide robust control of redroot pigweed (*Amaranthus retroflexus* L.) or wild buckwheat (*Polygonum convolvulus* L.) and stimulated emergence of stinkweed (*Thlaspi arvense* L.). Our study suggests that effective weed suppression and greater yield can be achieved in an organic crop production system when MWC methods are paired with cultural practice of increased crop SR.

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DEDICATION

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LIST OF ABBREVIATIONS

SMA - Saskatchewan Ministry of Agriculture

SPG - Saskatchewan Pulse Grower's

IWM - Integrated Weed Management

CPWC - Critical Period of Weed Control

MWC - Mechanical Weed Control

KCRF - Kernen Crop Research Farm

GRF – Goodale Research Farm

RH - Rotary Hoe

H - Harrow

IT - Inter-row Tillage

Untr – Untreated Control

HW – Hand Weeded Check

SR - Seeding Rate

ANOVA – Analysis of Variance

MANOVA – Multivariate Analysis of Variance

GDD – effective growing degree days (base temp 5 ^{o}C)

LIST OF EQUATIONS

Equation 3.1 Potential economic return.

R= (Y x PR) – (TC+ (SW x C)

R - return ($ ha^{-1})

Y - seed yield (kg ha^{-1})

PR - price received ($)

TC is treatment cost ($ ha$^{-1)}$

SW - seed weight planted (kg ha^{-1})

C - seed cost ($ kg^{-1})

1.0 Introduction

Field pea and lentil are two commonly grown pulse crops in Saskatchewan. Saskatchewan remains the Canadian leader in pulse production accounting for 68% of all global dry pea (*Pisum sativum* L.) exports and 96% of lentil (*Lens culinarus* L.) exports (Bekkering, 2014). In 2014, lentil occupied 1.6 Mha of agricultural land, whereas pea occupied 1.57 Mha (Statistics Canada, 2018). Currently, pulse crops attract much attention from both researchers and growers across Western Canada, because of their high economic returns, reduced requirements for nitrogen fertilization, as well as diversification of crop rotation. Adaptation to cool growing temperatures, and tolerance to drought, make pulse crops suitable for Saskatchewan. Increased consumer emphasis on health and nutrition makes them essential crops in the global agricultural industry due to their important dietary components: proteins, minerals, and vitamins (Saskatchewan Ministry of Agriculture (SMA), 2017).

Competition with weeds results in irreversible yield losses in pulse crops. Studies conducted in Western Canada have demonstrated 51% to 86% reduction in field pea yield under the absence of weed control (Blackshaw and O’Donovan, 1993). Under very high weed competition, pea yield losses as high as 100% were reported (Bastiaans and Kropff, 2003). The poor competitive ability of field pea and lentil with weeds can be attributed to several factors including the slow rate of growth, short height and slow canopy closure (Harker et al., 2001; McDonald et al., 2003). Numerous studies reported detrimental effects of weeds on physiological development of pulse crops (Townley-Smith and Wright, 1994, Baird et al., 2009a, 2009b; Rahimzadeh et al., 2013, Syrovy et al., 2015; Stanley et al., 2017, Redlick et al., 2017). Thus, the choice of weed control strategy is critically important to effectively manage weeds in uncompetitive crops as field pea and lentil. The occurrence of herbicide resistance worldwide requires diversification of weed control strategies to reduce reliance on herbicides by integrating them with alternative weed control strategies (O'Donovan et al., 2007; Mortensen et al., 2012, Harker and O'Donovan, 2013; Liebman et al., 2016). For weed control, organic producers primarily rely on mechanical and cultural weed management strategies. During the last two decades, studies at the University of Saskatchewan have resulted in the development of recommendations for separate use of in-crop mechanical weed control (MWC) methods, as rotary hoe, flex-tine harrow, and inter-row cultivation. Shirtliffe and Johnson (2012) demonstrated that two passes with the rotary hoe in field pea reduced weed biomass in field pea by 75% and increased seed yield to 87% of the herbicide treatment. A study by Benaragama and Shirtliffe (2013) reported 71% lower weed biomass with post-emergence harrowing in organic oat (*Avena sativa* L.). A recent study by Stanley et al. (2017) found that a early season single inter-row cultivator pass controls the majority of inter-row weeds in organic field pea.

There have been several studies examining cultural weed control practices. Baird et al. (2009a; 2009b) found that increasing seeding rate (SR) of organic field pea and lentil resulted in 68% and 59% reduction in weed biomass when compared to standard seeding rates, respectively. Increased density of a competitive oat cultivar resulted in 63% weed biomass reduction and 11% higher oat yield (Benaragama and Shirtliffe, 2013). Lastly, studies by Harker et al. (2001) identified weed control timing in field pea at two weeks after field pea emergence, while a similar study in lentil found weeds need to be controlled between the 5th and the 10th node stages (Fedoruk et al., 2011). To the best of our knowledge, the abovementioned methods have not been directly compared to each other, or the combined effects have not yet been evaluated. Hence, considering the weed control potential of both cultural and physical weed control practices, the question of which of these methods is the best for weed control in organic pulse crops requires a more refined answer.

It was hypothesized that different MWC methods would affect weed biomass and yield of organic field pea and lentil differently when applied at recommended and increased seeding rate. The objective of this research was to determine the effect of MWC (rotary hoeing, harrowing and inter-row cultivation) and seeding rate (recommended and 1.5 to 2X rate) on weed suppression and yield of organically grown field pea and lentil. At the conclusion of this study, we will determine the most effective MWC system for pea and lentil under organic conditions. This information could benefit both conventional and organic field pea and lentil producers resulting in sustainable weed management strategies with high economic returns.

2.0 Literature Review

2.1 Integrated Weed Management (IWM)

Weeds remain the major agricultural pest since the domestication of crops (Baker, 1991). Overreliance on herbicides over the last several decades has resulted in increased cases of herbicide-resistant weed biotypes worldwide (Mortensen, 2012; Owen, 2016). Agricultural weed management is generally split into herbicide based (conventional) and non-herbicide based (organic) management systems, although, weed control complexity is present in both systems (Knight et al., 2010, Heap, 2016, Liebman et al., 2016). To address weed management challenges some weed scientists revitalized the use of integrated weed management (IWM). The core elements of integrated weed management are cultural (Baird et al., 2009a, 2009b; Benaragama and Shirtliffe, 2013; Syrovy et al., 2015), biological (Bond and Grundy, 2001), mechanical (Johnson, 2001; Shirtliffe and Johnson, 2012; Stanley et al. 2017), and optimized chemical weed control (Redlick et al., 2017). A combination of these practices can provide the crop with a competitive advantage over weeds, resulting in reduced weed interference and fewer weeds seeds entering the seed bank (O'Donovan et al., 2007; Harker and O'Donovan, 2013). Thus, IWM will reduce the selection pressure for the development of herbicide-resistant weeds while maintaining adequate weed suppression (Blackshaw et al., 2008; Harker and O'Donovan, 2013); thus, increasing agricultural sustainability.

2.2 IWM in Organic Cropping Systems

Weed management is a significant barrier to organic system sustainability (Bond and Gundy, 2001, Shirtliffe and Johnson, 2012, Evans et al., 2016). In organic systems, the use of synthetic pesticides is strictly prohibited, and maintaining weeds at manageable levels with alternative methods is critically important (Blake, 1990). Thus, organic producers rely heavily on cultural and physical management strategies. Successful non-chemical weed control strategies; therefore, require the systematic use of multiple weed control tactics including extended crop rotations (Liebman and Dyck, 1993), crop competitive ability (Benaragama and Shirtliffe, 2013), elevated crop SR (Baird et al., 2009a, 2009b), MWC (Melander et al., 2017) and inter-cropping (Liebman and Davis, 2000). Up to date, little information is known on utilizing multiple mechanical and cultural practices together, which might limit the adoption of ecologically based weed management practices. Therefore, to fully utilize the potential of IWM in organic systems, new enhanced cultural and mechanical weed control strategies need to be developed.

2.3 Cultural Weed Control

Due to low cost and accessibility, cultural weed management practices, are widely practiced among organic producers worldwide (Mohler, 2001b). These practices include critical period of weed control (CPWC), which is defined as a period during the crop growth cycle when weeds must be removed to prevent yield losses (Bond and Grundy, 2001; Knight et al., 2010; Knezevic and Datta, 2015), crop rotation, increased crop SR, choice of crop with a high competitive ability, the choice of row spacing, as well as seeding depth and timing (Knight et al., 2010).

2.3.1 The Critical Period of Weed Control

Yield losses due to weeds can be minimized when weed control is performed during the CPWC. The CPWC starts with the duration of weed interference and ends with duration of the weed-free period, while the CPWC ends when the emergence of new weeds no longer affect crop yield (Knezevic et al. 2002). Radosevich et al. (1997) and Rajcan et al. (2004) reported a limited reduction in-crop yield due to early weed interference. Similarities in start and duration of the CPWC were reported in different crops (Hall et al., 1992, Martin et al. 2001; Harker et al., 2001; Knezevic et al. 2003), which in most cases occurred early after sowing; however, Zimdahl (1980), reported longer critical period of weed control in uncompetitive crops as lentil. Since early weed emergence may translate into an earlier beginning of CPWC (Fedoruk et al., 2011), it is critical to improve crop competitive ability under the presence of weeds (Blackshaw et al., 2002). Hence, it is essential to know when weeds start to cause unacceptable yield loss.

The CPWC for lentil was determined by Fedoruk et al. (2011) to last between the 5 to 10 node stage. According to Norsworthy and Oliveira (2004), crop canopy closure in lentil was associated with the end of CPWC as subsequent weed cohorts were shaded. These results correspond with Fedoruk et al. (2011) findings. In field pea, it was found that presence of weeds during the initial 20 days did not affect pea seed yield (Singh et al., 2016). A similar study by Harker et al. (2001) found that the beginning of the CPWC in field pea in Western Canada started 1 or 2 weeks after field pea emergence. Thus, early weed control is critical to avoid yield losses due to weeds.

2.3.2 Increased Crop Seeding Rate

Crop competitive ability can be improved though elevated crop SR (Baird et al., 2009a, 2009b; Benaragama and Shirtliffe, 2013). Higher crop population per area captures resources at a faster rate and thus remains more competitive in the presence of weed competition (Berkowitz, 1988; Mohler, 1996). Increased crop SR increases interspecific competition (Heege, 1993) and decreases intraspecific competition (Weiner et al., 2001). Numerous studies have reported limited yield loss due to increased crop competition with weeds through manipulation of plant SR (Ball et al. 1997; Lemerle et al., 2004; Mason et al., 2007; Mohler, 2001; Regnier and Bakelana, 1995; Weiner et al., 2001); although, some studies indicated that extremely high seeding rates no longer benefit yield or crop-weed competition. Higher than recommended crop SR of wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.) and lentil (*Lens culinaris* L.) had no significant effect on weed control, yield and net return in studies by Khan et al. (1996) and Kirkland et al. (2000). There are couple of reasons why there might be no benefit from higher SR. O'Donovan and Newman (1996) found that decline in weed growth did not affect canola yield when SR was increased. This can be explained by greater intraspecific competition between crop plants thus resulting in no reduction in weed competitive ability with the crop (Zimdahl, 1983). Since nutrient and moisture deficiency is common in Western Canada increased intraspecific competition can negatively influence crop production (Kirkland et al., 2000). Controversially, an Australian study suggested increasing lentil SR up to 230 plants m^{-2} for areas where environmental conditions are less favorable (Siddique et al., 1998). Redlick et al. (2017) reported in a concurring study that increasing SR of lentil to 260 plants m^{-2} supplemented with reduced herbicide rate resulted in similar weed suppression and yield when compared to single herbicide treatment applied in lentil seeded at a rate of 130 plants m^{-2}.

Indeed, increased crop SR does not always improve crop yield and grain quality; but it may improve weed control over the long-term as less seed weed seeds enter the seed bank (Boyd et al., 2009; Kolb et al., 2010). The current SR recommendation for lentil in Western Canada is 130 plants per square meter (Saskatchewan Pulse Growers, 2018). However, a study by Baird et al. (2009a) reported that increasing SR of lentil under organic conditions to 375 seeds per square meter reduced weed biomass by 59% and resulted in maximum economic returns at the same time. Similar results were achieved when increasing SR of field pea to 120 plants per square meter, which reduced weed biomass up to 68% and increased pea yield as well (Baird et al., 2009b). Hence, optimizing SR is critical for enhanced weed suppression and improved grain yields.

2.3.3 Crop Competitive Ability

Use of competitive crop varieties is an effective practice to reduce yield losses associated with weed-crop competition. Use of crop competitive ability is particularly important in organic systems where weed control strategies are limited. Many studies reported reduced crop yield losses when growing competitive genotypes (Lemerle et al., 1996; Mason et al., 2007, Benaragama et al. 2014); yield potential of highly competitive genotypes is rarely high (Huel and Hucl, 1996). Benaragama et al. (2014) stated that selected cultivars should retain a trade-off between both yield and weed suppressive ability. Understanding of crop physiology, morphology, phenology (Lemerle et al. 2001b) and growing environment (O'Donovan et al., 1999; Rassmussen et al., 2009) are critically important to better accommodate how crop varieties suppress or tolerate weed competition. Several studies associated increased crop biomass production (Spies et al., 2011), higher leaf area index and long vines (Wall and Townley-Smith, 1996; McDonald, 2003) with increased crop competitive ability. Along with above-mentioned characteristics, Syrovy et al. (2015) reported higher crop competitive ability when field peas were grown in a mixture of leafed and semi-leafless varieties. Growing a competitive cultivar resulted in 22% reduction in weed biomass in tame oat in a study by Benaragama and Shirtliffe (2013). Importantly, Benargama et al. (2014) found a minor difference regarding crop competitive ability with weeds among competitive and non-competitive tame oat parent. Since varieties developed for organic agriculture are bred under weed-free environments, there is a need to develop varieties suitable specifically for organic cropping systems (Mason and Spaner, 2006; Lammerts van Bueren et al., 2011; Carkner and Entz, 2017) where high weed pressure is more abundant (Mäder et al., 2002). Therefore, the choice of competitive cultivar should be integrated together with cultural (Weiner et al., 2001, Olsen et al., 2005, Baird et al., 2009a, 2009b) and MWC practices (Benaragama and Shirtliffe, 2013, Stanley et al., 2017).

2.3.4 The Choice of Crop Row Spacing

The choice of row spacing is a subject of many concerns among organic producers. Some farmers in Europe adopted wider row spacing in spring cereals (18 to 30 cm) for two reasons. First is the ability to control weeds between rows; second, wider rows result in higher protein concentration which provides higher price premiums for organic grain (Hiltbrunner et al., 2005). These results are not consistent as Boström et al. (2012) reported that an increase in row spacing from 12 to 24 cm resulted in a 12-16% decline in cereal grain yields. Several studies reported that crops seeded in narrow rows were more competitive with weeds (Weiner et al., 2001; Begna et al., 2001; Mohler, 2001b; Kolb et al., 2012; Gallandt et al., 2015) and led to increase in grain yield when compared to wider rows (Riethmuller, 2014; Fahad et al., 2015). However, Benaragama and Shirtliffe (2013) reported that narrow row spacing had no effect on weed biomass and final grain yield of organic oat. Therefore, growers may supplement the choice of narrow row spacing with MWC or higher than recommended SR.

2.3.5 The Choice of Seeding Depth

Large-seeded pulse crops, such as field pea and lentil can be planted deep (Johnson, 2001), although, studies by Johnston and Stevenson (2001) reported little benefit of seeding field peas deeper than 3 inches. Nevertheless, deep seeding allows for shallow pre-emergence mechanical weed control tillage. Since pulses are seeded deep, there is a chance to apply shallow pre-emergence rotary hoeing (Lovely et al., 1958; Peters et al., 1959; Mulder and Doll, 1993), rod weeding (Johnson and Holm, 2010), harrowing (Rasmussen, 1996) and shallow cultivation (Mohler, 2001) between the time of seeding and crop emergence. Since the majority of weeds germinate from the top 2 cm layer of soil (Mohler, 1996; Mohler and Galfrod, 1997); there is a limited risk of pulse crop seedling damage with shallow tillage applied immediately after seeding operations (Johnson, 2001). Importantly, field pea and lentil have underground nodes which allow them to recover physical hypocotyl damage caused by pre-emergence weed control application (Hnatowich, 2000).

2.3.6 The Choice of Seeding Timing

Seeding timing can be manipulated to facilitate weed control. In organic cropping systems, late seeding is often recommended to allow for a false seedbed and the cultivation of weeds before seeding or crop emergence (Rasmussen, 2004). Tillage and delayed seeding controlled greater than 70% of wild oat in wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) (Darwent and Smith, 1985). Johnson and Holm (2010) reported that delayed seeding of field pea until mid-to-late May, combined with deep seeding and pre-emergence tillage decreased weed biomass from 23 to 68%, and resulted in 81% of the yield where herbicide was applied. Nevertheless, despite the weed control benefit, studies by Douds et al. (2018) reported a decline in indigenous arbuscular mycorrhizal fungi population after false seedbed operation as weed host plants are killed. Thus, delayed seeding should focus on managing problematic weeds species while minimizing negative effects.

2.4 Mechanical Weed Control

All forms of tillage have impacts on weeds, but only tillage that is targeted against weeds is considered as MWC (Brandsaetter et al., 2012). Mechanical weed control is a common practice for weed control in organic cropping systems (Cloutier and Leblanc, 2001). Control measures can be applied to the entire cropping area or may be used for selective weed control within and or between the crop rows (Bond and Grundy, 2001). The concept of MWC is to ease crop competition with weeds by physical removal of weeds from the cropping system. Among weed control, it may loosen the soil and improve tilth, which occasionally is more important to crop yield than weed control itself (Brandsaetter et al., 2012); although reductions in soil organic matter and aggregate stability might occur with heavy reliance on cultivation (Grandy and Robertson, 2006). Despite a huge diversity of MWC tools available on the market, there are similarities regarding soil disturbance patterns within each approach used for MWC (Bowman, 1997; Van der Schans et al., 2006; Cloutier et al., 2007). Presently, in Western Canada, there is sufficient information on the use of MWC tools as a rotary hoe (Shirtliffe and Johnson, 2012), flex-tine harrow (Benaragama and Shirtliffe, 2013) and inter-row cultivation (Stanley, 2017). However, information on integrated use of abovementioned MWC practices is limited.

2.5 Minimum Tillage Rotary Hoeing

The first use of the rotary hoe in North America dates back to 1839, while, the first rotary hoe use in legumes was documented in 1915 (Peters et al., 1959). Nevertheless, conventional rotary hoe and min-till rotary hoe are not commonly used for weed control in Western Canada; as few organic producers utilize them as a part of their weed management strategy (Beckie, 2000). The minimum tillage rotary hoe has two separate wheels (Figure 2.1). The first row of wheels throws the soil from the depth of 3 to 5 cm. The second row buries or flicks the weeds out from the soil surface (Leblanc and Cloutier, 2011). The main idea of rotary hoeing is to uproot the weeds at the white thread stage, just prior to emergence. Weeds, at the white thread stage, can be detected merely by lightly wiping across the soil surface with a hand or a spade. The young weeds are "white" (have not been exposed to sunlight), tender, and very susceptible to injury caused by the curved spiked wheels of the min-till rotary hoe (Bowman, 2002; Shirtliffe and Johnson, 2012).

Figure 2.1 A minimum-tillage rotary hoe in operation (Photo credit: Oleksandr Alba)

The rotary hoe provides effective control of small-seeded annual weeds as green foxtail (*Setaria viridis* L.) and wild mustard (*Sinapis arvensis* L.) emerging from a depth less than 2.5 cm; however, control of large-seeded weeds emerging from a depth greater than 2.5 cm is limited (Endres et al., 1999; Boyd and Brennan, 2006; Shirtliffe and Johnson, 2006). Small-seeded weeds are also easy to control a few days after crop emergence. Weed control efficacy is reduced if grassy and broadleaf weeds exceed the one-leaf stage and cotyledon stage, respectively. Thus, it is critical to control shallow emerging weeds before their root system is well established (Cloutier and Leblanc, 2001).

The primary limitation for rotary hoe application is timing as there is a very narrow window when the rotary hoe is effective. Rotary hoe efficacy depends on weather conditions directly before and after application (Endres et al., 1999). Unfavorable environmental conditions can decrease the efficiency and restrict the timing for repeated rotary hoe use. Importantly, even after multiple passes of min-till rotary hoe crop residues were still evenly distributed across the field (Shirtliffe and Johnson, 2012); however, high levels of crop residue could reduce rotary hoe efficacy. Residue binding to an implement requires cleaning which therefore decreases operating time (Figure 2.2).

Figure 2.2 Cleaning of the minimum tillage rotary hoe after operation in high residue fields. (Photo credit: Oleksandr Alba)

It is critical to ensure that the rotary hoe has adequate clearance to avoid collection of large amounts of residue and thus extensive damage to the crop (Cox et al., 1999; Gonsolus, 1990). To avoid high crop injury and implement damage, the height the rotary hoe can be raised in high residue and stony areas. Alternatively, organic producers can utilize models designed for high-residue conditions, with longer (extended) arms which prevent plugging with crop residue

(Leblanc and Cloutier, 2011). Also, large stones and residue should be removed from the fields to prevent critical damage to an implement, ensure effective operation, and minimize reestablishment of displaced weeds (Bond and Grundy, 2001).

The rotary hoe can be used for both pre and early post-emergence weed seedling management (Endres et al., 1999; Forcella, 2000; Leblanc and Cloutier, 2001a, 2001b). Increased number of passes with the rotary hoe may also impact the relative crop tolerance to this implement (Shirtliffe and Johnson, 2012). A slight decrease in pea yield was observed after two passes with the rotary hoe; whereas, increased yield losses were observed after multiple passes with the rotary hoe, which overcomes the benefit of weed removal (Place et al., 2009). Accordingly, the crop must be deeper rooted than the weeds to prevent critical crop injury (Bowman, 2002). Appropriate rotary hoe timing is critical. Endres et al. (1999) reported that rotary hoe should be applied one to five days after planting with a consequent pass seven to ten days later. Rankin (2008) recommended that rotary hoeing be conducted 5-7 days after planting or just before crop emergence followed by another pass 5-10 days later if the weed pressure remains high.

The optimum conditions for rotary hoe application is a warm, windy day with bright sun conditions as more weeds will desicate before they can reroot. Rotary hoeing during midday will benefit the crop as it will be less turgid and consequently more flexible to rotary hoe application (Endres et al., 1999). At the time of application, soil surface should be dry, so the soil particles are not balling up (Bond and Grundy, 2001). Dry weather following application can maximize weed seedling mortality (Rankin, 2008). To make sure that weeds are efficiently controlled at field ends, starting and stopping should be at proper forward speed. To reduce crop seedling loss and increase the lifespan of the implement it is better to avoid making sharp turns unless the hoe is raised entirely out of the ground (Rankin, 2008). The speed of rotary hoe application should be in the range from 12 to 20 km h^{-1} (Endres et al., 1999; Boyd and Brennan, 2006; Cloutier et al., 2007; Rankin, 2008; Place et al., 2009; Shirtliffe and Johnson 2012). Increasing speed above that range does not improve the level of weed control (Bond and Grundy, 2001), although on heavy or crusted soil adding extra weight on a tool-bar or increasing speed of cultivation may be necessary. This would increase down pressure of curved spiked wheels on the soil surface, which improves the soil aeration, organic matter mineralization (Gilbert et al., 2009) and overall weed control performance (Leblanc and Cloutier, 2011).

Numerous studies have reported more than 70% weed control efficacy with a single rotary hoeing after weed seed germination but before seedling establishment (Lovely et al., 1958; Peters et al., 1959; Mulder and Doll, 1993; and Schweizer et al.,1994, Shirtliffe and Johnson, 2012). Nevertheless, high weed control efficacy, yield benefits of rotary hoeing are variable. Studies examining rotary hoeing in soybeans (*Glycine max* L.) and dry beans (*Phaseolus vulgaris* L.) reported limited to no yield benefit despite significant reduction in weed interference (Vangessel et al., 1995; Cox et al., 1999; Amador-Ramirez et al., 2001; Leblanc and Cloutier, 2001). Conversely, some researchers reported both increased yields and weed suppression when rotary hoeing was applied at white thread state in corn (*Zea mays* L.) (Forcella, 2000) and field pea (Shirtliffe and Johnson, 2012). Importantly, Shirtliffe and Johnson (2012) found that additional 20% yield increase was observed when rotary hoeing at three node stage. However, the crop yield increase from a third pass was lower compared to the double pass (Shirtliffe and Johnson, 2006). Weed control with a rotary hoe can be effective, but is typically not as efficacious as chemical weed control. Nevertheless, the cost of a single rotary hoe operation is less than most single herbicide applications (Endres et al., 1999; Place et al., 2009). Therefore, a minimum-tillage rotary hoe is a promising weed control tool for both conventional (Mulder and Doll, 1993; Redlick et al., 2017) and organic weed management systems (Shirtliffe and Johnson, 2012).

2.6 Harrowing

Harrow is the most widely used form of in-crop mechanical weed control among organic producers (Figure 2.3; Gilbert et al., 2009; Jacobsen et al., 2010; Armengot et al. 2013). Many studies have reported positive weed control benefit of harrowing in cereals (Kirkland, 1995; Cirujeda et al., 2003; Velykis et al., 2009, Benaragamna and Shirtliffe, 2013) and pulse crops (Johnson, 2001; Dastgheib, 2004a; Johnson and Holm, 2010) and weed control harrows can be used to break the soil crust in heavy soils. The primary action of harrowing is through shallow soil covering and uprooting of weakly anchored weeds (Kurstjens et al., 2000; Kurstjens & Kropff, 2001; Kurstjens, 2007; Armengot et al., 2013).

Since harrowing is applied on an entire cropping area, some crop damage is inevitable due to poor selectivity of this implement (Rasmussen, 1991; Jensen et al., 2004). Crop and weed selectivity is a ratio between crop injury and weed control benefit (Rasmussen, 1992). Selectivity is considered low if the yield loss from crop injury is greater than the yield benefit of weed control (Rasmussen et al., 2008). This concept is applied to rotary hoeing and harrowing (Rasmussen, 1992; Kurstjens & Perdok, 2000; Lotjonen & Mikkola, 2000; Jensen et al., 2004) and inter-row tillage (Fogelberg & Gustavsson, 1999; Melander et al., 2005). Low selectivity is associated with reduced crop yields especially under low weed pressure (Rasmussen, 2004), inappropriate harrowing timing (Rasmussen & Nørremark, 2006) and implement adjustment (Böhrnsen, 1993). There should be adequate difference between the size of the crop and weed to prevent a reduction in selectivity (Rasmussen, 1992). Rasmussen et al. (2008) claimed that harrowing selectivity decreased in late growth stages under narrow row spacing, whereas good selectivity was observed when harrowing was applied at an early growth stage, regardless of row spacing. Importantly, selectivity is not affected by direction and orientation of harrowing. Crop damage can be decreased when harrowing aggressiveness corresponds to appropriate crop growth stage (Böhrnsen, 1993; Rasmussen et al., 2010). Adjusting harrow tines at an angle of 45^{o} backward from the direction of travel resulted in a higher level of selectivity and minimized crop injury in field pea (Johnson, 2001). Thus, crop stage, weed density, and environmental conditions should be considered when determining a tine harrow setting and the level of soil disturbance.

Harrowing can be applied both pre and post-crop emergence. Pre-emergence harrowing is effective when the majority of weeds germinate earlier than the crop (Rasmussen, 1996). Jones et al. (1995, 1996) stated that cutting at the soil surface and burial to the 1 cm depth and are the most effective ways to control weed seedlings, although the entire seedling needs to be covered with soil to ensure consistent control. Hence, weed mortality caused by soil covering depends on tine angle, growth habit and size of the plant (Baerveldt & Ascard, 1999). Consequentially, in-crop harrowing in the absence of weed emergence may have no effect on weeds (Johnson and Holm, 2010) and may stimulate new flushes of weed seedlings (Lundkvist, 2009) or in some cases delay crop emergence (Heard, 1993). Post-emergence harrowing occurs after the crop has fully emerged. As a result, post-emergence harrowing uproots only some weeds, while the remainder can be still exposed to sunlight due to incomplete burial. Total fatality due to burial is achieved with 2 to 3 cm burial depth; however, it rarely occurs when harrowing (Terstra and Kouwenhoven, 1981; Kurstjens and Perdok, 2000).

The timing of post-emergence harrowing determines weed control efficacy. Harrowing as early as 1-2 leaf stage in cereals and cotyledon stage in broadleaf weeds often coincides with the most sensitive developmental stage to mechanical injury (Lancashire et al., 1991; Rasmussen, 1993). No significant yield losses were observed with one harrow pass in barley and spring wheat until the 2.5 leaf stage (Lafond and Kattler, 1992); however, Leblanc and Cloutier (2011) claimed that harrowing wheat at two-leaf stage decreased wheat density and yield by up to 45% and 16%, respectively. Additionally, harrowing at later growth stages in winter wheat (Auškalnis and Auškalnienė, 2009) and field pea (Dastgheib, 2004a) had a negative impact on crop density and grain yield, which agree with Rasmussen (1991) findings. Conversely, Velykis et al. (2009) reported no significant effect on crop density and 62% weed density reduction in field pea when harrowing was applied between second and third leaf stage. Hence, the timing of application is critical to prevent irreversible crop damage and yield loss.

Figure 2.3 The spring tine “Einbock” harrow (Photo credit: Oleksandr Alba)

The ability to recover from any soil covering describes the tolerance of crops to post-emergent harrowing (Hansen et al., 2007). Increased speed and high aggressiveness of tines could potentially cause damage to the crop, outweighing the benefits of weed control (Rasmussen, 1990; Rueda-Ayala et al., 2011). Good crop tolerance to weed harrowing has been reported in some studies (Smith et al., 1994, Rasmussen, 1998). Taller and less flexible plants were found to be more tolerant to harrowing than shorter cultivars with lower leaf area index (Rasmussen et al., 2004). Kurstjens and Perdok (2000), claimed that weed harrowing adjustments as timing, speed, tine angle as well as application timing should be tailored to specific crop as different plant groups have dissimilarities in response to changes in speed, working depth, and moisture content at the time of harrowing. Indeed, heterogeneous distribution of weed densities across fields could reduce the weed control efficacy if the harrowing intensity is not adjusted according to spatial weed distribution. A study by Rueda-Ayala et al. (2013), suggested utilizing a real-time harrow intensity adjustment algorithm to better accommodate weed spatial distribution and improve both weed control and crop yield performance. Indeed, Rueda-Ayala et al. (2015) found that real-time weed control intensity adjustment provided greater than 51% weed control and resulted in reduced crop damage.

Inconsistent effects of sequential pre and post-emergence harrowing have been reported in many studies. Dastgheib (2004) and Lundkvist (2009) reported that harrowing wheat and field pea pre and post-crop emergence provided adequate control of early and late emerging species and did not significantly reduce crop density. These results agree with Rasmussen & Rasmussen (1995, 2000), who reported that combination of pre and post-emergence harrowing reduced weed biomass by 61 to 74%. Brandsaeter (2012) reported that combination of both pre and post-emergence harrowing did not provide robust weed suppression when compared to harrowing pre or post-emergence alone. Hence, the success of pre and post weed harrowing might depend on the time of weed emergence and community composition.

The efficiency of harrowing is sometimes affected by the number of passes (Kirkland, 1995; Johnson, 2001). A single pass with a harrow in wheat at high speed resulted in same weed control intensity produced by multiple harrowing applications at low speed (Pannacci et al., 2017). Up to three or even four passes were required to decrease weed density by 80% in spring barley (Auškalnis and Auškalnienė, 2009) and spring wheat (Kirkland, 1995).

Environmental conditions in the field can be variable and may not allow for additional applications. Two passes with a spring tine harrow at the same time in wheat grown under narrow row spacing resulted in notable weed biomass decline and increased yield by 10% when compared to single harrowing pass (Pardo et al., 2008; Pannacci et al., 2017), this indicates that multiple weed control passes on the same day can be acceptable; although, a study by Leblanc and Cloutier (2004) reported 22 to 45% reduction in wheat crop density when flex-tine harrow was applied more than once.

Numerous studies reported that positive yield responses are rare with weed harrowing which are associated with low weed competition and when conducted at sensitive crop stage (Jensen et al., 2004; Lundkvist, 2009; Rasmussen et al., 2010; Johnson & Holm, 2010). The extent of crop damage caused by harrowing can vary both between crops (Lundkvist 2009) and in some cases, between varieties of the same crop species (Hansen et al., 2007). Nevertheless, a significant reduction in weed interference after the use of harrow was documented in several studies (Dastgheib, 2004; Benaragama and Shirtliffe, 2013; Armengot et al., 2013). Incorporation of harrowing into an IWM system could provide additional benefits. Several elements of IWM as narrow row spacing, choice of competitive variety, increased crop seeding rate combined with harrowing resulted in an oat (*Avena fatua* L.) yield increase by 25% in comparison to harrowing alone (Benaragama and Shirtliffe, 2013) indicating that harrowing should not be considered as standalone weed management method.

2.7 Inter-row Cultivation

Inter-row cultivation has been a critical component of a weed management strategy worldwide (Figure 2.4). Inter-row tillage remains vital for weed management in a variety of cropping systems including: vegetable production (Melander and Hartwig, 1997; Riemens et al., 2007) organic production (Bond and Grundy, 2001; Melander et al., 2005, Kolb et al., 2012; Staley et al., 2017) and for production of some specialty crops (Van der Schans and Bleeker, 2006). Due to increased cases of herbicide resistance (Mortensen et al., 2012; Heap, 2016) cultivation can serve as a cornerstone in the integrated management of herbicide-resistant weeds. Inter-row crop cultivating tillage is designed for weed control in row crops as only weeds that are present in-between crops row are subjected to removal (Melander et al., 2003, Melander et al., 2017). The primary mode of action of the inter-row cultivation is though burying weeds, uprooting them, breaking them apart and leaving them to desiccate (Terpstra and Kouwenhoven, 1981). Additionally, it can break up soil crusting and thus can increase mineralization, soil aeration, and water infiltration.

(a) (b)

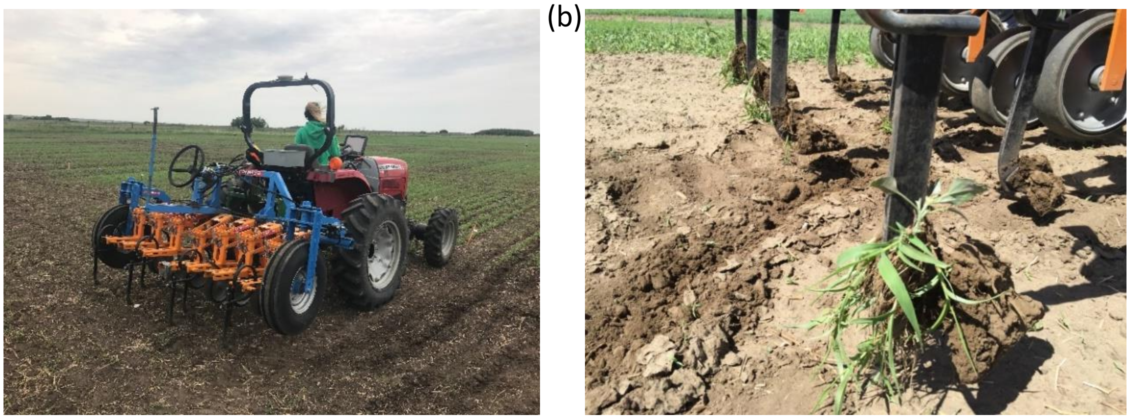


Figure 2.4 "Schmotzer" inter-row cultivator (a) inter-row cultivator sweeps (b) (Photo credit: Taryn Zdunich & Oleksandr Alba)

Inter-row cultivation is a highly selective form of mechanical weed control. Compared to other post-emergent weed control strategies, which have a narrow range of stages at which they can be performed, inter-row cultivation can be applied at later stages with minimal adverse effect on crop yield. In contrast to harrowing and rotary hoeing which control weeds when they are tiny, inter-row cultivation is effective in controlling large weeds (Gonsolus, 1990; Vangessel et al., 1998). Davies and Welsh (2002) considered inter-row cultivation as a highly selective method of weed removal resulting in minimal crop damage. Due to a high level of selectivity of inter-row cultivation, it can be used later during the crop growth cycle allowing for the crop to be relatively weed-free during the CPWC (Swanton and Weise, 1991), however, the CPWC for the crop must be determined to coincide with the proper timing for inter-row cultivation (Davies and Welsh, 2002). Inter-row cultivation can effectively control weeds that are present or emerging at the time of the cultivation event; however, recovered weeds would still compete with crop for resources if control measures are not applied to residual weed community (Bond and Grundy, 2001; Zimhdahl et al., 1988). Also, cultivation can stimulate germination of some weed species (Bond and Grundy 2001; Zimdahl et al. 1988) and restrict germination of others (Davis and Renner, 2007) by altering weed recruitment depth which increases the probability of fatal germination of several species.

Selective weed control may decrease with late cultivation timings (Melander et al., 2003) since crop roots are subjected to pruning when cultivator moves along the crop row (Stanley, 2016). Schweizer et al. (1994) reported an 8% corn crop stand loss with three in-row cultivations. A recent study by Stanley et al. (2017) observed minimal yield loss when field pea and lentil were cultivated once at early growth stages when compared to more frequent and delayed cultivations. These results agree with Vangessel et al. (1998) and Kolb et al. (2012). Stanley et al. (2017) reported that cultivating multiple times including late cultivations reduced yield by 15% to 30% in field pea and lentil; thus, cultivation should be applied as infrequent and as early as possible.

To minimize crop damage while increasing efficiency of weed removal the choice of speed and accuracy of inter-row cultivation are essential. Presently, cameras can locate the cultivator shank with a precision of ± 0.4 cm, and hydraulic side shift technology allows weed control to be performed at high speed without sacrificing precision (Tillett et al. 2002; Tillet and Hague, 2006; Nørremark et al., 2012). Additionally, a faster-driving speed results in greater soil disturbance intensity and thus weed control uniformity when compared to manual steering systems (Kunz et al. 2015b). Kunz et al. (2017) found that camera steered inter-row hoeing resulted in 78% weed control efficacy when compared to 65% using machine hoeing with manual guidance. Hence, vision-guidance technology allows accommodating both high speeds of operation while maintaining a high level of weed control accuracy (Connolly, 2003).

Hoe design may also play a crucial role in cultivation efficacy. Duck foot sweeps, which are currently used for inter-row hoeing, contribute to undesirable soil movement and consequently to significant crop soil covering. Additionally, weed control performance may be spatially uneven as cultivation depth with these sweeps is variable. Deformation of soil structure can also result in regrowth of weeds after weed control operation as weeds can survive on strong soil aggregates. (Melander et al., 2015). Recent advancement in hoe share design with L-share sweeps mounted on modified springs result in minor soil movement when cultivation depth is less than 0.5 cm (Znova et al., 2018).

Burial depth and moisture conditions after cultivation are critical to maximizing weed seedling mortality. Higher recovery rates may be related to the burial of small seedings immediately after germination, as they might have enough reserves to assist recovery, but recovery rates can be variable among species with different seed weight (Zhang and Maun, 1990; Maun et al., 1996; Shi et al., 2004; Maun, 2004). Large-seeded species often recover from burial better than small-seeded species (Habel, 1954; Baerveldt and Ascard, 1999). Pannacci and Tei (2014) reported that grasses were less sensitive to uprooting than broadleaf species, whereas Mohler et al. (2016) observed no effect on recovery from burial between them. These contradictory results suggest the recovery mechanism can be variable among different species. Higher rates of recovery were seen in Ambique-bean (*Strophostyles helvola* L.) even when burial exceed 150% of the seedlings height, which is mainly associated with greater seed mass (Yanful and Maun, 1996). In studies by Mohler et al. (2016) weeds which were only partially buried and still exposed to light exhibited recovery rates higher than 50%. Numerous studies reported similar high recovery when burial was incomplete (Shi et al., 2004; Baerveldt and Ascard, 1999; Jones et al., 1995a, 1995b). Increased cultivation depth may affect soil moisture, aggregate stability, and move weed seeds upward in the vertical soil profile; thus, deeper tillage may stimulate additional weed emergence (du Croix Sissons et al., 2000). Cultivating deeper than 7 cm should not target more weeds, since weed emergence rate tends to decline with depth (Cussans et al. 1996). Additionally, deeper tillage may dilute fertile organic soil layer by moving it deeper to anaerobic conditions where biological processes are no longer active. Therefore, Ovsinskiy (1899) suggested to cultivate only as shallow as 5 cm to achieve adequate aeration, nitrification, and adequate weed suppression. Mohler et al. (2016) reported no weed seedling recovery from 4 cm of burial, but even relatively shallow burial of 2 cm provided effective control of a wide range of weeds species if weeds were covered entirely with soil (Mohler et al., 2016). Hence, since soil covering increases with depth (Sogaard, 1998), the cultivation depth should trade-off between weed and crop soil covering. Importantly, single rain events followed by rapid dry conditions might decrease seedling recovery, while abundance in moisture after cultivation can promote recovery as moist soils offer less resistance to seedlings emerging from germinating seeds than dry soil (Morton and Buchele, 1960). Weeds deprived of light, recovering in continuously moist soils are at high risk to attack by fungi (Grime and Jeffrey, 1965) and microorganisms (Davis and Renner, 2007; Mohler et al., 2012). Cultivation can efficiently control tap rooted weed species (Melander et al., 2003) and some weeds established from roots, rhizomes, and tubers (Mohler et al.,1997). Inter-row cultivation provided excellent control of weeds emerging from seeds, while control of perennial species was limited due to their rapid regrowth. Mohler et al. (2016) found that perennial species emerging from seeds were the most sensitive to cultivation, as they have lower relative growth rate than annuals (Grime and Hunt, 1975). Hence, Mohler & Mohler (1996, 2016) claimed that species with higher seed mass are much more challenging to control due to their rapid seedling growth allowing them to escape burial.

Along with high selectivity (Davies and Welsh, 2002), weed control efficacy (Pullen and Cowell, 1997) and speed of operation (Kunz et al. 2015b) precision inter-row tillage comes with high initial investment cost (Joe Wecker, personal communication). Hence, adoption of inter-row cultivators would require a transformation of social, economic and management aspects of organic farming practices.

2.8 Ecologically Based Weed Management: Challenges and Opportunities

The use of non-chemical management has been substantially reduced since the introduction of synthetic pesticides; thus, weed control shifted to single herbicide based direct control of weeds (Blackshaw et al., 2008). Since weeds have evolved herbicide resistance, utilizing more herbicides for controlling the consequences of herbicide overuse use is no longer considered sustainable (Mortensen et al., 2012, Owen, 2016). As a result, some weed scientists have shifted their research focus on the integration of both indirect and direct weed control methods to understand the cause of weed problems in agroecosystems (Bond and Grundy, 2001; Blackshaw et al., 2008; Liebman and Davis, 2009; Redlick et al., 2017). Since ecologically based weed management implies the use of in-crop MWC, there is a need to improve selectivity, control of residual weed populations and optimize the timing of cultivation (Melander et al., 2017). Nonetheless, the intensity of in-crop MWC should trade off the weed control benefit and adverse effect on soil quality (Grandy and Robertson, 2006, Rasmussen et al., 2010).

Separate use of minimum tillage rotary hoe, flex-tine harrow or inter-row cultivation provided effective in-crop weed suppression in many studies conducted in Western and Eastern Canada (Figure 2.5) (Leblanc and Cloutier, 2011; Shirtliffe and Johnson, 2012; Benaragama and Shirtliffe, 2013; Stanley et al., 2017).

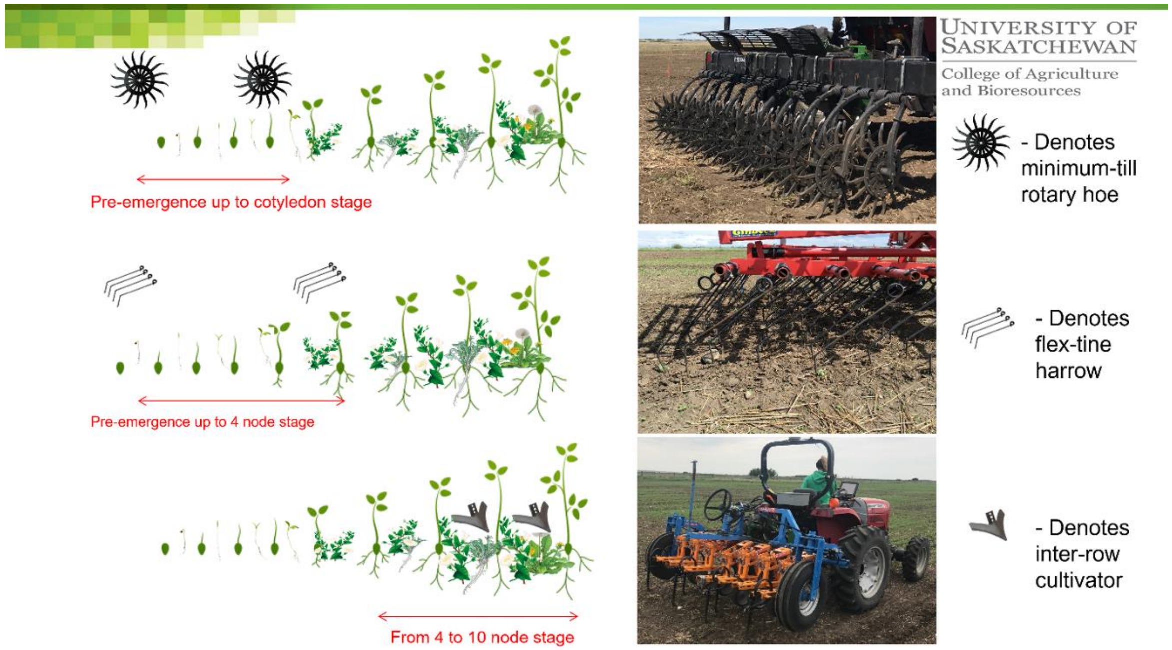


Figure 2.5 Timing of in-crop weed control. (Photo credit: Oleksandr Alba)

Some studies have reported enhanced weed control with multiple mechanical weed management practices (Swanton and Weise, 1991; Mohler et al., 1997; Kolb et al., 2012). Melander et al. (2001) claimed that harrowing in addition to inter-row cultivation results in 30% greater weed control when compared to harrowing alone. Integration of one rotary hoeing plus in-row cultivation in corn resulted in similar weed control when soil and post-emergence herbicides were applied (Vangessel et al., 1995).

Indeed, MWC cannot compete with herbicides in terms of weed control efficacy, however it can serve as a reliable alternative for integrated weed management (Riemens et al., 2007; Kunz et al., 2017). Thus, the practice of integrated weed management has the potential to decrease the cost of weed control while maintaining weed control efficacy (Mulder and Doll, 1993; Kolb et al., 2012; Benaragama and Shirtliffe, 2013; Redlick et al., 2017).

3.0 The Effect of Mechanical Weed Control (Rotary Hoeing, Harrowing, and Inter-Row Cultivation) and Crop Seeding Rate on Yield and Weed Suppression in Organically Grown Field Pea (*Pisum sativum* L.) and Lentil (*Lens culinaris* L.).

3.1 Introduction

The organic sector in Canada is rapidly growing. Organic acreage in Canada reached 2.43 million in 2015, 58% of which resides in the prairie region of Western Canada (Guerra, 2017). Field pea (*Pisum sativum* L.) and lentil (*Lens culinaris* L.) are two commonly grown crops among organic producers in Western Canada due to biological nitrogen fixation, which is very important for nutrient management in organic systems. In 2018, lentil occupied 1.6 Mha of all conventional and organic agricultural land, whereas pea occupied 1.57 Mha (Statistics Canada, 2018). Organic lentil and field pea production in Western Canada reached 11,760 and 17,759 hectares respectively (Guerra, 2017).

Poor competitive ability of pulse crops can translate into detrimental yield loses under presence of weed competition (Ball et al., 1997; Harker, 2001). Weed management in organic cropping systems relies on physical, cultural and biological control methods as herbicide use is strictly prohibited. Mechanical weed control (MWC) tools such as the rotary hoe (RH), harrow (H) and inter-row cultivator (IT) have been evaluated in several previous studies. The RH is very efficient in controlling small seeded weed species both pre- and post-crop emergence. Rotary hoeing in field pea at the white thread stage of weeds reduced weed biomass by up to 75% and increased yield up to 80% when compared to the untreated control (Shirtliffe and Johnson, 2012). Additionally, a 20% yield increase was observed when rotary hoeing was done at the three-node stage (Shirtliffe and Johnson, 2006), which indicates that there is a potential benefit of a double pass with the rotary hoe. Harrowing is another commonly used practice among organic producers, which controls weeds through a combination of uprooting and soil covering (Rassmussen, 1992). Dastgheib (2004) reported a 95% decline in weed biomass in field pea when harrowing pre-emergence at the two-node stage in comparison to the control treatment. However, control of large and late-season weeds with RH and H is limited. Generally, crops are tolerant to delayed rotary hoeing (Leblanc and Cloutier 2001a, 2001b, Leblanc et al., 2006), but effective control is achieved at the one-leaf stage in grassy weeds and cotyledon stage in broadleaf species (Boyd and Brennan, 2006; Shirtliffe and Johnson, 2012). Delayed harrowing at late growth stages result in lower crop-weed selectivity as crop injury overcomes the benefit of weed control (Rassmussen et al., 2008). Field pea density was reduced by 35% when harrowing at the three-leaf stage compared to untreated check. Nevertheless, in the study by Johnson (2001) adjusting harrowing tines backward in the direction of travel resulted in reduced crop injury and improved selectivity.

Control of large weeds can be achieved with the use of IT, which controls weeds by burial or uprooting, and breaking them apart (Mohler et al., 2016). Inter-row cultivation is highly selective (Davies and Welsh, 2002), and it controls weeds later during the critical period of weed control (Pullen and Covell, 1997). In a study by Stanley et al. (2017) more frequent and delayed cultivation was associated with reduced yield. Multiple cultivation reduced yield by 15% to 30% in both field pea and lentil, respectively; however, a single IT at the four-node stage of field pea and lentil was enough to control the majority of weeds in the inter-row spaces. Recent advancements in vison-guidance technology (Collony, 2003), allows inter-row weed control with increased speed and therefore improved cultivation intensity (Kunz et al., 2015b), while maintaining a high level of weed control precision (Tillett et al. 2002; Nørremark et al., 2012) by reducing the risk of crop injury. Nonetheless, to avoid substantial yield loss, weeds need to be removed before or during the critical period of weed control (CPWC), which was determined to last between 5th and 10th node stage in lentil (Fedoruk et al., 2011). In field pea, it begins two weeks after emergence (Harker, 2001; Singh et al., 2016).

There have been several studies examining cultural weed control practices in organic crop production: increased seeding rates (SR) (Baird et al., 2009a, 2009), and CPWC (Fedoruk et al. 2011), while other studies examined differences in-crop MWC used for weed control in cereals (Leblanc and Cloutier, 2011; Benaragama and Shirtliffe, 2013) and pulses (Johnson, 2001; Johnson and Holm, 2010; Shirtliffe and Johnson, 2012; Stanley, 2017). However, these cultural and MWC methods have not been directly compared to each other, or the combined effects have not yet been evaluated. The objective of this research is to determine the effect of mechanical weed control (RH, H and IT) and crop seeding rate on yield and weed suppression in organically grown field pea and lentil. It was hypothesized that different MWC methods would affect weed biomass and yield of organic field pea and lentil differently when applied at recommended and increased seeding rate.

3.2 Materials and methods

3.2.1 Site Description and Growing Conditions

The experiment was conducted on organically managed land during the 2016 and 2017 field season at Goodale Research Farm (GRF) (52°03'2N 106°30'W) and Kernen Crop Research Farm (KCRF) (52°09N 106°33'W) in Saskatchewan. The KCRF site is located on Dark Brown Chernozemic clay-loam soil (20% sand, 30% silt and 50% clay) with a pH of 7.5 and GRF site was located on Dark Brown Chernozemic loamy soil (42 % sand, 41% silt and 17% clay) with a pH of 6.9. Soil organic matter at GRF location was 2.4%, whereas soil organic matter at the KCRF was 4%. Pre-seeding tillage was conducted at both sites. In 2016 and 2017 field pea and lentil were seeded into wheat (*Triticum aestivum* L.) stubble.

3.2.2 Experimental Design and Location

This experiment was a two-factor randomized complete block design with four replicates for a total of 64 experimental units per location. The factors were an untreated control and all possible combinations of mechanical weed control methods: rotary hoe (RH), harrowing (H) and inter-row tillage (IT) (RH, H, IT, RH-H, H-IT, RH-IT, RH-H-IT) and two seeding rates (recommended and 1.5X and 2X increased rate of field pea and lentil respectively). Seeding rates were based on target plant populations, percent germinations and a predicted 70% emergence rate. Field pea (cv. CDC Meadow) and lentil (cv. CDC Maxim) were seeded at respective target density of 90 (1X) and 135 plants m^{-2} (1.5X), and 130 plants m^{-2} (1X) and 260 plants m^{-2} (2X). Increased crop seeding rates used in this experiment were based on optimal seeding rate recommendations developed for field pea and lentil by Baird et al. (2009a; 2009b).

3.2.3 Experimental Procedures

Crops were seeded in May of each field season with a hoe opener plot seeder in 2.25 x 8 m plots which had six rows spaced 30 cm apart. TagTeam® granular rhizobial-fungal inoculant (*Rhizobium leguminosarum*) was placed at a rate of at 4.4 kg ha^{-1} with the seed at the time of seeding. One meter of the plot from the front and the back were mowed off to achieve a total plot length of 6 meters as well as in 2017 tractor wheel spacings were extended (Figure 3.1) allowing to avoid any damage caused by entering and exiting the plots with mechanical weed control equipment.

The experiment evaluated the mechanical weed control implements: RH, H and IT in combination and alone (Appendix). They were applied based on the weed stage and weed populations at a given site. For the single method treatments, this meant that the method was used several times in the season based upon the weed populations and the weed and crop growth stage. For the multiple method treatments, the appropriate method was used based on the optimum crop stage and weed stage for the particular method. This resulted in the rotary hoe as the first treatment applied, followed by harrow and finally interrow tillage. To determine interactions with the competitive ability of the crop, the difference in terms of weed suppression between normal and increased SR was examined as well. Hand weeded controls were also included in treatment structure, but only in 2017.

Figure 3.1 The minimum-tillage (min-till) "Yetter" rotary hoe.

Pre- and post-emergence rotary hoeing was conducted using a 2-meter wide Yetter® RH (Yetter, Colchester, Illinois USA) (Figure 3.1). Rotary hoeing was performed when the soil was relatively dry, and the soil particles did not ball up. Each rotary hoe application was done between 11:00 AM to 3:00 PM to ensure adequate desiccation of weeds following treatment. A single application included two consecutive passes with a RH in both directions parallel to the direction of the seeded crop rows at a speed of 11-15 km h^{-1}. The working depth of the tool was approximately 2 cm, which according to Mohler (1996) targets the majority of weed seedlings, which germinate from the first 2 cm of the soil layer. Pre-emergence RH was done when the majority of weeds were in the white thread stage and were barely visible on the soil surface, whereas post-emergence hoeing was performed until the second node stage in both field pea and lentil across all site-years. Single and paired RH including treatments received one pre and one post crop emergence application, except GRF in 2016, where RH was applied once pre and twice post-emergence. In the case of multiple treatment combinations, RH was applied once before crop emergence.

Harrowing was performed using a 6-meter-wide Einbock® flex tine H (Einbock, Shatzdorf, Austria). Harrowing speed was approximately 4-5 km h^{-1} and the tine angle was set to 45° for field pea (Figure 3.2) and 65° for lentil respectively. Single post-emergence H treatments were applied twice early during the CPWC. First application was at 2nd node stage, while the second time between 3rd and 4th node stage in both field pea and lentil. In paired and multiple H treatments timing occurred between the 2nd and the 4th node in both crops.

Figure 3.2 The flex-tine harrow tine angle adjustment.

Inter-row cultivation was conducted using a hydraulically powered steerable Schmotzer® IT (Schmotzer Agrartechnic, Bad Windsheim, Germany). The IT hoe width was 12 cm, and hoes were spaced 30 cm apart from each other. The speed of cultivation was approximately 4-5 km h^{-1}. Due to the difference in soil moisture, soil type and residue levels across locations, some adjustments to cultivation depth were made, but the working depth of the implement did not exceed a 5cm depth. All IT including treatments were applied once between the 4^{th} and 6^{th} node stage of field pea and lentil development.

Multiple combinations of RH-H-IT were composed of a single application of each of the three tools. First RH was applied when the majority of weeds were emerging. Next, H was applied when field peas were past 2^{nd} node stage but were not beyond 4^{th} node stage. Finally, IT cultivation was applied once starting from the fourth node until the sixth node. Cultivation timing was mainly based on residual weed pressure present and crop recovery after the H treatment. In 2016, final H and IT cultivation was applied on the same date. Thus, resulting in reduced crop stand. In 2017, IT cultivation was delayed 7-11 days after the H treatment, except GRF where IT cultivation was performed three days after H treatment due to heavy weed pressure. Treatment application structure is outlined in Table 3.1.

Table 3.1 Field operations and treatments for studying mechanical weed control in field and lentil under organic management

[a]RH- Rotary hoe, [b]H – Harrow, [c]IT – Inter-row cultivation; **KCRF** – denotes Kernen Crop Research Farm

- denotes no mechanical weed control treatment occurred; **GRF** – Goodale Research Farm

	Field Pea			Lentil			
	2016		2017	2016		2017	
	KRF	**GRF**	**KCRF**	**KCRF**	**GRF**	**KCRF**	**Goodale**
Seeding	May 18	May 20	May 18	May 18	May 20	May 18	May 28
Rolling	May 18	May 22	May 19	May 18	May 22	May 19	May 29
RH 1st (All treatments including RH)	May 30	May 25	May 27	May 30	May 25	May 31	June 6
RH 2nd	June 6 (RH, RH-IT)	May 28 (All RH treatments)	June 1 (RH, RH-IT)	June 6 (RH, RH-IT)	May 28 (All RH treatments)	-	-
RH 3rd	-	June 7 (RH, RH-IT)	-	-	June 7 (RH, RH-IT)	-	-
H 1st	June 3 (H)	June 7 (H)	June 2 (H, H-IT)	June 3 (H)	June 7 (H)	June 6 (H, H-IT)	June 12 (H, H-IT)
H 2nd	June 6 (H, RH-H, H-IT, RH-H-IT)	June 22 (RH-H, H-IT, RH-H-IT)	June 7 (H, H-IT)	June 6 (H, RH-H, H-IT, RH-H-IT)	June 22 (RH-H, H-IT, RH-H-IT)	June 12 (RH-H, RH-H-IT)	June 19 (RH-H, RH-H-IT)
H 3rd	June 21 (RH-H, H-IT, RH-H-IT)	-	June 12 (RH-H, RH-H-IT)	June 21 (RH-H, H-IT, RH-H-IT)	-	June 15 (H, RH-H, H-IT)	-
IT 1st	June 13 (IT)	June 22 (IT, H-IT, RH-IT, RH-H-IT)	June 13 IT, H-IT, RH-IT	June 13 (IT)	June 22 (IT, H-IT, RH, IT, RH-H-IT)	June 13 (IT, H-IT, RH-IT)	June 22
IT 2nd	June 21 (H-IT, RH-IT, RH-H-IT)	-	June 23 (RH-H-IT)	June 21 (H-IT, RH, IT, RH-H-IT)	-	June 23 (RH-H-IT)	-
Biomass	July 25	July 20	July 19	July 25	July 20	July 23	July 29
Harvest	Aug 22	Aug 22	Aug 14	Sep 5	Sep 8	Aug 14	Sep 12

3.2.4 Data Collection

Emergence of field pea and lentil was counted three to four weeks after seeding in all site-years. Plants were counted in two 0.25 m^{-2} quadrats at the front and back of each plot. Weed density assessments were done to determine the effect of mechanical weed control treatments and seeding rate on total weed number in plots. During the 2016 and 2017 field season, two weed density assessments were made. The first weed population assessment was done after the first RH treatments were applied, while the last assessment was done after the last MWC treatment. Above-ground crop biomass was sampled using two 0.25 m^{-2} quadrats at the front and back of each plot after pod filling, but before natural crop desiccation. Biomass samples collected were oven dried in paper bags for 48 hours at approximately 70^{o}C and then weighed. The four center crop rows were harvested with a small plot combine (harvested area = 7.2 m^{-2}). All field pea site years were harvested in August, while lentil harvest was delayed until early September of 2016 and 2017 season, except KCRF in 2017 (Table 3.1). After dockage removal, seeds were weighed, and yield determined. Test weight was determined by the specifications of the Canadian Grain Commission's Official Grain Grading Guide (2009).

3.2.5 Statistical Analyses

Data was analyzed in SAS (SAS Institute, 2012) version 9.3 using PROC MIXED. Before analysis covariance parameter estimate and homogeneity of variance tests were performed. For both the 2016 and 2017 field season, data was analyzed together for both field pea and lentil. Contrasts between single, paired and multiple treatments grown under increased and normal SR were performed to define the number of in-crop MWC methods and seeding rates required to achieve adequate weed suppression, higher crop biomass and increased grain yield in both field pea and lentil. Site and block were assigned a random effect, and MWC and SR were assigned fixed effects. The effect of treatments was declared significant.

3.2.6 Economic Analysis

Economic analysis was conducted to determine the custom rate per hectare (ha) for application of RH, H, and IT. Rotary hoe, H, and IT prices were based on industry surveys and only prices for new MWC implements were used for this analysis. Machinery price list is outlined Table 3.2. Calculations were based on farm size of 405 ha^{-1}, 1214 ha^{-1}, and 2027 ha^{-1} respectively. For farm sizes of 405 ha^{-1} custom rates for RH, H and IT were based on an implement size of 8.5-9 m, while for estimation of custom rates for the farm sizes of 1214 and 2027 ha $^{-1}$ we used implement sizes of 12 and 18-19 m, respectively.

Custom rates per ha^{-1} were determined using 2018 Farm Machinery Custom Rental Rate Guide Calculator (Saskatchewan Ministry of Agriculture, 2018). Calculation included: equipment price, depreciation, base life of the equipment of 15 years, annual hours of use, as well as annual repair and maintenance cost. Annual hours of use calculation were based on implement hourly work rate efficacy (ha^{-1}/hour) and fixed farm sizes of 405, 1214 and 2027 ha^{-1}, which provided an estimate of how many hours were required to control weeds on the above-mentioned farm size. Work rate was calculated based on operation speed, the width of the implement, base field efficacy of 80%. For the RH, base speed was eight mph, while the base speed for H and IT was 3.5 mph and 6 mph respectively. We proposed that 50% of the tool price was financed under 6% rate for a 7-year loan payback back period with an opportunity rate of 1.5%. Labor rate was $22.00/hour, while the fuel cost was $0.82 per litre. Mechanical weed control tools of 8.5-9, 12 and 16-24 m required tractor horsepower of 160 hp, 185 hp and 220 hp (2018-19 Farm Machinery Custom and Rental Rate Guide, 2018).

The potential return for each MWC treatment as well as seeding rate was calculated by the equation (Norsworthy and Oliver, 2001):

Equation 3.1 Potential economic return.

$$R = (Y \times PR) - (TC + (SW \times C) \qquad (3.1)$$

where *R* is the return (\$ ha^{-1}), *Y* is the seed yield (kg ha^{-1}), *PR* is the price received, *TC* is treatment cost per ha^{-1}, *SW* is the seed weight planted (kg ha^{-1}), and *C* is the seed cost (\$ kg^{-1}). Field pea seed cost was at \$0.70 kg^{-1}, while lentil seed was \$2.2 kg^{-1} (Pivot and Grow, 2018). Planting rate was based on 1000-seed weight as counted and measured and multiplied by the number of seeds planted for each SR. Planting weight was based on field germination rate of 70%. Organic field pea selling price used was \$0.62 kg^{-1}. The average selling price used for lentil was at \$1.87 kg^{-1} (Carlson, 2018). Prices for MWC equipment were provided by Yetter Co®, Frontlink inc, Garford Farm Machinery, Schmotzer GMBH and Einbock GMBH (Personal communication).

Table 3.2 Prices for in-crop mechanical weed control equipment. Implement column denotes the brand and the model of the implement. Width and tractor horsepower column demonstrate the size of the implement and the tractor horsepower requirement for corresponding implement size. Tractor horsepower requirement increase with the size of the implement.

Implement	Width meters (m)	Tractor Horsepower requirement	Price ($Canadian)
Yetter Min-till rotary hoe	9	160	18,000.00
	12	185	21,600.00
	18	220	41,950.00
Einbock Aerostar flex tine harrow	9	160	20,000.00
	12	185	25,265.00
	16	220	45,000.00
Schmotzer inter row (VG) cultivator	8.5	160	102,750.00
Garford Farm Machinery (VG) cultivator	12	185	142,000.00
Einbock chopstar (VG) cultivator	19	220	200,000.00

VG – denotes vison guidance

3.3 Field Pea Results

3.3.1 Environmental Conditions

Environmental conditions for the 2016 and 2017 growing season are shown in Table 3.3 and Figure 3.3. During 2016 average temperatures in May and June were 2°C above the long-term average, while July and August temperatures were similar to the long-term average. Average temperatures in 2017 were not significantly different from the long-term average (Table 3.3).

The 2016 field season was favorable for crop production. Total precipitation in 2016 was 13% above the long-term average, with 30% less precipitation in June and 47% more precipitation in August. Despite the abundance of moisture, fields were accessible for treatment application as no heavy rain events were recorded during 2016 growing season (Figure 3.3).

The field season of 2017 was dry with 27% less precipitation in comparison to long-term normals. Rainfall in May of 2017 was 23% above long-term average, while precipitation in June, July and August was 33%, 42%, and 34% lower than normal (Table 3.3; Figure 3.3).

	Mean Temperature (°C)			Mean Precipitation (mm)		
	2016	2017	Historical Average	2016	2017	Historical Average
May	13.4	11.6	11.2	49.6	56	43
June	17.4	16	15.8	46.4	43.6	65.8
July	18.4	19.47	18.5	66.6	25.4	60.3
August	16.9	17.7	17.6	81	28	42.6
Mean	16.5	16.2	15.8	60.9	38.2	52.9
TOTAL				243.6	153	211.7

Table 3.3 Mean monthly temperatures and rainfall at Kernen Crop Research Farm for the 2016 and 2017 growing season (Historical average is 1981-2010 climate normal for Saskatoon Diefenbaker airport, Environment Canada).

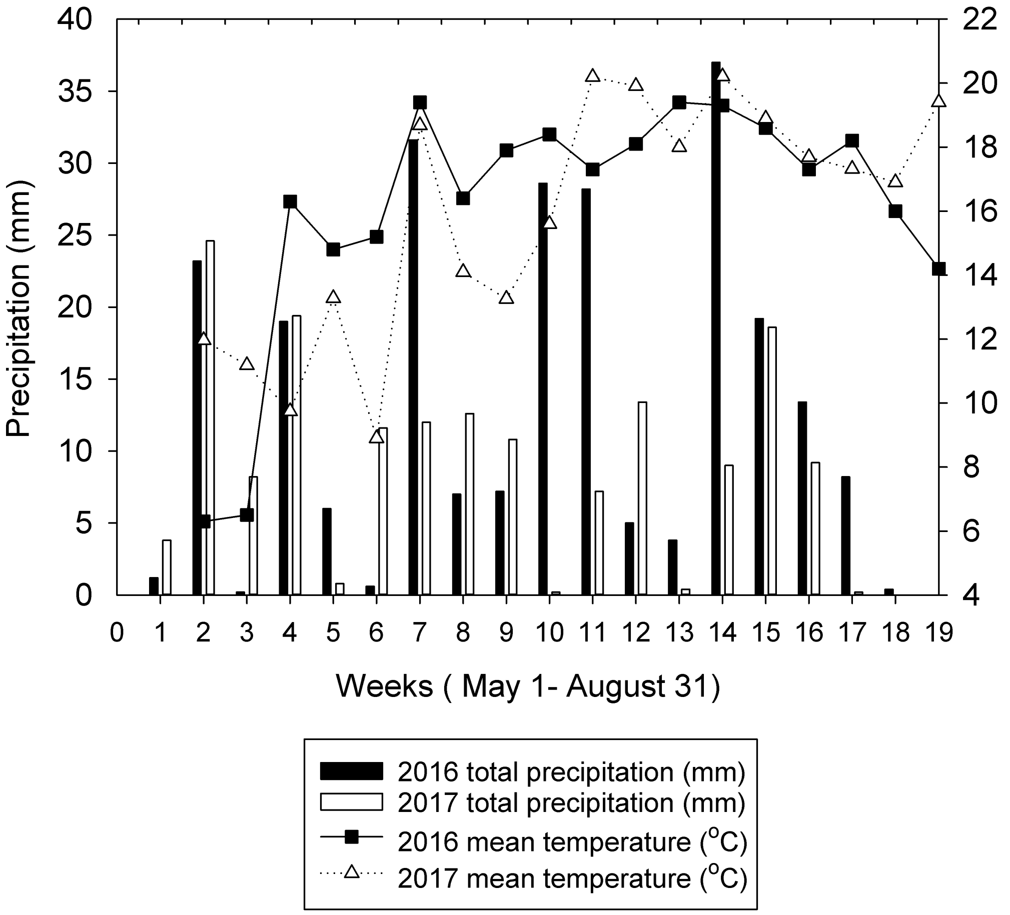


Figure 3.3 Average weekly temperature and total weekly precipitation from May 1st until August 31st at the Kernen Crop Research Farm Weather station during the 2016 and 2017 growing season.

3.3.2 Field Pea Emergence

Crop densities were lower in treatments that included RH; emergence assessments were done following pre-emergence RH treatments (data not shown). Mean field pea population density for 1X SR over all site-years ranged from 77% to 90% of the target population of 90 plants m^{-2}, while population density for 1.5X SR ranged from 64% to 93% of 135 plants m^{-2}.

3.3.3 Field Pea Weed Emergence

Weed species composition in field pea was represented mainly by: green foxtail *(Setaria viridis* L.*)*, wild mustard *(Sinapis arversis* L.*)*, common lambsquarters *(Chenopodium album* L.*)*, redroot pigweed *(Amaranthus retroflexus* L.*)* and wild buckwheat *(Polygonum convolvulus* L.*)*. Stinkweed *(Thlapsi arvense* L.*)*, wild oat *(Avena fatua* L.*)* flixweed *(Descurainia sophia* L.*)*, smartweed (*Polygonum aviculare L.*), annual sowthistle (*Sonchus oleraceus* L.) and field horsetail (*Equisetum arvense* L.) were also present in some plots, however, they were less common. Initial weed densities are given in Table 3.4.

Table 3.4 Mean weed species densities (plants m^{-2}) recorded after the first weed species assessments in field pea at KCRF and GRF in 2016 and 2017.

Species	Field pea		
	Site year		
	Kernen		Goodale
	2016	2017	2016
Green foxtail	420	101	7
Wild Mustard	107	12	NA[a]
Common Lambsquarters	NA	91	NA
Red Root Pigweed	88	12	NA
Wild Buckwheat	57	12	NA
Stinkweed	2	4	NA

[a] NA denotes absence or low density of weeds species (less than 2 m^{-2})

3.3.4 Field Pea Density

Crop density assessments were performed to determine the effect of MWC on crop population density. At the time of the first crop density assessments, RH treatments were already applied, but no statistically significant difference among crop stands among RH treatments or treatments without RH were observed.

Residual crop densities were variable across MWC treatments (Table 3.5; Figure 3.4a). Rotary hoe, IT and their combination resulted in the lowest crop density with declines ranging from 4% to 15% when compared to initial densities present in the same treatments. At the time the residual crop population was recorded, field pea crop density in treatments including H was reduced by 24% to 32% when compared to initial field pea density recorded in the same treatments. Dastgheib (2004) reported up to 35% reduction in field pea density when harrowed at or after the 3rd leaf stage. Thus, harrowing may cause greater crop population density reduction when applied at an inappropriate timing.

Table 3.5 ANOVA for field pea crop and weed density counts as affected by mechanical weed control, choice of seeding rate and their combination across three site years, at Kernen Crop Research Farm (2016-2017) and Goodale Farm (2016).

Source	**Crop density P value**
[a]time	<.0001
[b]mwc	0.2888
[c]sr	<.0001
mwc*sr	0.3218
time*mwc	0.0144
time*sr	0.0213
time*mwc*sr	0.4203
[d]rep(siteyr)	0.071
[e]siteyr	0.2177
siteyr*time	NA
siteyr*mwc	0.1196
siteyr*sr	NA
siteyr*mwc*sr	NA
siteyr*time*mwc	NA
siteyr*time*sr	NA

NA – denotes no output due to low variance, not significant

[a]time – denotes the effect of time when mechanical weed control treatments were applied

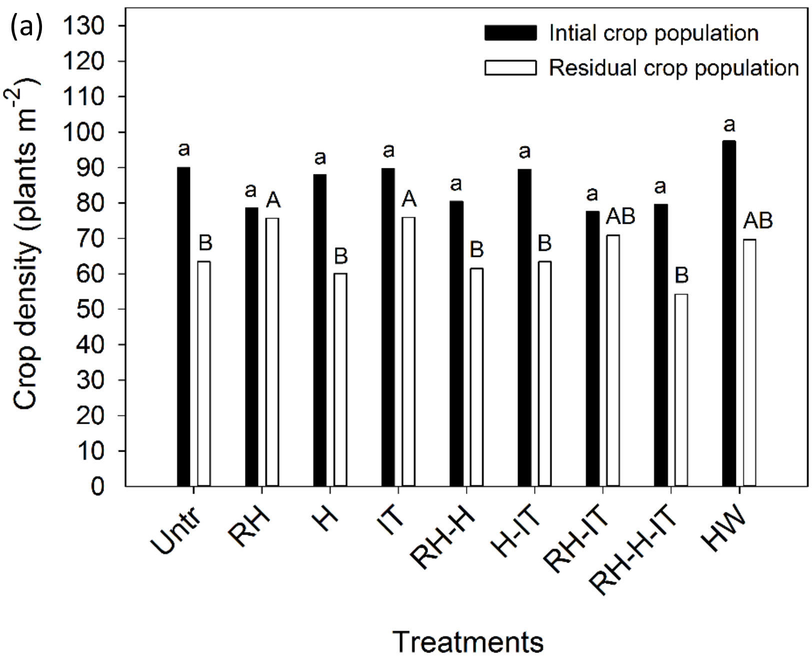
[b]mwc – denotes the effect of mechanical weed control

[c]sr – denotes the effect of seeding rate

[d]rep – denotes replication

[e]siteyr – denotes site year

Residual crop densities varied among 1X and 1.5X seeding rate (Figure 3.4b). Field peas grown under 1X rate exhibited 20% reduction in-crop density, while field pea grown under 1.5X seeding rate declined by 24% when compared to initial crop population respectively (P=0.0213).



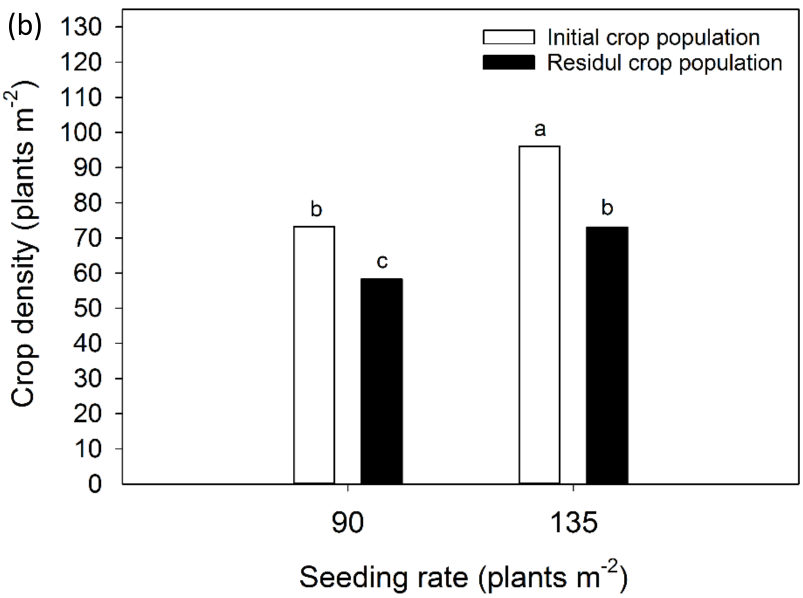


Figure 3.4 The effect of mechanical weed control (a) and seeding rate (b) on field pea crop density averaged over 3 site years at KCRF (2016-2017) and GRF in 2016 (a) lower (black bars) and upper-case (white bars) letters represent significant difference between treatments at the time when initial and residual crop density was recorded, (b) letter codes represent the difference in-crop density among crop density of 90 and 135 plants m^{-2}. Different letters represent a significant difference between treatment means at P<0.05.

3.3.5 Field Pea Total Weed Density

The effect of MWC on total weed density depended upon the time of MWC application at each specific location. The interaction of MWC with the time of their application (pre and post crop emergence) and site year had an effect on weed density (P=0.0071) (Table 3.6).

Table 3.6 ANOVA for the total weed density recorded across three site years at KCRF and GRF during 2016 and 2017 field season.

Source	**Field pea weed density P value**
[a]time	0.9853
[b]mwc	0.0521
[c]sr	0.8377
mwc*sr	0.0354
time*mwc	0.2028
time*sr	0.9735
time*mwc*sr	0.9865
[d]rep(siteyr)	0.0389
[e]siteyr	0.286
siteyr*time	0.2009
siteyr*mwc	0.2179
siteyr*sr	NA
siteyr*mwc*sr	NA
siteyr*time*mwc	0.0071
siteyr*time*sr	NA

NA – denotes no output due to low variance, not significant

[a]time – denotes the effect of time when mechanical weed control treatments were applied

[b]mwc – denotes the effect of mechanical weed control

[c]sr – denotes the effect of seeding rate

[d]rep – denotes replication

[e]siteyr – denotes site year

At the time of the initial weed density assessment treatments that included the RH had on average 80% to 91% lower weed densities when compared to RH non-including treatments. Weed densities changed dramatically since the initial weed assessments, with MWC treatments resulting in statistically similar declines in the range of 50% to 78% when compared to the untreated control (Figure 3.5). Rotary hoe alone and combined with H had 8 and 10-fold higher weed populations when compared to weed densities recorded in the same treatments at the time of the initial assessment (Figure 3.5). It may be that repeated RH use stimulates weed emergence, therefore, contributing to an increase in residual weed population.

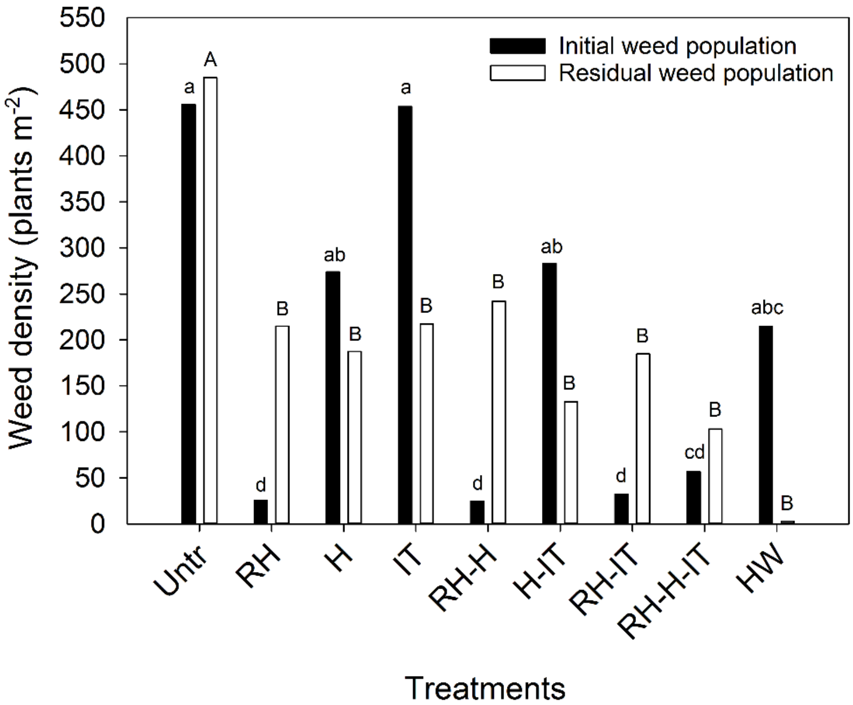


Figure 3.5 The effect of mechanical weed control on total weed density averaged over 3 site-years at the KCRF and GRF in 2016, and KCRF in 2017 (P=0.001). Bars represent initial weed density (black bars) and residual weed density (white bars) after mechanical weed control application. Different letters represent a significant difference between treatment means at P<0.05.

3.3.6 Field Pea Weed Biomass

Weed biomass in field pea was lower after all MWC treatments (P<0.05) compared to the untreated check, except IT alone, which had no significant effect on weed biomass (Figure 3.6). Additionally, H alone did not provide the same level of control as some of the combined treatments (Figure 3.6).

Table 3.7 ANOVA for field pea weed biomass, crop biomass and yield as affected by mechanical weed control, choice of seeding rate and their combination across three site years, at Kernen Crop Research Farm (2016 - 2017) and Goodale Farm (2016).

Source	**Weed biomass P value**	**Crop biomass P value**	**Yield P value**
[a]mwc	0.0012	0.0222	0.0664
[b]sr	0.2036	0.0045	0.0001
mwc*sr	0.942	0.8749	0.7223
[c]rep(siteyr)	0.1441	0.032	0.0194
[d]siteyr	0.2876	0.3181	0.4924
siteyr*mwc	0.0118	0.161	0.0151
siteyr*sr	0.3189	NA	NA
siteyr*mwc*sr	NA	0.3243	NA

NA – denotes no output due to low variance, not significant

[a]mwc – denotes the effect of mechanical weed control

[b]sr – denotes the effect of seeding rate

[c]rep – denotes replication

[d]siteyr – denotes site year

In field pea, single MWC tools (RH, H, IT) resulted in weed suppression ranging from 36% to 69%. Paired and multiple treatments reduced weed biomass by 73% to 86% in comparison with the untreated check, which is similar to the weed control achieved in the hand weeded control. Seeding rate had no effect on field pea weed biomass (P=0.2034). The reasons for this may be due to the use of competitive field variety CDC Meadow (Jacob et al., 2016), and the actual plant stand was not different between the two tested seeding rates. Wall and Townley-Smith (1996) reported field peas retained their weed competitive ability at a crop density of 90 plants m^{-2}, although some researchers reported increased weed suppression when field pea density exceeded 100 plants m^{-2} (Marx and Hagedorn, 1961; Lawson and Topham,1985). Hence, the small difference between two seeding rates may be the reason for the limited effect of increased crop seeding rate on weed biomass.

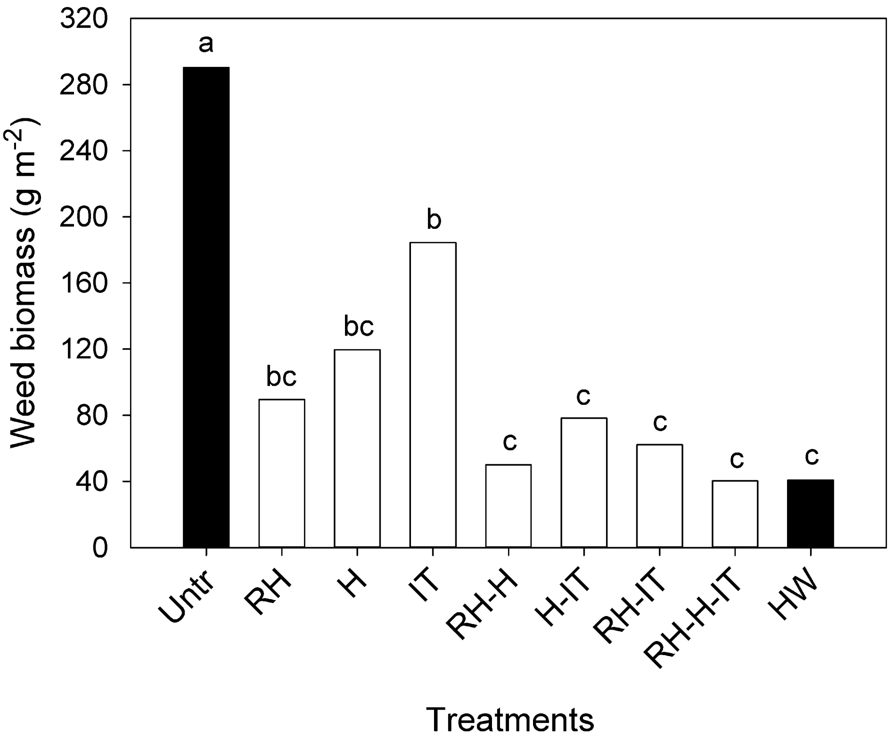


Figure 3.6 The effect of in-crop mechanical weed control treatments on field pea weed biomass averaged over 3 site-years at KCRF (2016-2017) and GRF in 2016. Different letters represent a significant difference between treatment means at P<0.05.

To determine the effect of the number of weed control operations on weed biomass in field pea, contrasts between single, paired and multiple treatments were performed (Table 3.8). With MWC operations, weed interference was on average reduced by 55% while adding a second operation resulted in an increase in weed suppression of up to 78% when compared to no MWC operations. However, a minor increase of only 8% was observed when utilizing three MWC tools together when compared with average weed control achieved with the two operations. Hence, adequate levels of weed suppression in field pea can be achieved when two MWC operations are applied (Figure 3.7).

Table 3.8 ANOVA for field pea weed biomass, crop biomass and yield CONTRASTS as affected by single, paired and multiple mechanical weed control operations, choice of seeding rate and their combination across three site years, at Kernen Crop Research Farm (2016 - 2017) and Goodale Farm (2016).

Source	Weed biomass P value	Crop biomass P value	Yield P value
[a]operations	0.0019	<.0001	0.0068
[b]sr	0.1202	0.0006	0.0005
operations*operations	<.0001	<.0001	<.0001
[c]rep(siteyr)	0.2658	0.0337	0.0125
[d]siteyr	0.3723	0.3393	NA
sr*siteyr	0.3645	NA	NA
operations*siteyr	0.1742	0.2276	0.1746
operations*sr	0.5494	0.6927	0.0363

NA - denotes no output due to low variance, not significant

[a]operations – denotes the effect of the number of mechanical weed control operations on weed biomass, crop biomass and yield

[b]sr – denotes the effect of seeding rate

[c]rep – denotes replication

[d]siteyr – denotes site years

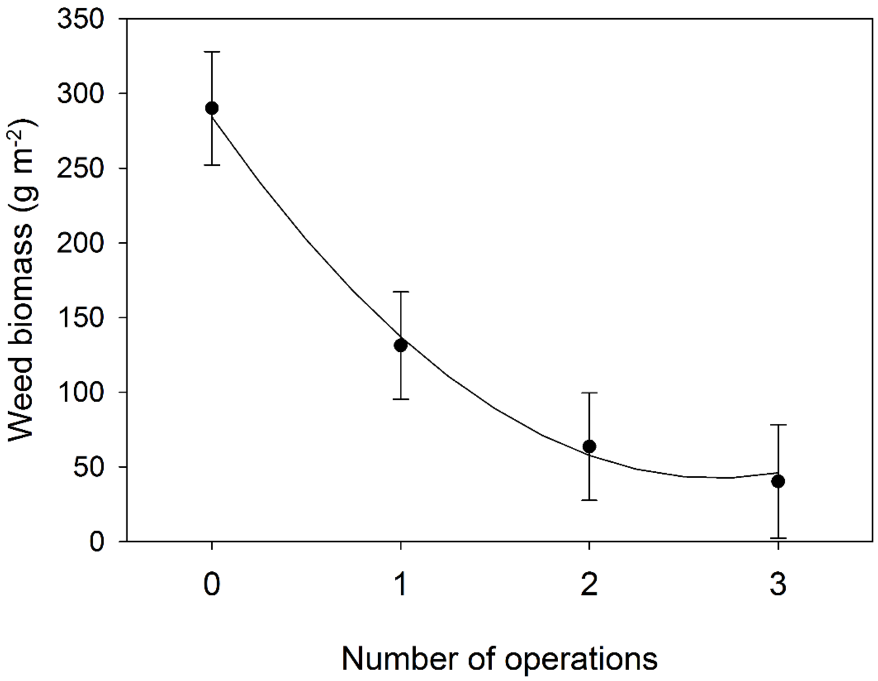


Figure 3.7 The relationship between the number of mechanical weed control operations and weed biomass in field pea averaged over 3 site-years at KCRF (2016-2017) and GRF in 2016 (P<0.0001). Error bars represent the standard errors of the least squares mean.

3.3.7 Field Pea Biomass

In field pea, all MWC treatments exhibited statistically similar crop biomass increases of 35% to 45% when compared to the untreated check (P=0.02) (Table 3.7; Figure 3.8a). Field pea grown at the 1.5X seeding rate had 15% greater crop biomass when compared to the 1X seeding rate (P=0.0045) (Figure 3.8b); however, the interaction of MWC and crop SR in field pea was not significant (P= 0.87).

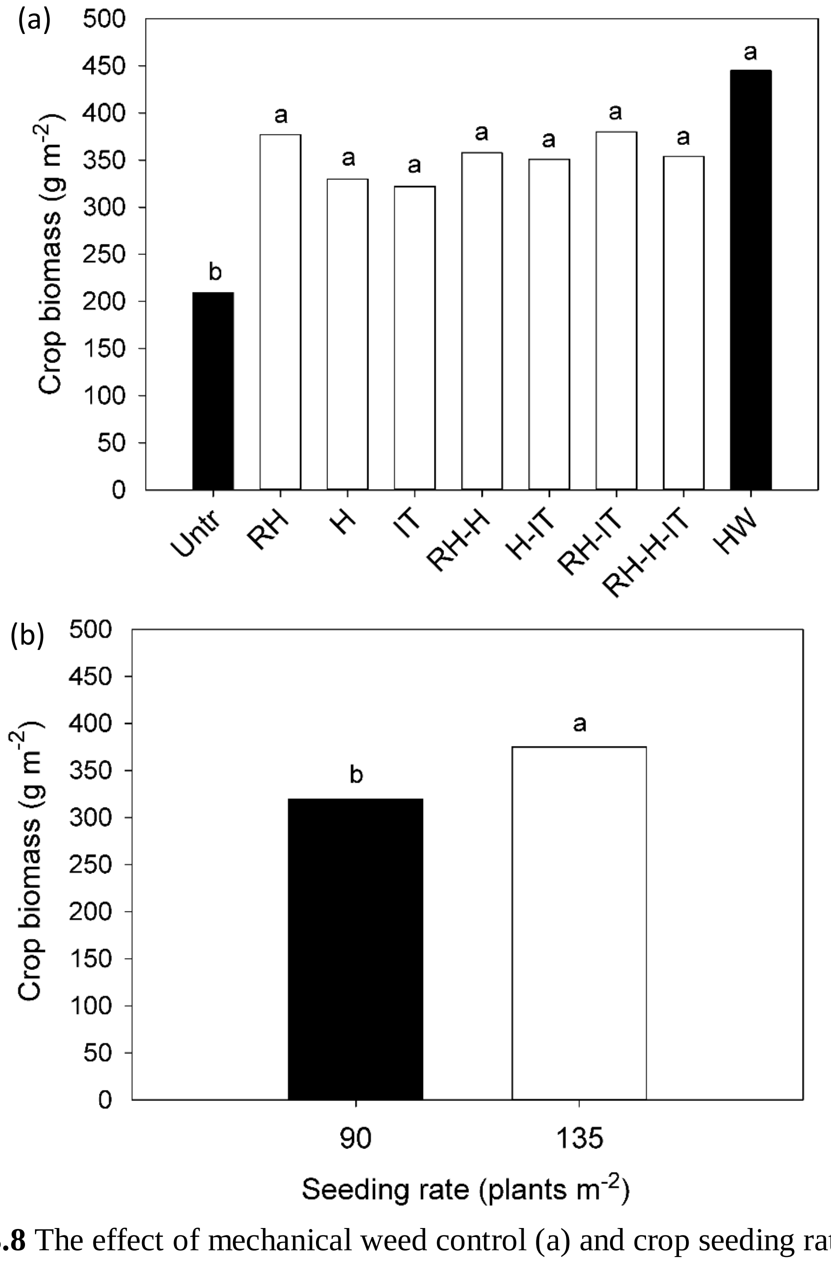


Figure 3.8 The effect of mechanical weed control (a) and crop seeding rate (b) on field pea biomass averaged over three site-years at KCRF (2016-2017) and GRF in 2016 (P<0.05). Different letters represent a significant difference between treatment means at P<0.05.

Contrasts between single, paired and multiple treatments were performed to define the number of in-crop MWC operations and SR, which would benefit crop biomass of field pea the most (Table 3.8; Figure 3.8). Field crop biomass response between 1.5X and 1X SR differed from 25% when no MWC was applied, and was less than 1% when all three implements were combined. On average, field pea crop biomass was 11% higher when a single MWC tool was applied under high crop density when compared to the 1X SR crop density. Two MWC tools applied in field pea grown at the 1.5X SR had 19% higher crop biomass when compared to the same number of tools applied under 1X SR. These results are similar to crop biomass results achieved from ANOVA where crop biomass was 15% higher at the 1.5X SR compared to the 1X SR.

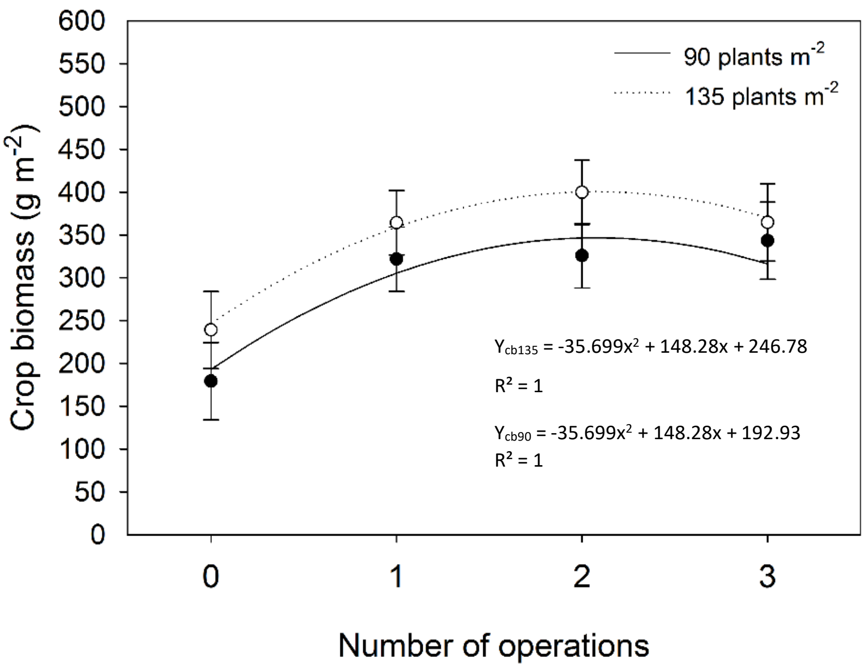


Figure 3.9 The association of number of mechanical weed control operations and crop seeding rate interaction and crop biomass of field pea (P=0.0001). Error bars represent the standard errors of the least squares mean.

Single MWC treatments increased crop biomass by 50% and 44% under crop densities of 135 plants m^{-2} and 90 plants m^{-2}, respectively. The benefit of adding a second MWC tool in field pea grown under 135 plants m^{-2} was minor and accounted for only 5% increase in-crop biomass when compared to uncultivated control with crop density of 135 plants m^{-2}, while no difference in-crop biomass was observed between single and paired treatments applied in field pea grown at crop density of 90 plants m^{-2}. The difference between multiple and paired MWC treatments was minor even between two seeding rates. When utilizing multiple MWC treatments in field pea grown under SR of 135 plants m^{-2} crop biomass was similar to the levels achieved when single treatments were applied in field pea grown under same crop density. Adding a third tool in field pea grown under crop density of 90 plants m^{-2} resulted in a 3% increase in-crop biomass compared to paired treatments applied in field pea grown under similar crop density. Thus, paired MWC tools on average resulted in the highest crop biomass increase of 55% when grown at crop density of 135 plants m^{-2} in comparison with no MWC applied in field pea grown under SR of 90 plants m^{-2}.

3.3.8 Field Pea Yield

In field pea, all MWC treatments resulted in statistically similar yield increase that ranged from 38% to 50% when compared to the control treatment (Table 3.7; Figure 3.10a). Field peas grown at the 1.5X SR exhibited 13% higher yield when compared to 1X SR (Figure 3.10b), although interaction of MWC and crop SR was not significant (P=0.72).

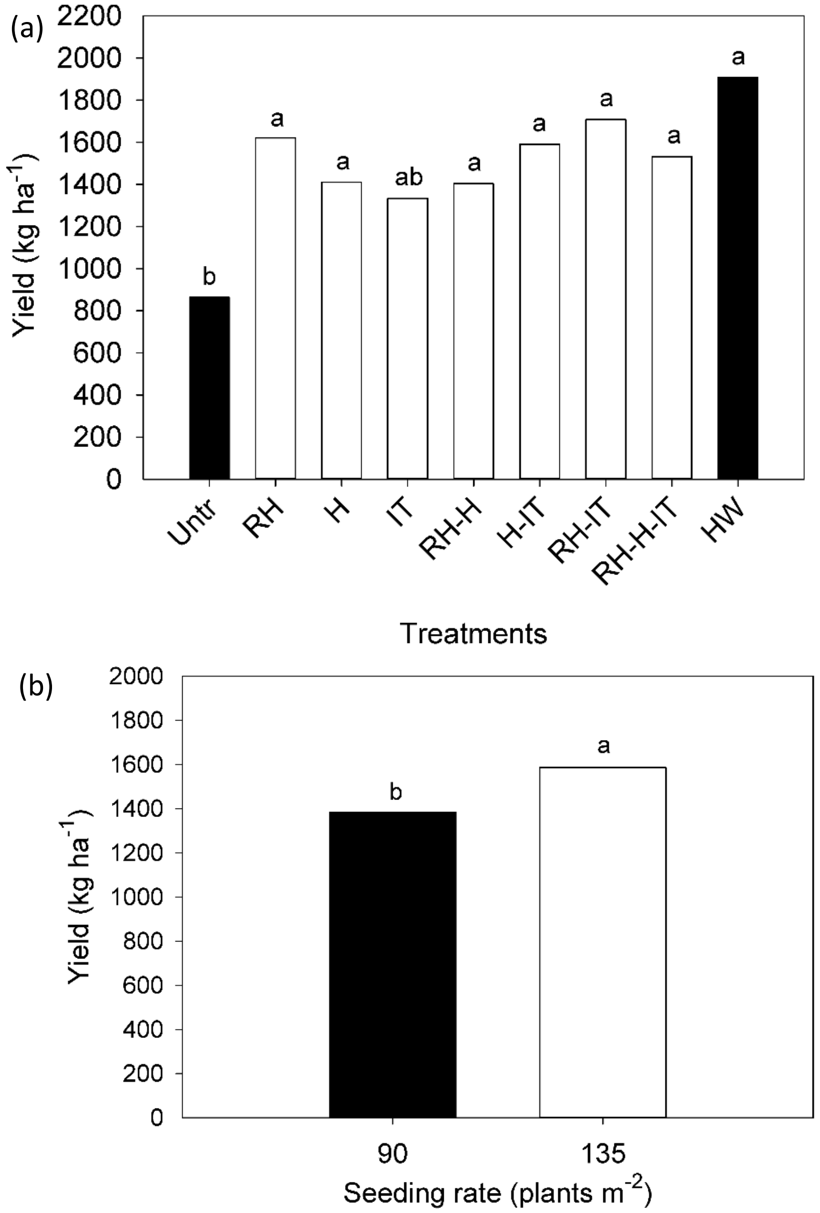


Figure 3.10 The effect of mechanical weed control (a) and seeding rate (b) on field pea yield averaged over 3 site years at KCRF (2016-2017) and GRF in 2016. Different letters represent a significant difference between treatment means at P<0.05.

To define the number of operations resulting in the highest field pea yield contrast between single, paired and multiple treatments were performed (Table 3.8).

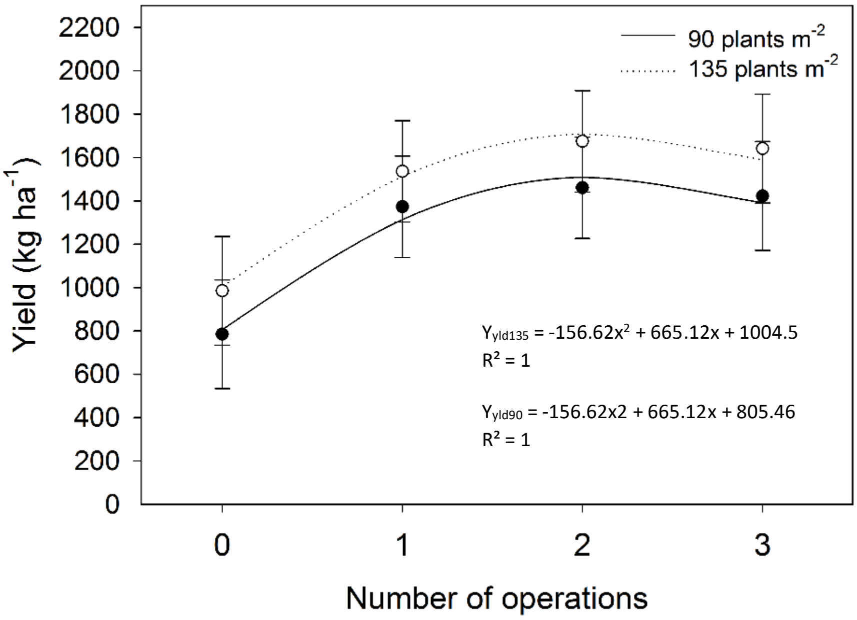


Figure 3.11 Association of mechanical weed control and crop seeding rate interaction and field pea yield averaged over 3 site years at KCRF (2016-2017) and GRF in 2016. Different letters represent a significant difference between treatment means at P<0.05. Error bars represent the standard errors of the least squares mean.

Single, paired and multiple MWC treatments resulted in a statistically similar yield increase of 40%, 45%, and 44%, respectively when compared to control (Figure 3.11). These results correspond with field pea grain yield results achieved from the ANOVA.

3.3.9 Field Pea Economic Analysis

Received Gross Margins for farm size of 405, 1214 and 2027^{-1} hectares were based on field pea crop density of 90 and 135 plants per m^{-2} respectively (Table 3.9; 3.10; 3.11). Increasing seeding rate alone to 135 plants per m^{-2} increased profitability by 15% when compared to crop density of 90 plants m^{-2}. Presence of in-crop MWC notably increased profitability when compared to no MWC applied, while increase in MWC equipment size and farm size was associated with further increase in profitability.

All MWC treatment applied in field pea grown under crop density of 90 plants per m^{-2} resulted in 47% to 50% higher profits when compared to untreated check grown under the same density. Mechanical weed control applied in field pea grown under crop density of 135 plants per m^{-2} increased profits in range from 56% to 66% when compared to no MWC applied under crop density of 90 plants m^{-2}. The greatest gross margin over untreated check of CAD$ 517.3-523.3 ha^{-1} was achieved with single RH treatment at a crop density of 90 plants m^{-2}. No economic benefit of increased SR can be associated with increased seed cost. Although, as the timing for the RH application can be very narrow, profitability may vary significantly from year to year. A robust alternative would be RH-IT and H-IT treatments as they provided consistently high yields under both SR. Nevertheless, we found no significant weed control benefit of increased crop SR; producers could use high SR to maintain their profit margins. For instance, at crop density of 135 plants per m^{-2} single H and IT had 12% and 28% higher economic return when compared to the same treatments applied in field pea under crop density of 90 plants per m^{-2} respectively. Hence, higher seeding rates are needed to maximize net returns when MWC is utilized.

According to the results of the economic analysis organic producers with the farm size of 405 ha^{-1} will need no more than two field seasons to recover the investment from a 9 meter minimum till rotary hoe, a 9 meter harrow and a 8.5 meter inter-row cultivator. Surprisingly, despite higher cost of larger weed control equipment, organic producers with a farm size of 1214 and 2027 ha^{-1} will need a single field season to recover the investment from all three mechanical weed control implements. Additionally, farmers who already own one of the in-crop tolls will benefit from reduced weed control costs per ha^{-1}. Thus, investment in MWC has immense potential to improve both weed control efficacy and organic farm profitability.

Table 3.9 Influence of in-crop mechanical weed control treatments and crop seeding rates on economic results in field pea production based on farm size 405 ha^{-1} (Gross Margin expressed in Canadian dollar)

Crop density		90 plants m^{-2} (1x SR)				135 plants m^{-2} (1.5x SR)			
Treatment	Treatment cost $ ha^{-1}	Total investment $ ha^{-1}	Yield kg ha^{-1}	Gross Margin	Gross margin over Untreated	Total investment $ ha^{-1}	Yield kg ha^{-1}	Gross margin	Gross margin over Untreated
Untr	0	205	742.3	255.5	0	309	985	301.6	0
RH 9	47.2	252.2	1653	772.8	517.3	356.2	1587	627.7	326
H 9	30	235	1291	565.7	310.2	339	1528	608.4	306.7
IT 8.5	34.3	239.3	1174	488.5	233	343.3	1493	582.6	281
RH + H	77.2	282.2	1331	543	287.5	386.2	1476	528.7	227.1
H + IT	64.3	269.3	1500	660.5	412.5	373.3	1682	669.4	367.8
RH + IT	81.5	286.5	1551	675.2	419.7	390.5	1866	766.4	464.8
RH + H + IT	91.1	296.1	1422	585.8	330.3	400.1	1641	617.3	315.6
HW	300	505	1792	606.2	350.7	609	2026	647	345.4

Table 3.10 Influence of in-crop mechanical weed control treatments and crop seeding rates on economic results in field pea production based on farm size of 1214 ha^{-1} (Gross Margin expressed in Canadian dollar)

Crop density		90 plants m^{-2} (1x SR)				135 plants m^{-2} (1.5x SR)			
Treatment	Treatment cost $ ha^{-1}	Total investment $ ha^{-1}	Yield kg ha^{-1}	Gross Margin	Gross margin over Untreated	Total investment $ ha^{-1}	Yield kg ha^{-1}	Gross Margin	Gross margin over Untreated
Untr	0	205	743	255.5	0	309	985	301.7	0
RH 12	46.3	251.3	1653	773.7	518	355.3	1587	628.6	326.9
H 12	27.9	232.9	1291	567.8	312	336.9	1528	610.5	308.8
IT 12	23.7	228.7	1174	499.1	243.6	332.7	1493	593.2	291.6
RH + H	74.2	279.2	1331	546	290.5	383.2	1476	531.7	230
H + IT	51.6	256.6	1500	673.3	417.7	360.6	1682	682.2	380.5
RH + IT	70	275	1551	686.7	431.1	379	1866	778	476.3
RH + H + IT	76	281	1422	601	345.5	385	1641	632.4	330.8
HW	300	505	1792	606.3	350.7	609	2026	647	345.4

Table 3.11 Influence of in-crop mechanical weed control treatments and crop seeding rates on economic results in field pea production based on farm size of 2027 ha^{-1} (Gross Margin expressed in Canadian dollar)

Crop density		90 plants m^{-2} (1x SR)				135 plants m^{-2} (1.5x SR)			
Treatment	Treatment cost $ ha^{-1}	Total investment $ ha^{-1}	Yield kg ha^{-1}	Gross Margin	Gross margin over Untreated	Total investment $ ha^{-1}	Yield kg ha^{-1}	Gross Margin	Gross margin over Untreated
Untr	0	205	743	255.5	0	309	985	301.7	0
RH 18	41.2	246.2	1653	778.8	523.3	350.2	1587	633.7	332
H 18	24.7	229.7	1291	571	315.4	333.7	1528	613.6	312
IT 19	20	225	1174	502.8	247.3	329	1493	596.9	295.3
RH + H	66	271	1331	554.3	298.7	375	1476	540	238.4
H + IT	44.7	249.7	1500	680.1	424.5	353.7	1682	689	387.3
RH + IT	61.2	266.2	1551	695.5	440	370.2	1866	786.8	485.1
RH + H + IT	66.6	271.6	1422	610.3	354.8	375.6	1641	641.8	340.1
HW	300	505	1792	606.3	350.7	609	2026	647	345.4

3.3.10 Field Pea Discussion

This study conducted over 3 site-years tested the ability of MWC methods as rotary hoe, flex-tine harrow and inter-row cultivator and crop SR to control weeds and improve field pea under organically managed conditions. It was hypothesized that different MWC methods would affect weed biomass and yield of organic field pea differently when applied at recommended and increased seeding rate. The results of this study supported our hypothesis for the effect of MWC, which resulted in a significant weed biomass decline and yield increase in field pea. Increased SR improved field pea seed yield but had no effect on weed biomass suppression ($P>0.05$). Presence of MWC and increased crop SR improved profitability of field pea.

Increasing SR had no effect on weed suppression (Table 3.7), but must consider that across all 3 sites field pea did not reach the targeted density of 90 and 135 plants m^{-2}. In a present study actual field pea density for 1X SR on average resulted in 58 plants m^{-2}, while crop density for 1.5X SR resulted in 98 plants m^{-2}. Thus, no weed control benefit from increased crop SR may be attributed to minor difference in-crop density between two tested SR. Wright & Townley-Smith (1994) reported that field pea remained equally competitive with weeds with crop densities between 50 to 90 plants m^{-2} which corresponds to our findings.

Single MWC methods resulted in high organic field pea yields, despite being less effective in terms of weed control (Figure 3.6a). In this experiment, RH and IT alone did not reduce crop density significantly (Figure 3.4a). Our results are supported by Burnside et al. (1993), VanGessel et al. (1995) and Shirtliffe and Johnson (2012) findings, who reported no significant crop density reduction following RH treatments. Nevertheless, crop density reduction due to repeated RH use has been reported (Burnside et al., 1994; Leblanc and Cloutier, 2001a). Importantly, repeated use of H alone or in combination resulted in 24 to 32% reduction in field pea crop stand when compared to initial crop density (Figure 3.4a). Datsgheib (2004) observed field pea crop density reduction of 35% when harrowing at 3 node stage, which agrees with our study findings. Despite the reduction in density, crop biomass (Figure 3.8a) and final grain yield (Figure 3.10a) was not statistically different when compared to harrow excluding treatments. However, one must also consider that under high weed density, incomplete weed biomass suppression with single MWC methods may result in greater recovery rates of the residual weed population (Sultan, 2000; Sultan, 2001).

Furthermore, heavy reliance on single MWC methods may result in weed control failure in years where environmental conditions may restrict the appropriate timing for their application.

The greatest weed suppression and the greatest profitability in field pea was achieved with paired MWC methods (Figure 3.7). Vangessel et al. (1998) reported that rotary hoeing twice in combination with single inter-row cultivation provided equivalent weed suppression to herbicdes. Since paired and multiple MWC treatments resulted in statistically similar weed suppression, crop biomass and grain yield, growers may utilize either RH or H together with IT for control of early and late weed emergence. Thus, integrating paired MWC methods with increased crop seeding rate may provide cost-effective and robust suppression of annual weeds in organic field pea.

3.3.11 Field Pea Conclusions

Mechanical weed control resulted in significant weed suppression and positive biomass and yield response regardless of the type of weed control method in most cases (Table 3.7). Interrow tillage on its own did not provide as equivalent weed control compared to other methods, but weed control was greater when inter-row tillage was supplemented with other MWC methods (Figure 3.7). This increased weed control resulted in similar seed yield for all weed control methods. Increasing pea seeding rate from 90 to 135 plants m^{-2} did not significantly improve weed control, but it increased seed yield. The consistency of weed control and yield benefits can be greatly affected by unfavorable environmental conditions, inappropriate weed control timing and incomplete suppression of either intra or inter-row weeds, therefore resulting in reduced weed control efficacy and yield loss. We conclude that organic field pea growers should target a crop density of 135 plants m^{-2} along with mechanical weed control to control weeds. Early weed control with a H or RH should maximize yield in most situations however, under weedy conditions following with an IT tillage operation can improve weed control.

3.4 Lentils Results

3.4.1 Environmental Conditions

Environmental conditions were the same as in section 3.3.1.

3.4.2 Lentil Emergence

Crop densities were lower in treatments that included pre-emergence RH; emergence assessments were done following pre-emergence RH treatments (data not shown). Mean lentil emergence across all site-years for 1x seeding rate ranged from 75% to 93% of 130 plants m^{-2} while population density for 2x SR ranged from 68% to 87% of 260 plants m^{-2}, except Goodale site in 2017 where emergence was significantly lower due to early season drought (data not shown). Hence, crop emergence was 38% and 40% of targeted 130 plants m^{-2} and targeted 260 plants m^{-2} crop density.

3.4.3 Lentil Weed Emergence

Weed species composition across all 4 site years was represented mainly by: green foxtail, wild mustard, common lambsquarters, redroot pigweed and wild buckwheat. Stinkweed, wild oat, flixweed, smartweed, annual sowthistle and field horsetail were also present in some plots, however, they were less common. Initial weed densities are given in Table 3.12.

Table 3.12 Mean weed species densities (plants m^{-2}) recorded after the first weed species assessments in lentil at KCRF and GRF in 2016 and 2017 respectively.

Species	Lentil			
	Site year			
	Kernen		Goodale	
	2016	2017	2016	2017
Green foxtail	269	14	138	8
Wild Mustard	147	1	NA	4
Common Lambsquarters	2	17	2	12
Red Root Pigweed	120	4	2	4
Wild Buckwheat	74	4	22	11

[a] NA denotes absence or low density of weeds species (less than 2 m^{-2})

3.4.4 Lentil Density

Crop density assessments were done to determine the effect of MWC and crop seeding rate on lentil crop density. Mechanical weed control resulted in significant crop stand reduction in lentil across all site years ($P<0.05$) (Table 3.13). Individual MWC tools differed in their effects on lentil crop stand ($P=0.002$) (Figure 3.12a). Lentils exhibited poor tolerance to H, RH-H, RH-H-IT treatments which resulted in 20%, 25%, and 29% crop stand reduction. Lentils exhibited good tolerance to RH, H-IT and RH-IT treatments where crop densities were reduced only by 12% to 15%. Lentils demonstrated the best tolerance to early inter-row cultivation, which had similar crop stand after treatment as in untreated and hand weeded control (Figure 3.12a). These results correspond with the findings of Stanley et al. (2017), where lentils exhibited the best crop tolerance to early single application with an inter-row cultivator.

Lentils crop density recorded after the last MWC treatments was 43% greater under 2X seeding rate when compared to 1X seeding rate (Figure 3.12b), although, one must also consider that initial crop density before MWC application in lentil was 75% to 93% of 130 plants m^{-2} while population density for 2X seeding rate ranged from 68% to 87% of 260 plants m^{-2}. According to average lentil crop densities recorded before MWC application, crop density decline following MWC was greater under 2X seeding rate when compared to 1X seeding rate. For instance, decline in lentil density seeded at 1X seeding rate ranged from 6% to 24%, while under 2X seeding rate lentil density was reduced from 8% to 28% (data not shown). Nonetheless, despite greater reduction in-crop density under 2X seeding rate, growers may still consider increasing their seeding rate to account for crop density reduction when utilizing more than one MWC operation.

Table 3.13 ANOVA for lentil crop density counts as affected by mechanical weed control, choice of seeding rate and their combination across three site-years, at Kernen Crop Research Farm (2016 - 2017) and Goodale Farm (2016-2017).

Source	Crop density P value
[a]time	0.4587
[b]mwc	0.0301
[c]sr	0.0019
mwc*sr	0.7366
time*mwc	0.2368
time*sr	0.1205
time*mwc*sr	0.2833
[d]rep(siteyr)	0.013
[e]siteyr	0.1879
siteyr*time	0.1466
siteyr*mwc	0.2527
siteyr*sr	0.2551
siteyr*mwc*sr	0.0732
siteyr*time*mwc	0.0613
siteyr*time*sr	0.2825

NA - denotes no output due to low variance, not significant

[a]time – denotes the effect of time when mechanical weed control treatments were applied

[b]mwc – denotes the effect of mechanical weed control

[c]sr – denotes the effect of seeding rate

[d]rep – denotes replication

[e]siteyr – denotes site year

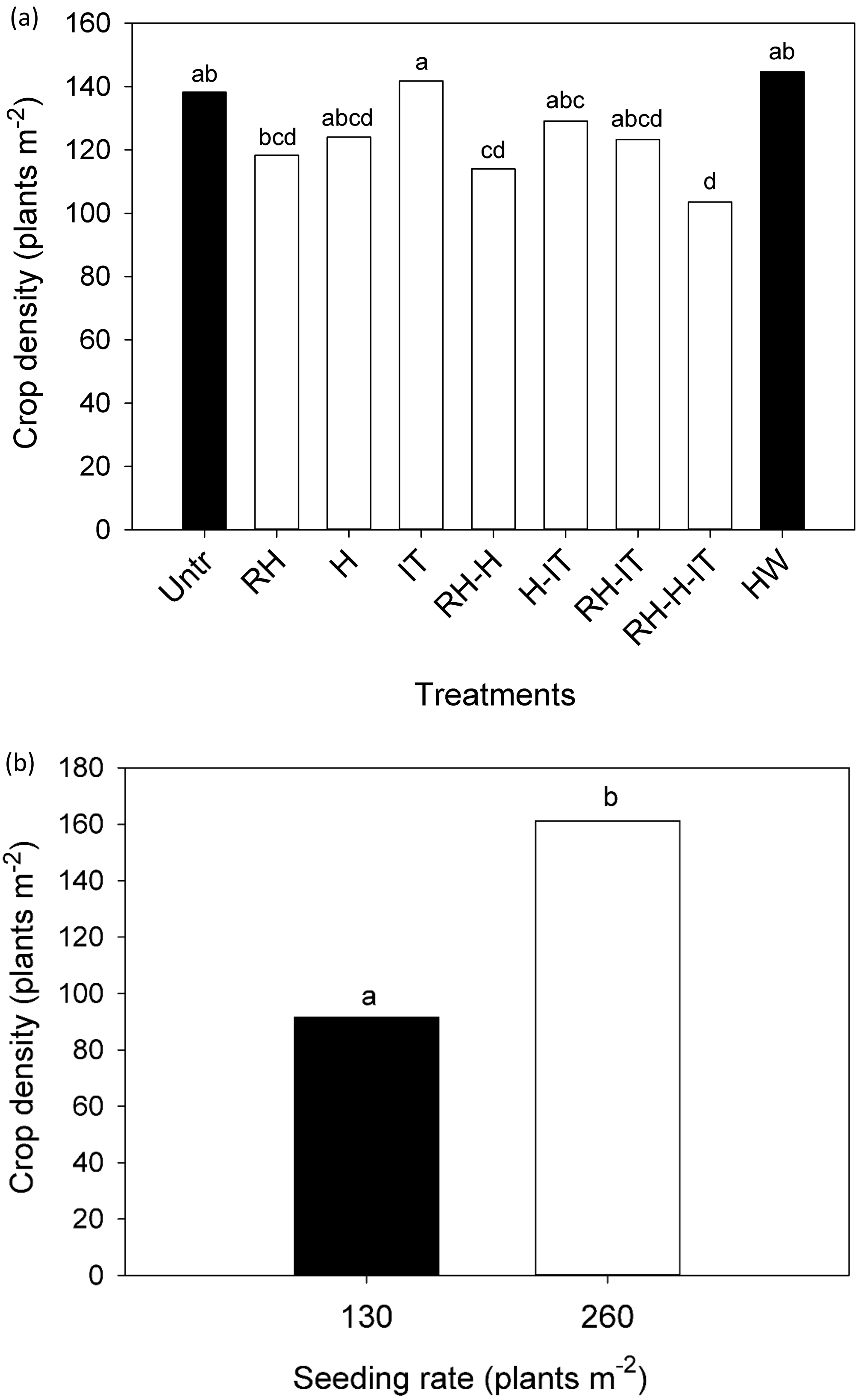


Figure 3.12 The effect of mechanical weed control treatments (a) and seeding rate (b) on lentil density averaged over 4 site years KCRF (2016-2017) and GRF (2016-2017). Different letters represent a significant difference between treatment means at P<0.05.

3.4.5 Lentil Total Weed Density

In lentil, neither MWC nor SR had an effect on average weed population across all site years (P=0.0568) (Table 3.14).

Table 3.14 ANOVA of mean total weed species density recorded in lentil across 4 site years at the KCRF and GRF during 2016 and 2017 field season.

Source	**Lentil weed density P value**
[a]time	0.5849
[b]mwc	0.1224
[c]sr	0.2574
mwc*sr	0.9716
time*mwc	0.1552
time*sr	0.6462
time*mwc*sr	0.7753
[d]rep(siteyr)	0.0483
[e]siteyr	0.4534
siteyr*time	0.1385
siteyr*mwc	0.1575
siteyr*sr	NA
siteyr*mwc*sr	0.4568
siteyr*time*mwc	0.0009
siteyr*time*sr	NA

NA - denotes no output due to low variance, not significant

[a]mwc – denotes the effect of mechanical weed control

[b]sr – denotes the effect of seeding rate

[c]rep – denotes replication

[d]siteyr – denotes site year

3.4.6 Lentil Weed Biomass

Weed biomass in lentil was lower after all MWC treatments (P<0.05); however, IT only reduced weed biomass by 40% compared to reduction of 63 to 93% of RH, RH-H, RH-IT, RH-H-IT, and HW (Table 3.15; Figure 3.13a).

Table 3.15 ANOVA for lentil weed biomass, crop biomass and yield as affected by mechanical weed control, choice of seeding rate and their combination across 4 site years, at Kernen Crop Research Farm (2016 - 2017) and Goodale Farm (2016-2017).

Source	Weed biomass P value	Crop biomass P value	Yield P value
[a]mwc	<.0001	0.0004	0.0012
[b]sr	0.0158	0.0146	0.0463
mwc*sr	0.7255	0.54	0.634
[c]rep(siteyr)	0.0206	0.0662	0.0138
[d]siteyr	0.1182	0.1236	0.1184
siteyr*mwc	0.0071	0.0437	0.036
siteyr*sr	NA	0.2106	0.1606
siteyr*trt*sr	0.3169	0.3328	0.0955

NA - denotes no output due to low variance, not significant

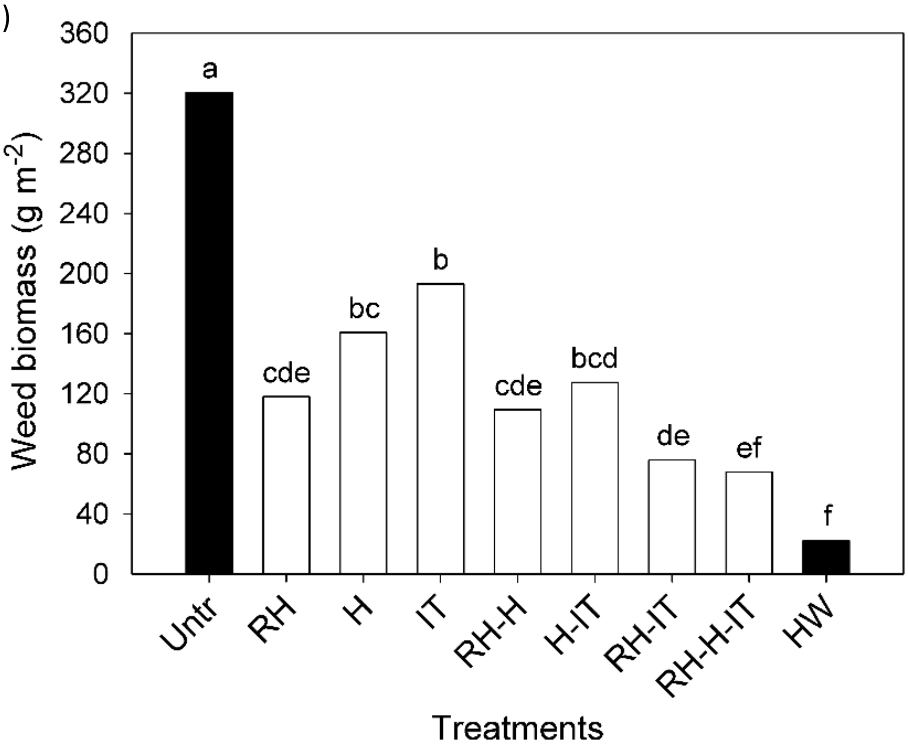
[a]mwc – denotes the effect of mechanical weed control

[b]sr – denotes the effect of seeding rate

[c]rep – denotes replication

[d]siteyr – denotes site year

(a)



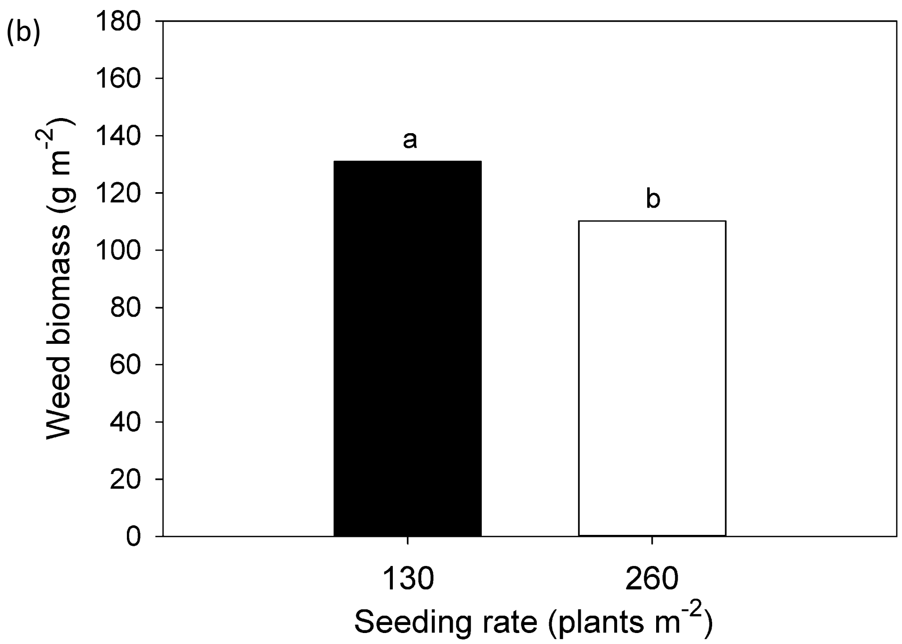


Figure 3.13 The effect of mechanical weed control treatments (a) and crop seeding rate (b) on lentil weed biomass averaged over 4 site-years at KCRF (2016-2017) and GRF (2016-2017). Different letters represent a significant difference between treatment means at P<0.05.

Single and paired treatments reduced weed biomass by 40% to 66%, while the combination of RH-IT and RH-H-IT resulted in 76% and 79% decline in weed biomass respectively, when compared to the untreated control. Weed interference in lentil was reduced by 16% when grown at a 2X seeding rate (P=0.01) when compared to 1X seeding rate (Figure 3.14b). Weed suppression from increased seeding rate was not as high as results reported by Boreboom and Young (1995) where a 1.5X times seeding rate translated into a 70% weed control when compared to recommended rate.

According to contrast between single, paired and multiple MWC treatments, it was found that on average single MWC treatments reduced weed biomass by 48%, whereas paired MWC treatments increased weed suppression by an additional 16% when compared to single MWC treatments.

Table 3.16 ANOVA for lentil weed biomass, crop biomass and yield CONTRASTS as affected by single, paired and multiple mechanical weed control operations, choice of seeding rate and their combination across 4 site years, at Kernen Crop Research Farm (2016 - 2017) and Goodale Farm (2016-2017).

Source	Weed biomass P value	Crop biomass P value	Yield P value
[a]operations	0.0007	0.0012	0.0003
[b]sr	0.798	0.0078	0.0537
operations*operations	<.0001	0.0026	<.0001
[c]rep(siteyr)	0.2045	0.0606	0.017
[d]siteyr	0.1139	0.1238	0.1182
siteyr*operations	0.1270	0.0903	0.1419
siteyr*sr	NA	0.3763	0.1515
operations*sr	0.9163	0.2805	0.7286

NA - denotes no output due to low variance, not significant

[a]operations – denotes the effect of the number of mechanical weed control operations on weed biomass, crop biomass and yield

[b]sr – denotes the effect of seeding rate

[c]rep – denotes replication

[d]siteyr – denotes site year

Importantly, applying all three tools together on average resulted in 74% weed biomass decline, which is 10% higher than weed control efficacy achieved with a paired MWC treatments. Hence, overall paired weed control operations result in greater weed control when compared to single MWC operations, while a third operation may provide notable weed suppression in the presence of a heavy weed pressure. Contrasts between single, paired and multiple MWC treatment operations are demonstrated in Figure 3.14.

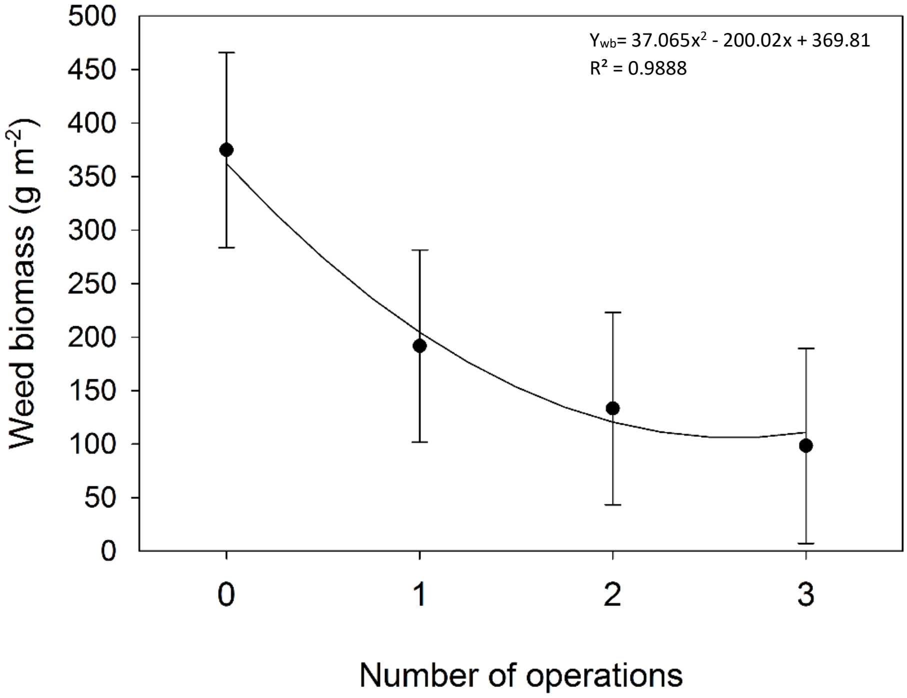
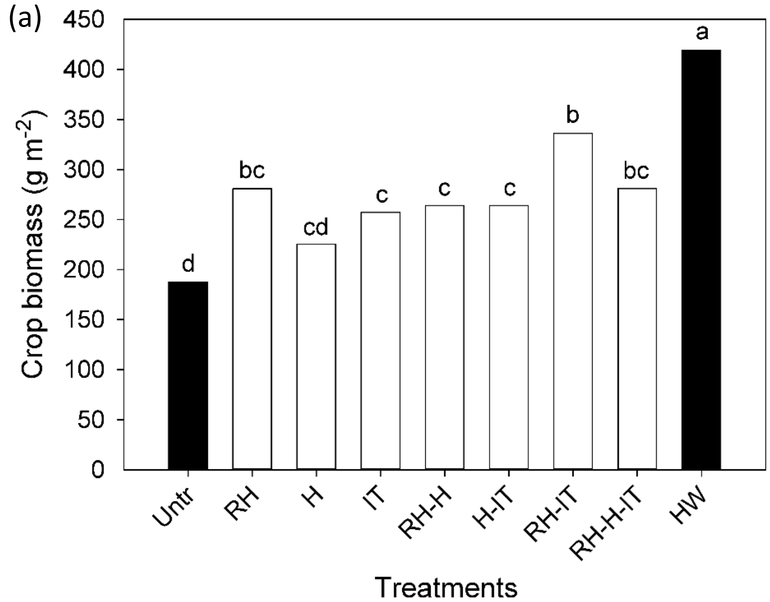


Figure 3.14 The relationship between number of mechanical weed control operations and weed biomass in lentil averaged over 4 site years at the KCRF (2016-2017) and GRF (2016-2017) (P=0.0001). Error bars represent the standard errors of the least squares mean.

3.4.7 Lentil Biomass

Regardless of MWC methods applied lentil biomass was greater than the untreated control (P<0.05) (Table 3.15); although the level of crop biomass response to MWC differed between treatments (Figure 3.15a). Harrowing alone resulted in the lowest increase in lentil biomass of 17%, while RH and RH-H-IT treatments resulted in 33% more crop biomass compared to control treatment. Overall, the highest lentil crop biomass was recorded in RH-IT treatment as it was 44% higher than in untreated check (Figure 3.15a).



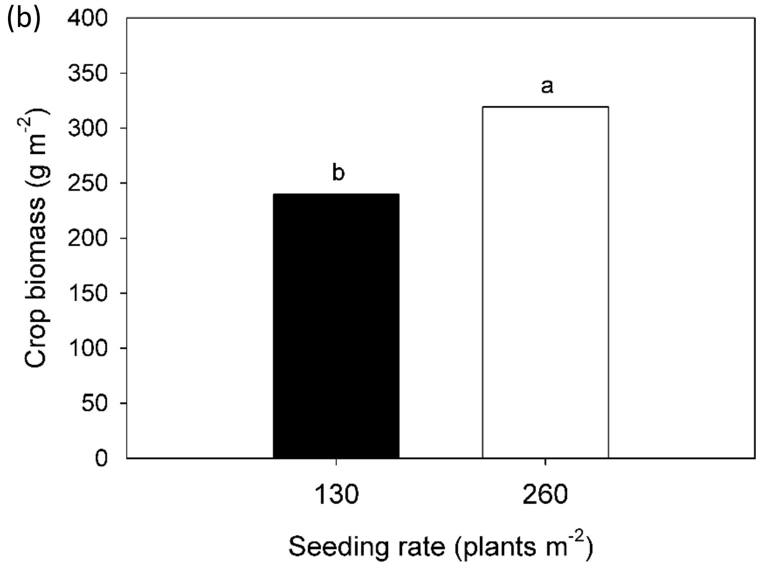


Figure 3.15 The effect of mechanical weed control treatments (a) and crop seeding rate (b) on lentil biomass averaged over 4 site years at KCRF (2016-2017) and GRF (2016-2017). Different letters represent a significant difference between treatment means at P<0.05.

Lentil grown at a 2X seeding rate accumulated 25% more crop biomass when compared to 1X seeding rate (Figure 3.16b); however, the interaction of MWC and seeding rate in lentil had no effect on lentil biomass (P=0.54).

According to contrasts between single, paired and multiple MWC treatments, it was found that on average single mechanical weed control treatments had a positive effect on crop biomass of lentil when grown under both 1X and 2X seeding rate. Under 1X seeding rate, two MWC operations resulted in the highest crop biomass increase of 33%, while single and multiple treatments on average resulted in similar crop biomass increase of 23% when compared to no MWC applied. Under 2X seeding rate, single MWC treatments resulted in 43% increase in lentil biomass when compared to untreated check under 2X seeding rate, while paired treatments increased crop biomass by additional 5%. Utilizing three MWC operation resulted in a two-fold increase in lentil biomass when compared to no MWC applied in lentil grown under organic SR. However, the difference between paired and multiple treatments was minor and on average accounted for only 3%. Therefore, paired MWC combinations in lentil grown under 2X seeding rate could be considered adequate to achieve high lentil crop biomass. These findings correspond with abovementioned crop biomass ANOVA results where paired combination RH-IT (Figure 3.15a), and choice of crop SR alone (Figure 3.16b) resulted in the highest crop biomass increase of 44% and 25%

respectively. Accordingly, choice of 2X SR in combination with paired MWC treatments can be considered as an effective strategy to maximize crop biomass accumulation in lentil (Figure 3.16) (P value: seeding rate=0.0078, operations= 0.0012, operations*operations=0.0026).

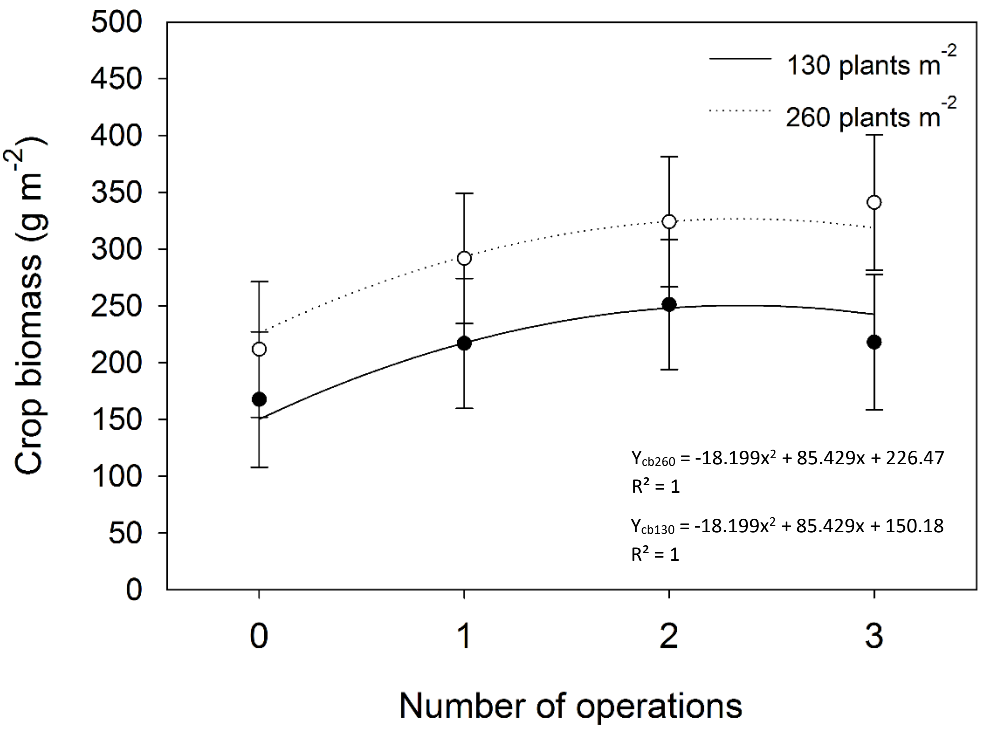


Figure 3.16 The relationship between number of mechanical weed control operations and crop seeding rate interaction and lentil biomass averaged over 4 site years at KCRF (2016-2017) and GRF (2016-2017). Error bars represent the standard errors of the least squares mean.

3.4.8 Lentil Yield

The highest yield of 1311 kg ha^{-1} was recorded in RH-IT treatment, which resulted in 40% higher grain yield when compared to untreated check (Figure 3.17a). In lentil, harrow applied alone and in combination with other MWC treatments resulted in only 18% to 23% yield increase when compared to the untreated check. Relatively low yield increases after harrowing alone may be associated with high sensitivity of lentil crop to damage caused by harrow tines. Treatments of RH, RH-H and IT resulted in 28%, 30% and 31% more lentil yield than in control treatment, respectively. Lentils grown at a 2X seeding rate exhibited 23% higher yield response when compared to normal SR (Figure 3.17b). There was no interaction of MWC and crop SR on lentil yield (P=0.63).

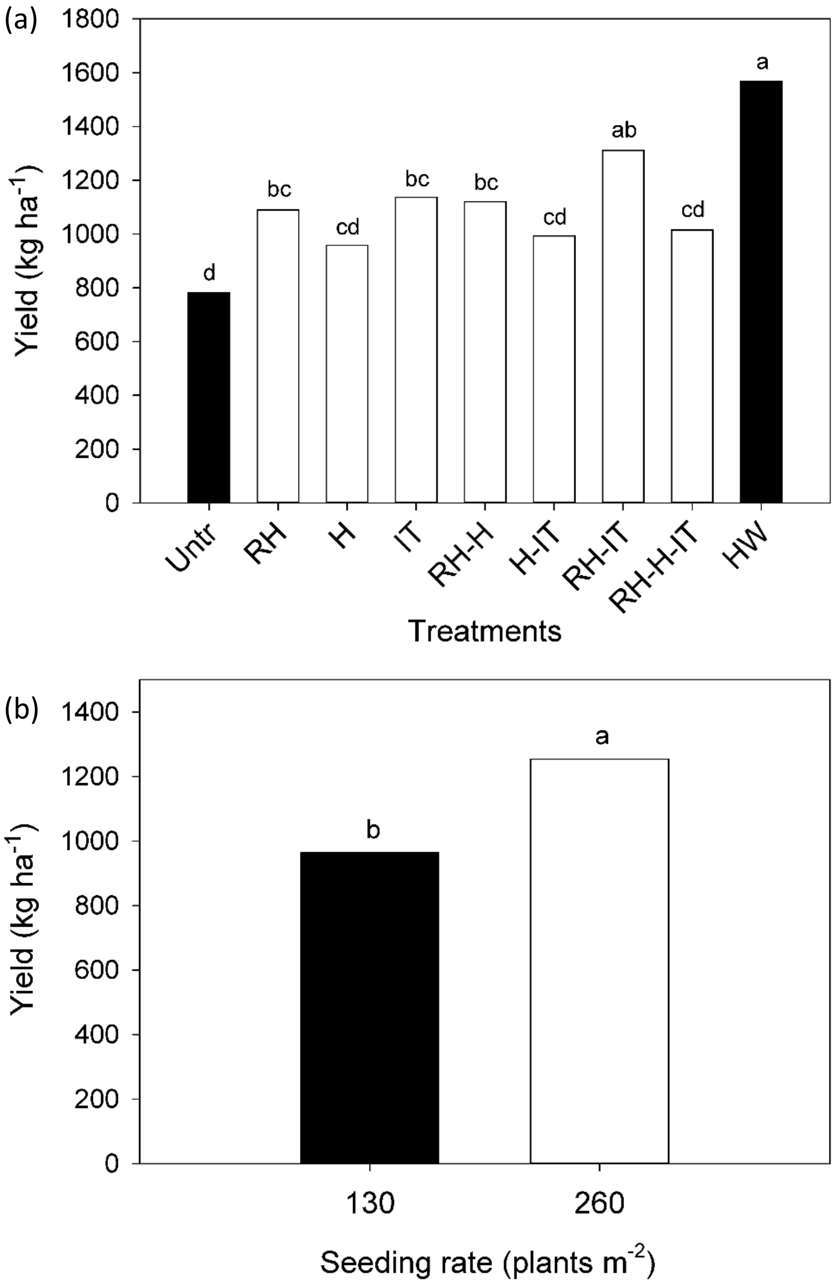


Figure 3.17 The effect of mechanical weed control (a) and crop seeding rate (b) on lentil yield averaged over 4 site years at KCRF (2016-2017) and GRF (2016-2017) ($P<0.05$). Different letters represent a significant difference between treatment means at $P<0.05$.

According to contrasts between single, paired and multiple MWC treatments all treatments exhibited a significant increase in lentil yield (Table 3.16; Figure 3.18). Under 1X seeding rate paired MWC treatments increased lentil yield by 33%, on average, whereas single and multiple treatments resulted in only 23% and 20% lentil grain yield increase when compared to untreated check, respectively. Under 2X seeding rate paired treatments on average resulted in an 46% increase in lentil yield, while yield increase with single and multiple treatments was statistically similar when compared to no MWC applied under 1X SR. Nevertheless, contrasts reveal that the overall yield difference between paired versus single and multiple treatments is minimal, although, all MWC treatments applied in lentil grown at a 2X seeding rate outyielded the same MWC treatments applied in lentil grown at a 1X seeding rate. (P value - operations 0.0003; seed rate - 0.0537; operations*operations 0.0001) Hence, integrating MWC along with higher than normal lentil SR is critical to achieve good lentil yield.

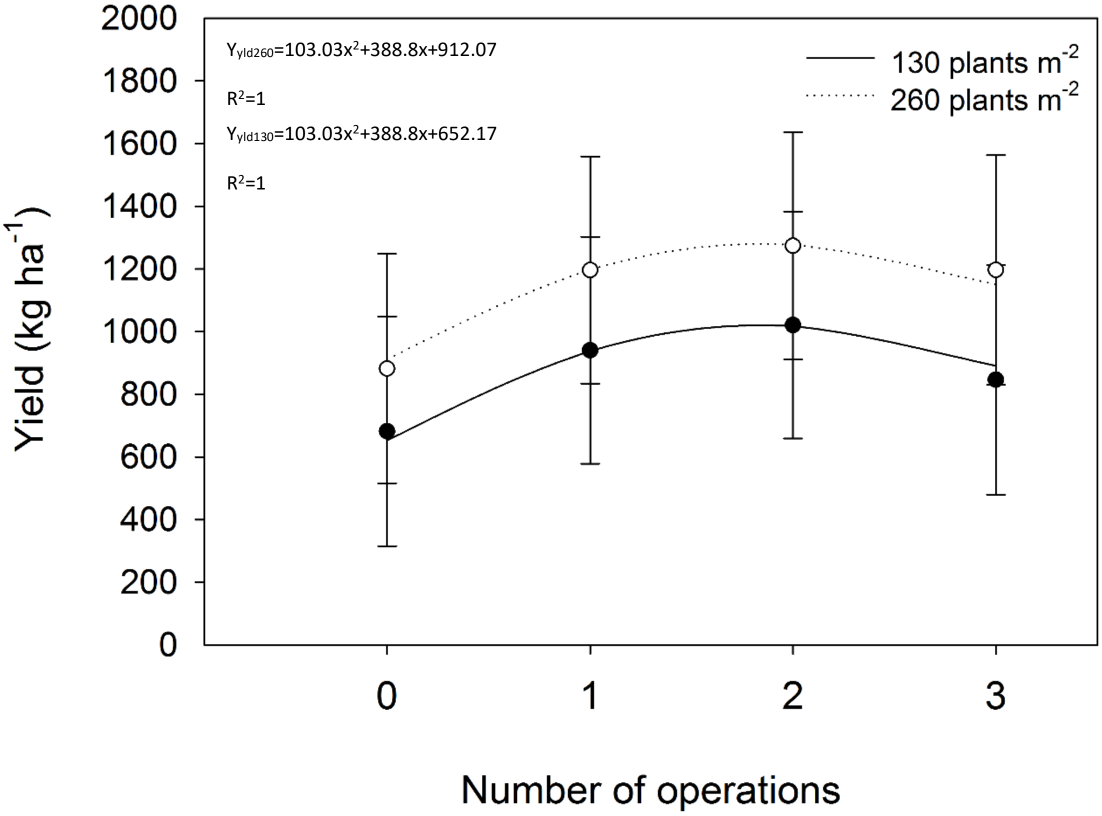


Figure 3.18 The association of number of mechanical weed control operations and crop seeding rate interaction on yield of lentil averaged over 4 site years at KCRF (2016) and GRF (2016-2017) (p=0.0001). Error bars represent the standard errors of the least squares mean.

3.4.9 Lentil Economic Analysis

Received gross margins for farm size of 405, 1214 and 2027 hectares were based on lentil crop density of 130 and 260 plants m^{-2} respectively (Table 3.17; 3.18; 3.19). Increasing seeding rate to 260 plants m^{-2} increased profitability by 20% when compared to crop density of 130 plants m^{-2}. All harrow including treatments except RH-H applied in lentil under crop density of 130 plants per m^{-2} exhibited the lowest profitability when compared to the rest of the treatments applied in lentil grown at the same crop density. Importantly, economic returns in lentil were maximized for all treatments at crop density of 260 plants m^{-2} when compared to no MWC applied at crop density of 130 plants m^{-2}. The best economic returns in lentils regardless of seeding rate were achieved with two passes with the min-till rotary hoe in combination with a single inter-row cultivation. Hence, integrating more than one MWC method for weed control together with higher crop SR would maximize weed suppression and profitability of organic lentil production.

According to the profitability of MWC achieved in our study, producers could recover the investment regardless of implement and farm size within a single field season. Farmers who already own one of the above mentioned in-crop weed control machinery would benefit from lower weed control costs per ha^{-1}.

Table 3.17 Influence of in-crop mechanical weed control treatments and crop seeding rates on economic results in lentil production based on farm size of 405 ha^{-1} (Gross Margin expressed in Canadian dollar)

Crop density	130 plants m^{-2}					260 plants m^{-2}			
Treatment	Treatment cost $ ha^{-1}	Total investment $ ha^{-1}	Yield kg ha^{-1}	Gross Margin	Gross margin over Untreated	Total investment $ ha^{-1}	Yield kg ha^{-1}	Gross margin	Gross margin over Untreated
Untr	0	79	681	1195.5	0	152.8	882	1497	0
RH 9	47.2	126.2	954	1657	462	200	1227	2095.2	598.2
H 9	30	109	885	1546.5	351	182.8	1030	1744.3	247.3
IT 8.5	34.3	113.3	975	1710	514.4	187.1	1298	2240	743
RH + H	77.2	156.2	981	1679	483.4	230	1259	2125.2	628.2
H + IT	64.3	143.3	865	1475.3	279.8	217.1	1121	1880	383
RH + IT	81.6	160.5	1201	2085.9	890.4	234.4	1422	2425.4	928.4
RH + H + IT	91.1	170.1	842	1404.2	208.7	243.9	1188	1977.6	480.6
HW	300	379	1284	2023.3	827.8	452.8	1849	3006.2	1509.2

Table 3.18 Influence of in-crop mechanical weed control treatments and crop seeding rates on economic results in lentil production based on on farm size of 1214 ha^{-1} (Gross Margin expressed in Canadian dollar)

Crop density		130 plants m^{-2}				260 plants m^{-2}			
Treatment	Treatment cost $ ha^{-1}	Total investment $ ha^{-1}	Yield kg ha^{-1}	Gross Margin	Gross margin over Untreated	Total investment $ ha^{-1}	Yield kg ha^{-1}	Gross Margin	Gross margin over Untreated
Untr	0	79	681	1195.5	0	152.8	882	1497	0
RH 12	46.3	125.3	954	1658.4	463	199.1	1227	2096.1	599.1
H 12	27.9	106.9	885	1548.6	353.1	180.7	1030	1746.4	249.4
IT 12	23.7	102.7	975	1720.6	525.1	176.5	1298	2250.7	753.7
RH + H	74.2	153.2	981	1681.9	486.4	227	1259	2128.2	631.2
H + IT	51.6	131.6	865	1488.1	292.6	204.4	1121	1892.8	395.8
RH + IT	70	149	1201	2097.4	901.9	222.8	1422	2436.9	939.9
RH + H + IT	76	155	842	1419.4	223.9	228.8	1188	1992.8	495.8
HW	300	379	1284	2023.3	827.8	452.8	1849	3006.2	1509.2

Table 3.19 Influence of in-crop mechanical weed control treatments and crop seeding rates on economic results in lentil production based on farm of 2027 ha^{-1} (Gross Margin expressed in Canadian dollar)

Crop density		130 plants m^{-2}				260 plants m^{-2}			
Treatment	Treatment cost $ ha^{-1}	Total investment $ ha^{-1}	Yield kg ha^{-1}	Gross Margin	Gross margin over Untreated	Total investment $ ha^{-1}	Yield kg ha^{-1}	Gross Margin	Gross margin over Untreated
Untr	0	79	681	1195.5	0	152.8	882	1497	0
RH 18	41.2	120.2	954	1663.5	468	194	1227	2101.2	604.2
H 18	24.7	103.7	885	1551.7	356.2	177.5	1030	1749.6	252.6
IT 19	20	99	975	1724.3	528.7	172.8	1298	2254.4	757.4
RH + H	66	145	981	1690.2	494.7	218.8	1259	2136.5	639.5
H + IT	44.7	123.7	865	1494.9	299.4	197.5	1121	1899.6	402.6
RH + IT	61.2	140.2	1201	2106.3	910.8	214	1422	2445.7	948.7
RH + H + IT	66.6	145.6	842	1428.7	233,.3	219.4	1188	2002.1	505.1
HW	300	379	1284	2023.3	827.8	452.8	1849	3006.2	1509.2

3.4.10 Lentil Discussion

In this experiment, we evaluated the effect of MWC tools including rotary hoe, flex-tine harrow, and inter-row cultivator combined with crop seeding rate to control weeds and improve lentil yield under organically managed conditions. It was hypothesized that different MWC methods would affect weed biomass and yield of organic lentil differently when applied at recommended and increased seeding rate. The results of this study supported this hypothesis for the effect of MWC and the effect of increased crop SR which resulted in significant decline in weed biomass and yield increase in lentil. Profitability of organic lentil production increased when MWC was utilized together with the cultural practice of increased crop SR.

Increased crop SR reduced weed interference in lentil (Figure 3.13b; Table 3.15). Several studies have reported enhanced weed control when lentil SR was increased (Boreboom and Young, 1995; Baird et al., 2009a; Redlick et al., 2017). Additionally, along with increased weed suppression, elevated SR resulted in increased crop biomass (Figure 3.16), yield (Figure 3.17) and profitability (Table 3.17; Table 3.18; Table 3.19) for the majority of MWC methods applied. Thus, organic producers may utilize higher than recommended SR to improve MWC efficacy and profitability of organic production.

In most cases, MWC resulted in a notable decline in weed interference. A single MWC operation on average reduced weed biomass in half (Figure 3.16). Studies by Velykis et al. (2009), Shirtliffe and Johnson (2012) and Stanley et al. (2017) agree with our study findings. Single MWC methods tested in this study may not stand alone for robust weed control in lentil due to several reasons. For instance, RH may be effective only when weeds are at emergence until the cotyledon stage. Harrowing may be effective after the 2nd node but not beyond the 5th node stage, while, inter-row cultivator disturbs only between 50% to 70% of the soil surface between crop rows (Mohler, 2001b). Thus, early or late-emerging weeds, if uncontrolled, may result in a notable decline in yield and grain quality.

Repeated physical disturbance may result in increased lentil crop injury. For instance, treatments including H (H, RH-H, RH-H-IT) except H-IT reduced lentil biomass up to 46%. Several studies reported that low H selectivity may be associated with reduced crop yields especially under low weed pressure (Rasmussen, 2004), inappropriate harrowing timing (Rasmussen & Nørremark, 2006) and implement adjustment (Böhrnsen, 1993). One may also consider that repeated physical disturbance may cause crop stand reduction via excessive soil covering of a short lentil crop. Rasmussen (1991) and Jensen et al. (2004) reported that crop damage caused by harrowing is inevitable since H is applied to the entire cropping area. Rasmussen (2008) reported good selectivity when harrowing was performed early regardless of row spacing; however, it is important to note that Rasmussen used barley as a model crop in his study, which is taller and more flexible when compared to lentil. In our study, we observed significant crop biomass reduction followed by yield decline when harrowed early (2^{nd} node stage), thus our results do not correspond to Rasmussen (2008) findings. Our results indicate that, lentils may be vulnerable to harrowing when compared to field pea crop. Thus, harrowing in lentil should be performed at an appropriate speed, crop stage and with corresponding implement adjustment (Section 5.2) to prevent significant crop injury in lentil.

In this study, paired and multiple MWC methods resulted in the greatest weed biomass suppression. This agrees with other studies where effective weed control with paired and multiple MWC methods was previously reported (Vangessel et al., 1995; Mohler et al., 1997; Swanton and Weise, 1991; Kolb et al., 2012). Hence, since the difference in weed suppression between paired and multiple MWC methods was minor in this study (Figure 3.14), growers may improve control of annual weeds while minimizing the risk of crop injury with paired MWC methods. In addition to increased weed suppression, the combination of pre- and post-emergence RH followed by single IT resulted in the highest crop biomass, yield, and profitability. Thus, considering detrimental crop injury with H including MWC methods, supplementing RH with early IT cultivation may facilitate weed control in both inter- and intra-row spaces. As a result, utilizing MWC together with elevated crop seeding rate may reduce weed management cost while maintaining high profitability of organic production over the long term.

3.4.11 Lentil Conclusions

Mechanical weed control and doubling the SR improved weed control and seed yield of organic lentil across all four site-years combined. This finding supports our initial hypothesis. Of all the treatments, pre- and post-emergence application with the RH in combination with single IT in lentil between 4^{th} to 6^{th} node stage resulted in among the greatest weed suppression and the greatest lentil yield. Lentils reached their maximum yield potential when paired MWC treatments were applied in lentil grown at 2X SR. Hence, integrating RH with IT cultivation allows for more robust control of early-season inter and intra-row weeds and later season inter-row weeds. In lentil, harrowing usually had an adverse effect on lentil plant populations indicating lesser tolerance.

4.0 The Effect of in-crop Mechanical Weed Control on Weed Community

4.1 Introduction

Weed control is one of the major challenges in organic crop production (Evans et al., 2016). Detrimental effects of weeds on crop growth, yield, and quality have been reported in numerous studies (Radosevich et., 1997, Blackshaw and O'Donovan, 1993; Bastiaans and Kropff, 2003; Fedoruk et al., 2011). Among cultural weed control methods, tillage is one of the primary tactics for reducing the abundance of weeds in organic systems (Rassmussen, 2004), while in conventional systems its serves as an element of integrated weed management (Swanton and Weise, 1991). Presently, in organic systems, early season physical weed removal is performed by shallow disturbance with either a minimum tillage rotary hoe (RH) or flex tine harrow (H). A minimum tillage RH controls weeds by flicking them out of the ground at the white thread stage (Leblanc and Cloutier, 2011; Shirtliffe and Johnson, 2012), while H controls weeds by uprooting and shallow soil covering of weakly anchored weeds (Kurstjens et al., 2000; Armengot et al., 2013). Large weeds in between crop rows may be removed with vison guided inter-row cultivators (IT) (Nørremark et al., 2012; Kunz et al., 2017) which bury them, dig them out or break them apart (Terpstra and Kouwenhoven, 1981). However, heavy reliance on cultivation may reduce soil quality (Grandy and Robertson, 2006) and increased weed emergence (Rasmussen, 2004). A change in vertical distribution of weeds seeds in the soil (Cardina et al., 1991), along with a change in physical and chemical characteristics of the soil environment (Gardarin et al., 2010) can promote weed seed germination and seedling emergence (Rasmussen, 2004). Tillage can serve as a weed community filter, which can both promote or constrain certain members of specific weed communities (Smith, 2006; Ryan et al., 2010).

Many researchers suggest that weeds affect crops as a part of the community, rather than individual species (Paul and Robertson, 1989; Lampkin, 1990; Derksen et al. 1993; Swanton et al. 1993; Booth and Swanton 2002; Zimdahl, 2004). The rate of response to timing and intensity of tillage varies among species. Some researchers suggested that weed species germination timing (Stoller and Wax, 1973; Egley and Williams, 1991) and timing of the tillage operation can affect weed community structure (Smith, 2006). Shirtliffe and Johnson (2012) reported that in pulse crops, small-seeded weeds, such as green foxtail and wild mustard that germinated before crop emergence were effectively controlled by RH application when the weeds were just emerging.

Although, control of late emerging weed species was limited, Rasmussen & Rasmussen (1995, 2000) reported that combinations of pre and post-emergence harrowing reduced weed biomass by 61 to 74%, but, only 78% of wild mustard (*Sinapis arvensis* L.) was controlled when H was performed pre-emergence. Cultivation efficiently controlled large tap rooted weed species in a study by Melander et al. (2003), but, Mohler et al. (2016) claimed that weed control varies among different ecological groups with IT providing excellent control of weeds emerging from seeds, while suppression of perennial species was limited due to their rapid regrowth. Another study by Alarcón et al. (2018) found that abundance of *Avena sterilis* was associated with a no-tillage system, whereas abundance of *Lolium rigidum* and *Polygonum aviculare* was linked to minimum and conventional tillage systems.

Some researchers claimed that several factors such as tillage system (Armengot et al., 2016), intensity (Armengot et al., 2015), timing and growing environment Cordeau et al. (2017) shape weed communities. Indeed, environmental conditions before and following mechanical weed control event can affect community composition and abundance of some species (Morton and Buchele, 1960) but not others (Grime and Jeffrey, 1965; Davis and Renner, 2007; Mohler et al., 2012). Importanlty, Cordeu et al. (2017) observed a difference in species emergence between early and late tillage operations. Many studies reported that in most weed species, light (Everson, 1949; Best and McIntyre, 1975; Gallagher and Cardina, 1998a, 1998b), exposure to favorable temperatures (Lawrence et al., 2004), seed distribution in the vertical soil profile (Vanden Born, 1971; Van Acker, 2003) and the presence of moisture (Bliss and Smith, 1985; Mulgeta and Stoltenberg, 1997) can affect weed seed germination.

Tillage can be used to strategically deplete the seed bank of dominant weed community members (Cordeau et al., 2017). This was challenged by Alarcón et al. (2018), who reported that core weeds species present in the weed community were only slightly affected by shallow non-inversion tillage over 9 years of the study period, whereas less common weeds species were affected the most. Hence, very little correct information is known on how different in-crop mechanical weed control tools affect weed communities. If in-crop mechanical weed control can selectively control specific weed communities, then growers may assemble weed communities that may be easier to manage (Ryan et al., 2010) and therefore facilitate future weed control. The objective of this research was to characterize and quantify how in-crop mechanical weed control (MWC) methods as a RH, H and IT applied alone and in combination with normal and increased crop seeding rate (SR) would affect weed community structure and composition in organic field pea and lentil crops. We hypothesize that weed community structure and composition would differ following different MWC methods utilized in field pea and lentil seeded at recommended and increased seeding rate.

4.2 Materials and Methods

The experiment was conducted on organically managed land during the 2017 field season at the Goodale Research Farm (GRF) (52°03'2N 106°30'W), Kernen Crop Research Farm (KCRF) (52°09N 106°33'W). The KCRF is located on Dark Brown Chernozemic clay-loam soil (20% sand, 30% silt and 50% clay) with a pH of 7.5 and GRF site was a Dark Brown Chernozemic loamy soil (42% sand, 41% silt and 17% clay) with a pH of 6.9. Soil organic matter at GRF was 2.4%, whereas soil organic matter at the KCRF was 4%. Pre-seeding tillage was conducted at both sites. Field pea and lentil, which were used as experimental crops, were seeded into wheat stubble.

4.2.1 Experimental Design and Management

The experimental design and management were the same as in Section 3.2.1.

4.2.2 Data Collection

The data collection process was the same as in Section 3.2.2, except that data from GRF and KCRF was collected only during the summer of 2017. Weed biomass of individual species was collected at the same time that crop biomass was obtained (Table 3.1). Weed community biomass and density assembly were performed after all MWC treatments were applied to determine the effect of MWC treatments on individual weed species alone as well as on the entire weed community.

4.2.3 Statistical Analyses

Data was analyzed in SAS statistical software (SAS Institute, 2012) version 9.3. Before initial data analysis covariance parameter estimate and homogeneity of variance tests were performed. The data was analyzed using Multivariate Analysis of Variance (MANOVA) to determine how MWC methods and choice of crop SR affect different weed species within the weed community (Table 4.2). Next, we conducted analysis of variance (ANOVA) to identify the effect of MWC methods and the choice of crop SR on individual weed species within the weed community. Analysis of variance (ANOVA) was conducted separately for each crop and site due to differences in weed community composition. Mean weed species densities and biomass values derived from separate ANOVA outputs were combined into stacked bar graphs using Sigma Plot 13® (Systat Software Inc, 2018) visualization software (Table 4.3). Replicate was assigned as a random effect and MWC and SR were assigned as fixed effect. A $P<0.05$ was used to indicate a significant effect of treatments on weed biomass and density of weed species within the community.

4.3 Results

4.3.1 Weed Community Composition

Weed species composition across all 3 site years was represented mainly by: green foxtail (SETVI) *(Setaria viridis* L.*)*, wild mustard (SINAR) *(Sinapis arversis* L.*)*, common lambsquarters (CHEAL) *(Chenopodium album* L.*)*, redroot pigweed (AMARE) *(Amaranthus retroflexus* L.*)* and wild buckwheat (POLCO) *(Polygonum convolvulus* L.*)*. Stinkweed (THLAR) *(Thlapsi arvense* L.*)*, wild oat (AVEFA) *(Avena fatua* L.*)* flixweed (DESSO) *(Descurainia sophia* L.*)*, smartweed (POLLA) (*Polygonum aviculare L.*), annual sowthistle (SONAU) (*Sonchus oleraceus* L.) and field horsetail (EQUAR) (*Equisetum arvense* L.) were also present in some plots, but they were less common. Initial weed densities are shown in Table 4.1.

Table 4.1 Mean weed species densities (plants m^{-2}) recorded after the first weed species assessments in field pea and lentil at KCRF and GRF in 2016 and 2017.

Species	Site		
	Field pea	Lentil	
	Kernen	Kernen	Goodale
	2017	2017	2017
Green foxtail	101	14	8
Wild Mustard	12	1	4
Common Lambsquarters	91	17	12
Red Root Pigweed	12	4	4
Wild Buckwheat	12	4	11
Stinkweed	4	NA	NA

[a] NA denotes absence or low density of weeds species (less than 2 m^{-2})

4.3.2 The Effect of Mechanical Weed Control and Crop Seeding Rate on Weed Community Density and Biomass

The effect of MWC and crop SR on the weed community present in field pea and lentil at the KCRF site and lentil at the GRF site during the summer of 2017 was determined using MANOVA analysis (Table 4.2). Weed community structure and composition varied both among and within sites. Mechanical weed control and crop SR affected both weed biomass and density of weeds in all three environments differently. According to MANOVA results it was indicated that MWC affected species biomass density present within the community differently at each of the three environments. However, we also found that the effect of crop SR had differential effect on weed species biomass and density only in field pea at the KCRF and lentil at the GRF, while in lentil at KCRF, no difference in weed species biomass among two tested crop SR was observed (Table 4.2).

Table 4.2. Multivariate analysis of variance (MANOVA) results for the effect of the mechanical weed control, seeding rate and combination thereof on biomass and density of weed species present within the weed community in field pea and lentil at KCRF and lentil at GRF in 2017. MANOVA output with a P value of <0.05 denotes a difference in weed biomass and density between species as affected by mechanical weed control, seeding rate and their interaction.

Treatment	The difference in weed biomass among members of weed community	The difference in weed density among members of weed community
	Field pea (KCRF)	
[a]mwc	0.001	0.001
[b]sr	0.02	0.462
mwc*sr	0.768	0.809
	Lentil (KCRF)	
mwc	0.001	0.001
sr	0.275	0.876
mwc*sr	0.83	0.955
	Lentil (GRF)	
mwc	0.001	0.001
sr	0.042	0.89
mwc*sr	0.205	0.841

[a]mwc – denotes the effect of mechanical weed control

[b]sr – denotes the effect of seeding rate

Green foxtail density

Density of green foxtail was reduced significantly following all MWC treatments (Table 4.3) except single RH and H at GRF in lentil. In field pea at KCRF, MWC reduced green foxtail density by 61% to 87%, with the exception of IT, which reduced green foxtail density by only 44% when compared to the control treatment (Figure 4.1a). In lentil at KCRF, RH alone, paired and multiple MWC treatments reduced green foxtail density by 60 to 82% respectively, when compared to untreated check; whereas, reduction in green foxtail density following single H and IT cultivation was 32% and 46% respectively when compared to untreated control (Figure 4.1c). Incomplete reduction of green foxtail following H may be attributed to larger weed size and less aggressive H tine adjustment, which may result in incomplete soil covering, reduced uprooting and thus, reduced overall control of green foxtail.

In lentil at GRF, repeated early weed control resulted in among the greatest green foxtail density reduction. Harrowing and RH resulted in 10% and 14% increase in green foxtail density. One must also consider that lentil density was 38% and 40% of the targeted 130 plants m^{-2} and targeted 260 plants m^{-2} crop density due to severe early season drought conditions when compared to lentil density at the KCRF respectively. Thus, since crop density was reduced green foxtail plants may have occupied the open space. Importantly, the combination of RH-H and RH-IT resulted in among the greatest green foxtail density reduction of 42% and 44%, respectively when compared to the untreated control (Figure 4.1e). Hence, under low crop density growers may focus on reducing the residual green foxtail weed densities by controlling early emerging small and the remainder of large green foxtail plants.

Green foxtail biomass

Overall the greatest green foxtail control in both field pea and lentil was achieved with rotary hoe including paired and multiple MWC treatments. At KCRF in field pea, treatments including RH reduced foxtail biomass from 77% to 98% when compared to the control treatment (Figure 4.1b). In lentil at KCRF, rotary hoe including paired treatments reduced green foxtail biomass by 84% to 94% when compared to control (Figure 4.1d). In lentil, at GRF, the greatest weed suppression was achieved with pre and post-emergence rotary hoeing followed by post-emergence harrowing as green foxtail biomass was reduced by 68% (Figure 4.1f). Nevertheless, low crop density due to early season drought and, repeated early season mechanical disturbance may limited lentils crops ability to compete with green foxtail. Control of large green foxtail plants with aggressive harrow adjustment may result in crop damage; hence, growers may substitute harrowing with early (4-5 node stage) inter-row cultivation. Additionally, at GRF, increased lentil crop seeding rate resulted in 37% reduction in green foxtail biomass. Therefore, growers may increase crop seeding rate along with using more than one MWC method to further improve crop competitive ability with green foxtail.

Wild mustard density

The effect of MWC had variable effects on wild mustard density. At KCRF in pea, all MWC treatments resulted in significant increase in wild mustard density in range from 1.6X to 3.5X when compared to uncultivated control, except IT cultivation where wild mustard density was reduced by 24% when compared to uncultivated control (Figure 4.1a). Importantly, despite bi-weekly hand weeding during the critical period of weed control in field pea and lentil at KCRF, respective wild mustard density in hand-weeded check was only 5% and 48% lower than in untreated control (Figure 4.1a; 4.1c). In lentil at KCRF, the effect of MWC had no effect on wild mustard density (P=0.2) (Table 4.3). In fact, wild mustard density in lentil at the KCRF in lentil was 17-fold lower than in field pea at the same location. Thus, very small overall wild mustard density explains why the effect of MWC was not statistically significant in lentil at KCRF.

Wild mustard biomass

Mechanical weed control had a significant effect on wild mustard biomass of in field pea at KCRF. The most notable control of wild mustard was accomplished with single RH and the combination of all three methods together which suppressed 52% and 69% of wild mustard biomass respectively, when compared to the untreated check. Importantly, increasing SR of field pea 1.5X of the recommended rate resulted in 51% decline in wild mustard biomass (Figure 4.1b). In lentil at KCRF, the effect of MWC on wild mustard was not significant (P>0.17) (Table 4.3).

Common Lambsquarters density

The lowest common lambsquarters densities were observed when inter-row cultivation was applied alone or in combination. For example, at the KCRF field pea common lambsquarters density following inter-row cultivation was reduced by 52% when compared to untreated control (Figure 4.1a). In lentil at KCRF, treatments including inter-row cultivation resulted in 4% to 58% reduction in common lambsquarters density when compared to the control treatment (Figure 4.1c). Not surprisingly at GRF in lentil, inter-row cultivation including treatments had lower common lambsquarters densities when compared to RH and H applied alone and in combination (Figure 4.1e). Repeated early season disturbance resulted in increased common lambsquarters densities. For instance, rotary hoeing pre and post crop emergence followed by harrowing resulted in 33%, 37% and 39% increase in common lambsquarters densities in lentil at GRF, field pea and lentil at KCRF, when compared to untreated check (Figure 4.1a; 4.1c; 4.1e). Accordingly, it can be hypothesized that the higher the intensity of soil physical disturbance the greater may be the common lambsquarters emergence periodicity and abundance. Growers utilizing rotary hoe and harrow for early weed control may consider monitoring the residual common lambsquarters density.

Common Lambsquarters biomass

In field pea and lentil at KCRF, harrowing and inter-row alone cultivation resulted in incomplete common lambsquarters suppression. However, RH alone, paired and multiple MWC methods reduced common lambsquarters biomass at the KCRF by 71% to 95% in field pea and by 70% to 93% in lentil when compared to untreated check (Figure 4.1b; 4.1d). Results differed in lentil at GRF. Nevertheless, inter-row cultivation resulted in incomplete common lambsquarters suppression; single H pass reduced lambsquarters biomass by 57% when compared to the control treatments (Figure 4.1f). At the GRF, common lambsquarters suppression with single harrowing was statically similar to combination of harrowing with inter-row cultivation. The reason for limited suppression with inter-row cultivation may be attributed to large size of the majority of common lambsquarters plants at the time of the cultivation event, which thus might recover from cultivation. Not surprisingly, early weed control with RH including treatments resulted in the highest common lambsquarters biomass decline in range from 75% to 85% when compared to the uncultivated control (Figure 4.1f). Thus, on average the greatest common lambsquarters control across two locations was achieved with rotary hoe including treatments; although, timely application of H followed by early inter-row cultivation may be a robust alternative for control of common lambsquarters.

Red root pigweed density

Mechanical weed control resulted in significant reduction in redroot pigweed density across both locations. In lentil at KCRF, mechanical weed control treatments and hand weeding treatment resulted in statistically similar reduction in redroot pigweed density in the range of 35% to 87% (Figure 4.1c). In lentil at GRF, the greatest redroot pigweed suppression was achieved with the combination of harrow with inter-row cultivation and inter-row cultivation alone as they resulted in 46% and 74% density reduction when compared to untreated check (Figure 4.1e). One must also consider that, at GRF, early season drought may have affected emergence of redroot pigweed. Thus, H and IT cultivation treatments may be more effective at reducing the density of redroot pigweed when redroot pigweed emergence is delayed.

Red root pigweed biomass

The effect of MWC treatments had variable effects on redroot pigweed biomass across two locations. In lentil at KCRF, all MWC treatments resulted in statistically similar reduction in redroot pigweed biomass in the range of 64% to 94% when compared to control (P=0.0154) (Figure 4.1d); however, at the GRF in lentil the effect of MWC on redroot pigweed biomass was not significant (P>0.05) (Table 4.3).

Wild buckwheat density

The effect of MWC on wild buckwheat density was found to be inconsistent. The effect of MWC on wild buckwheat density was not significant in field pea and lentil at KCRF (P>0.05) (Table 4.3). At GRF in lentil, all MWC treatments significantly reduced wild buckwheat density, but the rate of density reduction varied between methods applied. The greatest wild buckwheat density decline was achieved with the combination of RH with H and combination of all three MWC methods together as they reduced wild buckwheat density by 52% when compared to uncultivated control (Figure 4.1e). Hence, repeated early wild buckwheat suppression alone or when combined with early inter-row cultivation may be a more robust strategy to reduce wild buckwheat abundance.

Wild buckwheat biomass

Wild buckwheat biomass in field pea and lentil was not affected by MWC across two locations (P>0.05) (Table 4.3).

Stinkweed density

Mechanical weed control had a significant effect on density of stinkweed in lentil at GRF. Rotary hoeing and harrowing alone resulted in 2.5X and a 1.8X increase in stinkweed density (Figure 4.1e). Conversely, treatments including IT, except combination of RH-IT, resulted in 23% to 62% reduction in stinkweed density when compared to control treatment. In fact, abovementioned 62% reduction in wild buckwheat density was achieved with single IT (Figure 4.1e). Thus, growers with high stinkweed infestation may obtain greater density reduction with single early IT.

Stinkweed biomass

Biomass of stinkweed was very variable among all MWC treatments with the highest biomass in RH treatment and the lowest in untreated check. In fact, biomass of stinkweed was 87% to 97% higher following MWC treatments when compared to the untreated check (Figure 4.1f). It can be suggested that soil disturbance might affect stinkweed germination, as stinkweed biomass was the lowest in untreated check. Importantly, increasing SR to 260 plants m^{-2} resulted in 55% decline is stinkweed biomass (Figure 4.1f).

Table 4.3 ANOVA for field pea and lentil at the KCRF and lentil at GRF weed biomass and density of species present within the weed community as affected by the effect of mechanical weed control, crop seeding rate and their interaction.

[a] NA denotes absence or low density/biomass

	Weed biomass						Weed density					
						Field Pea (KCRF)						
Treatment	SETVI[b]	SINAR[c]	CHEAL[d]	AMARE[e]	POLCO[f]	THLAR[g]	SETVI	SINAR	CHEAL	AMARE	POLCO	THLAR
mwc	<.0001	0.026	<.0001	N/A[a]	0.3865	N/A	<.0001	<.0001	<.0001	N/A	0.565	N/A
sr	0.155	0.0011	0.4141	N/A	0.7155	N/A	0.8676	0.2577	0.7909	N/A	0.5592	N/A
mwc*sr	0.9968	0.7242	0.8697	N/A	0.998	N/A	0.0435	0.9331	0.8033	N/A	0.555	N/A
						Lentil (KCRF)						
mwc	<.0001	0.171	<.0001	0.0154	0.4741	N/A	<.0001	0.2025	0.0005	0.131	0.3198	N/A
sr	0.5649	0.6323	0.2377	0.3577	0.6573	N/A	0.2462	0.2849	0.3595	0.6958	0.3706	N/A
mwc*sr	0.8197	0.992	0.0578	0.9767	0.3125	N/A	0.1959	0.5143	0.8904	0.8811	0.6571	N/A
						Lentil (GRF)						
mwc	0.0658	N/A	<.0001	0.4965	0.3246	0.0273	<.0001	N/A	0.0012	0.0159	0.001	0.0031
sr	0.0259	N/A	0.3296	0.1478	0.6213	0.0096	0.3511	N/A	0.6528	0.8856	0.4024	0.223
mwc*sr	0.7054	N/A	0.4665	0.0721	0.6791	0.4154	0.862	N/A	0.4754	0.6973	0.4669	0.0784

[b]SETVI – green foxtail, [c]SINAR – wild mustard, [d]CHEAL – lambsquarters, [e]AMARE – redroot pigweed, [f]POLCO – wild buckwheat, [g]THLAR – stinkweed.

The overall effect of mechanical weed control of weed community structure and composition

In this study rotary hoe including treatments resulted in significant reduction in green foxtail and common lambsquarters biomass across all site years, although control of remainder of weed community was inconsistent (Figure 4.1). Mechanical weed control in this study resulted in incomplete wild mustard suppression. Thus, growers may consider alternative weed control methods other than in-crop physical removal for control of wild mustard. Mechanical weed control had significant effect on biomass of redroot pigweed in lentil at the KCRF, while in lentil at the GRF it had no effect on redroot pigweed and wild buckwheat biomass. Nonetheless, repeated early mechanical disturbance with a combination of RH followed by H resulted in a significant decline in redroot pigweed and wild buckwheat density at the GRF. Adversely, H followed by early IT significantly reduced redroot pigweed density. In studies by Mohler et (2016) the greatest control of redroot pigweed was achieved when it was small. Thus, growers with high redroot pigweed infestations may need to apply control measures immediately after first redroot pigweed plants are present. Intensive mechanical disturbance was associated with an increase in stinkweed biomass. However, one must also consider that increase in stinkweed biomass may be associated with biomass removal of other species. Hence, timely MWC may not only reduce weed interference of dominant community members, but also may stimulate emergence of less common weed species.

The overall effect of seeding rate on weed community structure and composition

Altering crop density had variable effects on weed species within the community as it affected some weeds but not others (Table 4.3). Wild mustard biomass was 51% lower when seeding rate of field pea at KCRF was increased 1.5X times of the standard rate. Similar effect of increased crop SR was observed in lentil at the GRF, where doubling seeding rate of lentil resulted in 37% and 55% lower biomass of green foxtail and stinkweed when compared to standard SR, respectively. Growers with high densities of abovementioned weed species may consider increasing SR of field pea and lentil 1.5X and 2X of the standard recommended SR to improve crop competitive ability respectively.

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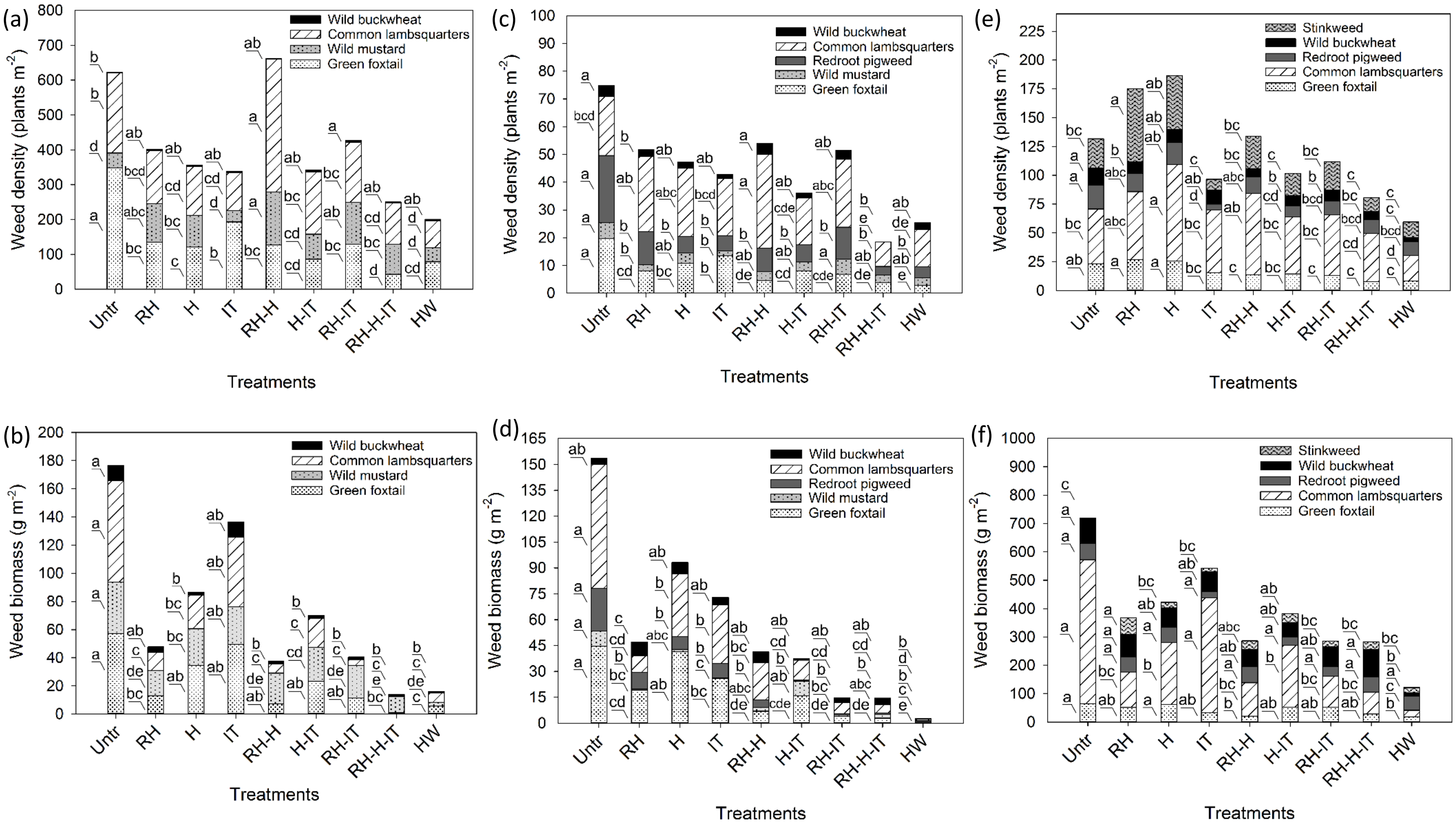


Figure 4.1 The effect of mechanical weed control on density and biomass of weed species present in field pea (a, b) and lentil (c, d) at KCRF, and lentil at GRF (e, f) respectively. Letters indicate statistically significant differences between a given weed species between treatments at P<0.05.

4.4 Discussion

Green foxtail

The greatest green foxtail suppression was achieved with RH including paired treatments, while control with single MWC treatments was variable. Inconsistent weed suppression with single MWC treatments may be attributed to variability in recruitment depth, which therefore might affect periodicity of green foxtail emergence. One might also consider that green foxtail favors shallow emergence (3.8 cm) (Dawson & Bruns, 1962; Vanden Born, 1971). Thus, RH application might displace more seeds to the germination depth.

Increased overall green foxtail density may be the reason for reduced weed control efficacy of IT in field pea at KCRF (Figure 4.2b). Despite the fact that green foxtail density with a single pass with an inter-row cultivator was reduced by 44%, weed biomass was reduced by only 13% when compared to the control treatment. Thus, since inter-row cultivation was applied early (5-node stage in field pea), green foxtail plants grown in intra-row spaces may compensate for open space by growing more biomass. The opposite effect of inter-row cultivation occurred at KCRF in lentil (Figure 4.3a; Figure 4.3b). Despite a reduction in weed density by 32%, weed biomass was reduced by 42% when compared to control. This can be attributed to low overall green foxtail density, which in fact was 17-fold lower than in field pea at the same site.

Increased suppression of green foxtail with paired MWC treatments may be attributed to control of both early and late emerging plants. Green foxtail favors germination between late May to mid-June, which possibly allowed the weed to escape early MWC application. Thus, greater control with paired rotary hoe including treatments further highlights the importance of controlling late emerging green foxtail plants with harrow or inter-row cultivation. Holm et al. (1977) suggested that late spring and early summer cultivation is required for robust green foxtail suppression, which agrees with our study findings. One may also take into consideration that green foxtail has a very short life cycle. Schreiber and Oliver (1971) reported that on average it took 37 days from seeding green foxtail to reach 25% flowering. Thus, control of green foxtail should be done during the first two two-to-three weeks following identification of first plants in the field. Growers may consider using repetitive early MWC methods with increased SR to further improve crop competitive ability with green foxtail; and may consider combining early, repetitive MWC methods with an increased crop SR to further improve crop competitive ability with green foxtail.

Wild mustard

Control of wild mustard in this study was inconsistent. The effect of MWC had an effect on wild mustard in field pea at KCRF, while no significant effect was observed at KCRF in lentil. However, increasing SR of field pea at KCRF resulted in a 51% reduction in wild mustard biomass, when compared to the recommended SR.

In lentil at KCRF, no effect of MWC can be attributed to very low initial wild mustard density (Figure 4.3b). Therefore, all MWC methods resulted in greater than 75% control of wild mustard when compared to untreated control, except the combination of harrow with inter-row cultivation. At KCRF in field pea, wild mustard biomass was 4-fold greater than in lentil at the same site (Figure 4.2a). All MWC treatments except inter-row cultivation resulted in a 1.5X to 3.5X increase in wild mustard density, although increase in density did not contribute to higher wild mustard biomass. For instance, single H and RH despite having 2X and 2.5X higher wild mustard density resulted in 39% and 51% lower wild mustard biomass when compared to the untreated check. Similar results were observed with RH and H including paired treatments where despite the increase in wild mustard density, biomass was reduced in range from 59% to 87% when compared to the control treatment. Results were different for inter-row cultivation as despite a 24% reduction in wild mustard density; weed biomass was reduced only by 14% when compared to the control treatment.

Reduced control with the IT may be attributed to high wild mustard plasticity allowing to compensate for the open space caused by IT. Donohue (2002) reported that in *Arabidopsis*, later emerging plants had faster relative growth rate and shifted to reproduction earlier than early emerging plants. Despite the higher growth rate late emerging plants did not reach the size of early emerging plants. Not surprisingly, in our study, late season increase in density did not contribute more to vegetative biomass, since more wild mustard plants may allocate their energy to reproduction rather than vegetative development. Weed life cycle strategy depending on time of emergence weeds was previously discussed in several studies examining phenotypic plasticity. A study by Zhou et al. (2005) found that phenotypic plasticity depended on germination timing. For instance, early spring emerging common lambsquarters and red root pigweed plants allocated more resources to vegetative biomass and roots, but less to reproductive organs, when compared to late spring and late summer emerging plants. Zhou et al. (2005) stated that common lambsquarters and red root pigweed plants that germinated late in season had a ruderal life cycle strategy since they allocated majority of resources to reproduction. These results agree with our study observations. From an evolutionary perspective, a short life cycle with maximal allocation to reproduction may be advantageous under unfavorable environmental conditions. In wild populations of *Boechera stricta*, which is a member of *Brassica* family, plasticity may even improve adaptation and persistence in a new habitat (Wagner and Mitchell-Olds, 2018).

I speculate that wild mustard may recover after single early or late MWC application through high phenotypic plasticity and growth rate. Thus, when wild mustard density is high, early MWC with a RH or H followed by IT may provide better control of wild mustard. However, since the greatest control of wild mustard in this study decreased wild mustard by only by 68%, growers may increase their seeding rate to improve crop competitive ability with wild mustard.

Common Lambsquarters

Rotary hoe including paired treatments controlled between 80 to 93% of common lambsquarters on average across all three site years (Figure 4.2a; Figure 4.3a; Figure 4.4a). Interestingly, H controlled 57% of lambsquarters, and RH alone 81% on when compared to untreated check. Control with IT did not exceed 34% when compared to the untreated check. Since IT does not provide control of weeds in the intra-row spaces. Enhanced control of common lambsquarters with RH including treatments indicate that early emerging lambsquarters are highly vulnerable when they are small. Hence, growers using RH together with IT may achieve more robust control of common lambsquarters.

Wild buckwheat

Mechanical weed control had no significant effect on wild buckwheat biomass and density at KCRF. Mechanical weed control affected wild buckwheat density at GRF, but there was no significant effect on wild buckwheat biomass.

Delayed emergence may be one of the reasons for insignificant wild buckwheat suppression. Wild buckwheat germinates from 1.5 to 5cm depth, with emergence from up to 19 cm has also been reported (Kollar, 1968); although, in this study the practice of burying seed to inhibit emergence failed. Contrary, in a study by Koch (1964), pre-emergence harrowing increased the numbers of several species including wild buckwheat and stinkweed.

The majority of wild buckwheat germinate during the first periods of warm spring weather in May and June. However, wild buckwheat germination is continuous with some seeds emerging in September. In this study, the majority of MWC was applied between late May and mid-July. Thus, since greater than 50% of weeds were suppressed with MWC, wild buckwheat that emerged following MWC had enough chance to fill the open space with its own biomass (Holm et al., 1977). Under good growing conditions, single early emerging wild buckwheat plants can produce up to 30,000 seeds. Furthermore, Witts (1960) stated that late emerging plants completed full life cycle from vegetative to seed production 15 to 20 days faster while producing half of seeds produced by early emerging plants. Since the plant has an indeterminant growth habit (Holm et al., 1977), it is critically important to prevent vegetating wild buckwheat plants from setting seeds.

Red root pigweed

Control of redroot pigweed was inconsistent. At KCRF in lentil, MWC reduced pigweed weed biomass by 61% to 99%, but at GRF, the effect of MWC was not significant. An significant effect of MWC can be attributed to early season drought, which may have prolonged redroot pigweed emergence periodicity. Also, it is important to note that lentil crop density at GRF did not exceed 40% of targeted 130 and 260 plants m^{-2}. Not surprisingly, despite redroot pigweed density recorded in untreated control was similar across both locations, weed biomass of redroot pigweed in control treatment at GRF was 3-fold higher when compared to control treatment at KCRF. Thereby, I speculate that red root pigweed plants may exhibit phenotypic plasticity in response to open space (Sultan, 2000) which was available due to lower lentil density. Furthermore, in studies by Zhou et al. (2005) redroot pigweed plants that emerged in early spring allocated the majority of resources to vegetative growth (aboveground biomass and root biomass) rather than to reproduction when compared to late spring and summer emerging redroot pigweed plants. In this study, we observed that at GRF redroot pigweed plants that escaped early rotary hoeing or harrowing at GRF application were too large to be affected by inter-row cultivation.

Despite inconsistent weed suppression in our study, Schonbeck (2015) and Mohler et al. (2016) found that redroot pigweed was highly vulnerable to rotary hoeing and inter-row cultivation when it was small. In our study, inter-row cultivation provided adequate control of early emerging redroot pigweed plants at KCRF in lentil (Figure 4.1c, 4.1d), while control of large plants was limited, which corresponds to Mas and Verdu (1996), Schonbeck

(2015) and Mohler et al. (2016) findings. Accordingly, it can be suggested that timely control of new emerging redroot pigweed plants is critical.

Stinkweed

Mechanical weed control was effective in reducing stinkweed biomass and density. Doubling SR of lentil decreased stinkweed biomass by 55% when compared to the untreated check. Weed biomass of stinkweed was variable among all MWC treatments with the highest biomass in the single RH treatment and the lowest in the untreated check.

Treatments including IT reduced stinkweed density from 2% to 62% when compared to the untreated control. Rotary hoeing and H alone resulted in a 2.5X and a 1.8X increase in stinkweed density when compared to the untreated check; although the combination of RH and H had the same density as the untreated check. Nonetheless, the density of stinkweed was lower in IT including treatments, weed biomass of stinkweed was not significantly different among all MWC treatments. Thus, I speculate that physical soil disturbance may stimulate stinkweed emergence.

Previous studies reported improved stinkweed emergence when seeds were exposed to mechanical damage (Crocker, 1906; Schulte & Balbach, 1941), prolonged cold and wet soil conditions (Kolk, 1962; Hazebroek and Metzger, 1990), displaced to recruitment depth (Van Acker et al., 2003) and illumination (Best and McIntyre, 1975). Our study observations concur with Ryan et al. (2010), who found that stinkweed was absent in a long-term conventional system; whereas, it was abundant in organically managed systems, where soil disturbance is more common. Since the highest stinkweed density was recorded after a single RH treatment, it can be hypothesized that soil disturbance removes the filters which limit stinkweed emergence. One must also consider that this weed was present in only one out of three site years; therefore, more data is needed to prove abovementioned observations.

All weeds

In this study, we hypothesized that weed community structure and composition would differ following different MWC methods utilized in field pea and lentil seeded at recommended and increased seeding rate. Results of this study support the hypothesis for the effect of MWC, but the effect of SR on weed community structure and composition was inconsistent. Mechanical weed control affected different weeds within the community differently (Table 4.2). Treatments including RH effectively controlled green foxtail and lambsquarters; however, control of wild mustard, redroot pigweed, buckwheat, and stinkweed was inconsistent (Table 4.3). The reason for erratic control may be attributed to the difference in weed recruitment depth (Du Croix Sissons et al., 2000), light requirements (Best and McIntyre, 1975) temperature (Lawrence et al., 2004) timing of emergence (Boyd and Van Acker, 2003) and weed phenotypic plasticity (Sultan, 2000). Phenotypic plasticity in agricultural weeds has previously been reported in several studies (Neffer and Hurka, 1986; Sultan, 2001; Donohue, 2002; Zhou et al., 2005; Wagner and Mitchell-Olds, 2018). It is still unclear which factors may affect the rate of phenotypic plasticity and how it may affect crop competitive ability. Since control of wild mustard, wild buckwheat, and redroot pigweed was variable, it can be hypothesized that the rate of phenotypic expression may vary between different weed species (Sultan, 2000).

In this study, soil disturbance differed among the MWC methods used. On the whole, I speculate that weed stage, density, and soil covering depth at the time of cultivation may significantly affect weed recovery following MWC operation. Mohler et al. (2016) reported variable recovery rates in different weed species following burial. In the lentil study at KCRF control with single rotary hoe and harrow was reduced despite lower weed density. Conversely, under high weed density in field pea at KCRF, inter-row cultivation resulted in incomplete weed control as weeds still compensated in the open space in the inter-row spaces through phenotypic plasticity. Since our study found that soil disturbance affected the emergence of stinkweed and wild buckwheat, growers may need to scout their fields following MWC application.

Mechanical weed control tactics applied based on the knowledge of the similarities in weed community biology and physiology might improve weed control. In this study, increased crop SR reduced biomass of green foxtail, wild mustard and stinkweed (Table 4.3), so growers may consider increasing SR to improve crop competitive ability. Hence, growers utilizing more than one MWC tool along with higher than standard SR may benefit from reduced weed interference and retain functional weed communities (Strokey et al. 2006, Violle et al., 2007) which could provide beneficial ecosystems services (Storkey and Westbury, 2007) thus facilitating control.

4.5 Conclusion

Mechanical weed control affected weed community structure and composition while the effect of increased crop SR was not significant. Ryan et al. (2010) claimed that abiotic (mechanical weed control) and biotic (crop and competition, pathogens) filters determine structure and composition of weed communities. Mechanical weed control can serve as a reliable filter, which similarly to herbicides can select for susceptible species and when composed of multiple MWC tactics provide some residual weed control activity. In pulse crops, early season weed control is critical as they are unable to compete for resources efficiently before N_2-fixing bacterial infection (Di Tomasso, 1995; Blackshaw and Brandt, 2008). Hence, based on the results of our study we suggest that paired in-crop MWC methods and cultural practice of increased crop SR can facilitate management of weed communities in uncompetitive crops.

5.0 General discussion

5.1 The Effect of Mechanical Weed Control and Seeding Rate on Yield and Weed suppression of Organically Grown Field Pea and Lentil

The focus of this study was determining the ability of MWC methods as RH, H and IT and crop SR to control weeds and improve field pea and lentil yield under organically managed conditions. It was hypothesized that different MWC methods would affect weed biomass and yield of organic field pea and lentil differently when applied at recommended and increased seeding rate. The outcome of this study supported this hypothesis for the effect of MWC, which resulted in a significant decline in weed biomass and yield increase in both field pea and lentil. In this experiment, the effect of seeding rate supported this hypothesis in lentil, while in field pea increased seeding rate improved field pea yield but had no effect on weed biomass suppression. Presence of MWC and increased crop seeding rate improved profitability of both field pea and lentil.

Increased crop SR reduced weed interference in lentil (Figure 3.13b). Enhanced weed control with higher than normal lentil seeding rate was previously reported in some studies (Baird et al., 2009a; Redlick et al., 2017). In field pea, increasing SR had no effect on weed suppression (Table 3.6). Importantly, in this study, we tested double seeding rate of lentil, while in field pea seeding rate was increased only 1.5X times the standard rate. Thus, minor difference in actual crop density among two examined seeding rates explains why there was insignificant weed control response of increased field pea crop seeding rate. Conversely, some studies reported decreased weed biomass and higher yields when seeding rate of field pea exceeded 100 plants m^{-2} (Marx and Hagedorn, 1961; Lawson and Topham,1985). Increasing SR of field pea to 120 plants m^{-2} resulted in a positive yield response in a study by Baird et al. (2009), which concurs with our research findings. Increasing SR above 135 plants m^{-2} may provide a weed control benefit, but limited yield response (O'Donovan and Newman, 1996) as more plants will suffer from intraspecific competition (Zimdahl, 1993).

Single MWC methods tested in this study resulted in incomplete weed suppression in both crops (Figure 3.6a; Figure 3.13a). Single MWC methods may not provide robust weed suppression as timing for their application may be restricted by unfavorable environmental conditions. Lötjönen and Mikkola (2000) reported poor weed suppression and no yield increase of RH and H, as wet field conditions restricted the appropriate timing of application. Moist soils assisted weed recovery following cultivation, thus reducing the overall weed control efficacy. One must also conclude that consistency of weed suppression, yield and profitability of single MWC methods are valid only for conditions and environment where the experiment was conducted (Orykot et al., 1997). Therefore, stability of weed control efficacy over the long term may be improved by supplementing early mechanical weed methods with late MWC methods or vice versa.

Multiple treatment combinations resulted in the highest weed suppression in field pea. Conversely, in lentil, crop damage due to multiple MWC methods resulted in similar yield when compared to single MWC methods applied (Figure 3.18a). Hence, multiple MWC methods should take place when detrimental effects of crop injury are outweighed by weed control benefits.

The greatest weed suppression in field pea was achieved with paired MWC methods (Figure 3.7). In lentil, paired H including treatments resulted in lower grain yield, caused primarily due to crop injury from harrow tines. Two passes with a RH in combination with single IT resulted in increased weed suppression (Figure 3.13a), reduced crop injury (Figure 3.15a) and highest lentil grain yield (Figure 3.17a). There are several reasons for enhanced weed suppression with paired MWC methods. First, is reduced interspecific competition early during the critical period of weed control. Second, weeds that emerge before the crop can be controlled with pre-emergence rotary hoeing application and when supplemented by early post-emergence RH or H gives the crop competitive advantage over remaining weeds (Pavylchenko, 1949). Third, it provides growers with more weed control flexibility as weeds can be controlled later during the critical period of weed control with IT

(Fedoruk et al., 2011; Stanley et al., 2017). Finally, integrating RH or H with IT tillage allows to target weeds within the row and in the inter-row spaces (Lötjönen and Mikkola, 2000).

Clearly, adoption of diverse MWC management has it costs including an expensive initial machinery investment (Table 3.2), and increased labor rates for operating the machinery. Additionally, it requires more detailed attention to application timing (Zimdahl, 2004). In a present study, single early RH or H were effective in controlling of species emerging before at the time of the weeding operation, but large weeds and weed species with prolonged or delayed emergence periodicity may not be controlled with RH or H. In this study, single MWC methods resulted in high organic field pea yields, despite being less effective in terms of weed control. Machleb et al. (2018) reported that IT with low disturbance no-till sweeps in 12.5 and 15cm rows resulted in the highest cereal grain yields. However, Machleb et al. (2018) also found that no-till sweeps had lower weed control efficacy when compared to remainder of tested hoeing implements. Furthermore, they reported that goosefoot sweeps resulted in greatest weed control efficacy; but, weed control efficacy varied across locations. For example, at an organically managed site, weed control efficacy of goosefoot sweeps was 38.2% lower when compared to the conventionally managed site due higher weed densities present in the organically managed site. These results agree with our study findings as weed biomass with a single goosefoot sweep cultivator pass was reduced by only 36% and 40% in field pea and lentil, respectively. Hence, under high weed density incomplete weed biomass suppression with single mechanical methods may result in greater weed biomass recovery rates through phenotypic plasticity (Sultan, 2000; Sultan, 2001). Thus, remaining weeds if uncontrolled can create future weed control problems, thus increasing the cost of future weed control and posing a threat to future crop yields.

Weed community adaptation to agricultural practices has been reported in several studies (Storkey et al., 2012; Gardarin et al., 2012; Colbach et al., 2014) Thus, since repeated use of same weed control practices may select for resistant biotypes, more diverse weed control methods should not be underestimated. Paired MWC methods may not result in the greatest weed suppression; however, growers may benefit from reduced risk of weed control failure. In this study, paired MWC methods resulted in increased weed suppression (Figure 3.6: Figure 3.13) and more stable profits in both crops (Table 3.9; 3.10; 3,11; 3.17; 3.18; 3.19). The combination of H or RH with inter-row cultivation applied in field pea seeded at higher than recommended seeding rate resulted in greater profitability when compared to single and multiple MWC methods applied under same crop seeding rate. In lentil, two passes with the rotary hoe in combination with single inter-row cultivation had 20% higher profitability when compared to cultivation alone regardless of seeding rate. Importantly, increasing seeding rate of field pea 1.5X times of recommended rate increased profitability by 13% (Table 3.9; 3.10; 3.11), while doubling seeding rate alone in lentil resulted in 20% higher profits when compared to standard seeding rates (Table 3.17; 3.18; 3.19). Studies by Baird et al. (2009a, 2009b) and Redlick et al. (2017) reported positive effect of increased seeding rate on yield and profitability of field pea and lentil, which concurs with our study findings.

Numerous studies highlighted that weeds that emerge before the crop translate into significant yield loses (Nelson and Nylund, 1962; Harper, 1997; O'Donovan et al., 1985; Forcella et al., 2000; Willenborg, 2004). Early weed control with the rotary hoe or harrow has a high potential to provide the crop with a competitive advantage over remaining weeds and when supplemented with post-emergence weed control tactics would maintain the crop weed free longer during the critical period of weed control (Fedoruk et al., 2011). Integrated use of MWC methods and cultural practice of increased crop SR (Benaragama and Shirtliffe, 2013) may provide growers with robust weed suppression, high crops yield and more stable profits. Prior to selecting MWC methods for weed control, growers may need to understand their weed community composition and structure to selectively filter or reduce the abundance of dominant weed community members. Therefore, along with knowledge of how to successfully manage weeds it requires management skill for a grower knowing when to apply it on particular farm (Zimdahl, 2004). Intelligent intensification of organic production may result in better land use efficacy and on farm profitability, while contributing to regeneration of native flora and fauna since less land is involved in-crop production.

5.2 Field Pea and Lentil Management Recommendations

Since single and paired MWC treatments resulted in statistically similar field pea yield increase regardless of the choice of implement (Fig 3.10a), it can be concluded that management is more important than just the choice of the tool. Not surprisingly, presence of timely applied single MWC reduced weed biomass on average by 48%. Thus, to maintain MWC efficacy aspects as weed control stage, driving speed, tine angle adjustment and environmental conditions need to be considered. The management recommendations for each of the MWC treatments used in our study are outlined below:

Rotary hoeing

Among all single MWC tools examined in our study, pre and post-emergence RH had the highest weed control performance, as weed biomass was reduced by 63% and 69% in field pea and lentil, respectively. Several studies reported higher than 70% weed control with a single rotary hoe when applied after weed seed germination but before seedling establishment (Lovely, 1958; Peters et al., 1959; Mulder and Doll, 1993; Schweizer et al., 1994), which agrees with our study findings.

Rotary hoe as a single MWC approach needs to be applied at least twice; Once at pre-emergence followed by one post crop emergence treatment. In our study, the best weed mortality was observed when RH was performed on a hot, windy day when the soil surface was dry. Prior to conducting pre-emergence RH, it is critical to scout the field for white thread weed seedlings or the ones at the ground crack stage. If there are not enough weed seedlings, RH can be delayed until higher weed density is observed.

Post-emergence RH should be applied depending on residual weed population present in the field. Johnson and Shirtliffe (2012) reported that field peas tolerated RH up to 9th node stage. However, it is important to note that the highest RH efficiency in our study was achieved when it was applied until the 1st leaf stage in grassy weeds and cotyledon stage in broadleaf weeds. When weeds exceed that stage, RH efficacy is reduced. Rotary hoe application can be significantly affected by environmental conditions before and after RH application, weed germination events and density (Boyd and Brennan, 2006). In a study by Vangessel (1995) single RH application controlled up to 86% of annual weeds in 1992, while in 1993 single and double application with RH controlled 40% and 50% of annual weeds, respectively. High weed control efficacy in 1992 can be attributed to timing of RH application, which coincided with emergence of both corn and the majority of weeds species. This corresponds to Rassumsen's (1999) slogan – "Timing is everything." Hence, a double minimum till rotary hoe unit (Figure 5.1) can be a possible solution in years when a second pass is not possible due to unfavorable environmental conditions.

(a) (b)

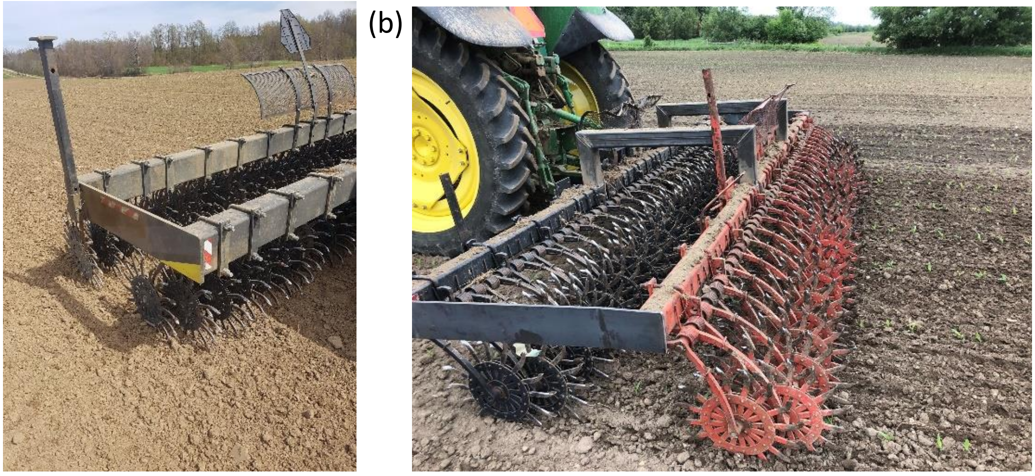


Figure 5.1 Double rotary hoe units. (Photo credit: (a) Terry Good (b) Calvin Horst)

Timely applied RH may effectively control wild mustard and green foxtail or any small-seeded weeds with short emergence periodicity. Delaying RH for the sake of targeting more weeds in the white thread stage may increase the percentage of weeds that may not be targeted by the rotary hoe application. Thus, significantly delayed RH increases the risk of escaped weeds. Growers may rotary hoe the field immediately once the white thread stage weeds are observed and control the residual or new weed emergence shortly after first application.

Harrowing

In our study H, when performed twice post crop emergence, reduced weed biomass by 50% and 58% in lentil and field pea respectively, when compared to untreated check. Harrowing can be applied pre and post-emergence; however, several studies reported little to no effect of pre-emergence H (Heard, 1993; Lundkvist, 2009; Johnson and Holm, 2010). Post-emergence harrowing can be applied as early as the 2nd node stage until the 4th node stage. To improve H selectivity, the tines can be adjusted 45^{o} backward in the direction of travel; this will allow to target more weeds and result in less crop injury. Harrowing frequency depends on the weed pressure in the field. Single H application can decrease weed interference more than two-fold; however, if the weed pressure is high, a second H pass is required. In lentil, despite weed biomass being reduced by 50% with two H passes compared to the control treatment, yields were only 18% higher than the untreated check. Since two passes with H reduced 46% of lentil crop biomass in comparison with hand-weeded control, we suggest that second pass with the H in lentil results in higher crop injury than the weed control benefit and thus a decline in yield. As H is not very useful in controlling large weeds, late applications beyond a 5th node stage would result in less effective weed control and increase crop injury.

Inter-row cultivation

Inter-row cultivation is a very selective weed control tool and can be applied from 4th to10th node stage in field pea. Single IT between the 4th and the 6th node stage reduced weed biomass by 36% and 40% in field pea and lentil respectively, when compared to untreated check. Despite being highly selective, it is effective only in controlling large weeds in inter-row spaces, while there is very limited effect on weeds present in intra-row spaces (Tardif-Paradis et al., 2015). As a single MWC approach, it can be applied later during the CPWC. In this experiment, we utilized IT with manual guidance under 30 cm row spacing. Therefore, growers considering cultivation under narrow row spacing may consider purchasing cultivators with vision guidance to improve precision while maintaining cultivation speed and efficacy of weed control (Kunz et al., 2017). Weed control performance can also be affected by soil type. At KCRF, where soil clay content was high, cultivation in even moderately wet soil resulted in more weed seedling recovery as they survived on strong soil aggregates. These observations agree with Melander et al. (2015) findings. Hence, under environmental conditions, one pass early is enough to control the majority of weeds in the inter-row spaces (Stanley et al., 2017); although, under very high weed density growers may consider double application. The first applications should be done as early as 4th node stage and the second no later than 6th node stage. Importantly, before controlling residual weed density, growers need to ensure that the crop is fully recovered after the initial pass with the IT.

Rotary hoeing & Harrowing

Pre and post-emergence RH application followed by single H applied between 2nd till 4th node stage reduced weed biomass by 66% and 83% in lentil and field pea respectively in comparison with control treatment. Importantly, under heavy weed pressure H can be applied twice in field pea. Repeated early season control may be especially effective when crop density is low. Importantly, if the residual weed density following rotary hoeing is dominated by large weeds growers may take the risk of adjusting the aggressiveness of harrowing tines at 45^{o} or even 35^{o} backwards to the direction of travel. However, if more aggressive harrowing results in uprooting or fatal burial of the crop, growers may consider double rotary hoe followed by double harrow application with less aggressive tine angle adjustment. Thus, first H pass may be done at 2nd node stage and the second immediately after the crop was recovered from the first pass. This may result in improved control of larger weeds that were only partially affected by the first harrowing pass.

Harrowing & Inter-row cultivation

Combination of H-IT was the most effective when H was applied once at 2nd node stage followed by a single IT cultivation at the 4th node stage. Treatments where H was applied later between 3rd and 4th node stage and IT cultivation was delayed to 6th node stage allowed us to target the majority of recovered weeds and ensure that the crop is fully recovered after harrowing. Weed interference with H-IT was reduced by 60% and 73% in lentil and field pea respectively, when compared to untreated control. This combination was particularly effective in controlling redroot pigweed as it emerged later than wild mustard and green foxtail and had prolonged emergence periodicity. Thus, H when redroot pigweed was small followed by IT allowed to target both early and late emerged redroot pigweed.

Rotary hoeing & Inter-row cultivation

Pre and post-emergence application with the RH followed by single IT cultivation between 4th till 6th node stage resulted in weed biomass decline as low as 76% and 79% in lentil and field pea respectively, when compared to the untreated check. Thus, growers may supplement pre and post-emergence rotary hoeing with a choice of single or double inter-row cultivation depending on residual weed density following rotary hoeing. The second inter-row cultivation pass should take place only when weed control benefit is greater than crop injury.

Rotary hoeing, Harrowing & Inter-row cultivation

For multiple treatment combination, all three individual MWC tools were applied once. Rotary hoe application should be applied before crop emergence followed by H between 2nd till 4th node stage and then followed by single pass with IT cultivation between 4th and 6th node stage. Multiple MWC treatments resulted in greatest weed suppression of 79% and 86% in lentil and field pea respectively, when compared to control treatment.

5.2.1 Concentric-Circular Concept for Organic Weed Management in Field Pea

In this study, the effect of MWC resulted in incomplete suppression of wild mustard, redroot pigweed, stinkweed, and wild buckwheat. Hence, growers may search for vulnerable periods in the life cycle of individual weeds and the entire weed community for effective control. Applying weed control practices based on similarities in weed community emergence periodicity and flowering duration may reduce the population of dominant weed community members, thus facilitating weed management over the long term.

High weed plasticity may affect the success of mechanical weed control. Different weeds favor different emergence timing and have different emergence periodicity. Thus, if mechanical control of some weeds is incomplete, growers may supplement their weed control practices with weed clipping (Johnson and Hultgreen, 2002) and harvest weed seed control (Walsh et al., 2013). Targeting weeds at flowering and at harvest may decrease weed seed production and destroy viable seeds, thus decreasing the return of weed seeds to the seed bank.

At the completion of this study a circular weed control concept was designed to demonstrate alternative methods of weed control in field pea based on 2017 season field pea data (Figure 5.2). Each month of the year is indicated as a colored sector. Pink, green, violet, yellow and blue represent the month of May, June, July, August, and September, respectively. The center scale demonstrates precipitation (mm) received at the KCRF at the corresponding month of the 2017 growing season. The outer scale represents effective growing degree days (GDD) (base temperature 5 °C) recorded at the KCRF during the 2017 field season. Inner colored circles denote emergence periodicity of weed species present within the community (Van Acker et al., 2003). Each color represents individual species. Emergence periodicity was marked by small circular indicators representing <1%, 25%, 50%, and 80% weed emergence respectively. Yellow flowers show the flowering duration of wild mustard, while yellow dots denote the wild mustard weed clipping timing.

The first outer ring beyond the GDD scale shows field pea crop life cycle from seeding till harvest. The red stripe layered on field pea crop lifecycle ring denotes the duration of the critical period for weed control developed by Baird et al. (2009a; 2009b). Orange dot on the field pea life cycle ring demonstrates field pea harvesting date and alternative methods for harvest weed seed control (Walsh et al., 2013; Walsh et al., 2018). Each following outer ring represents the timing for in-crop MWC application for minimum tillage RH, flex-tine H and the IT. Periods for MWC application were divided into three zones: red, yellow and green. Red zone implies inappropriate timing for MWC application. Yellow zone implies that MWC may be applied under sufficient weed emergence, appropriate weed stage and if the benefit of weed removal is not outweighed by crop injury. Green zone stands for recommended time frame for in-crop MWC application. White, pink and blue dots on the MWC rings demonstrate the respective actual timings when the minimum RH, flex-tine H and the IT was applied in this study.

5.2.2 Concentric-Circular Concept Guideline

To use the concentric-circular weed control concept (Figure 5.2), the grower may need to collect following information. First, the producer should monitor precipitation and cumulative GDD data. Second, it is important to identify the dominant weed community species. Third, based on the dominant weed community, grower may design their weed control system based on their emergence periodicity. Thus, growers should group weed community based on inception of emergence and duration of emergence periodicity (from <1% to 80% emergence). Weeds present within the community may be divided into three groups:

Competitive strategy (Group 1) - early emerging (initiate emergence within 190 - 290 GDD) with short (requires cumulative 250- 350 GDD to reach 80% emergence) or long (requires cumulative < 400 GDD to reach 80% emergence) emergence periodicity. (*ex. wild mustard*)

Competitive/ruderal strategy (Group 2) - delayed emerging (initiate emergence within 290 - 350 GDD), with short (requires cumulative 250- 350 GDD to reach 80% emergence) or long (cumulative < 400 GDD to reach 80% emergence) emergence periodicity. (*ex. common lambsquarters and green foxtail*)

Ruderal strategy (Group 3) - late emerging (< 350 GDD) with short (requires cumulative 250 - 350 GDD to reach 80% emergence) or long (cumulative < 400 GDD to reach 80% emergence) emergence periodicity. (*ex. Redroot pigweed*)

Following the identification of weed emergence periodicity groups, growers should focus weed scouting based on GDD and precipitation. For instance, growers may check whether wild mustard, wild buckwheat and stinkweed initiate emergence at 190 GDD. If so, grower may consider rotary hoe application shortly after abovementioned weeds are present at high density and are in the white thread to cotyledon stage. Before MWC, application grower may need to concur whether application timing is within the yellow or green zone.

Selection of MWC system for weed control can be based on emergence periodicity group. For example, if weed community is dominated by *Group 1,* then grower may focus on repeated early MWC application with RH, H or combination of both. Weed community dominated by *Group 2,* can be suppressed with post-emergence RH, post-emergence H or combination of both. When weed community is dominated by *Group 3,* then grower may consider late H, early IT or combination of both. When weed community is a mixture of all three groups, growers may consider integrating early (RH), delayed (H) and late (IT) MWC methods. For instance, according to Figure 5.2 growers may apply rotary hoeing to control early emerging wild mustard, stinkweed, and wild buckwheat population (between <1% to 25% emergence) and then utilize inter-row cultivation when the majority of redroot pigweed plants are still small.

Weed clipping operations may be performed approximately 120 GDD days after first wild mustard flowering plants are observed. Second clipping operation may be performed about 180 GDD following first application. Weed control at harvest (1480 GDD) may be performed with a choice of chaff collection cart, chaff liner or harvest weed seed destructor (internal or external).

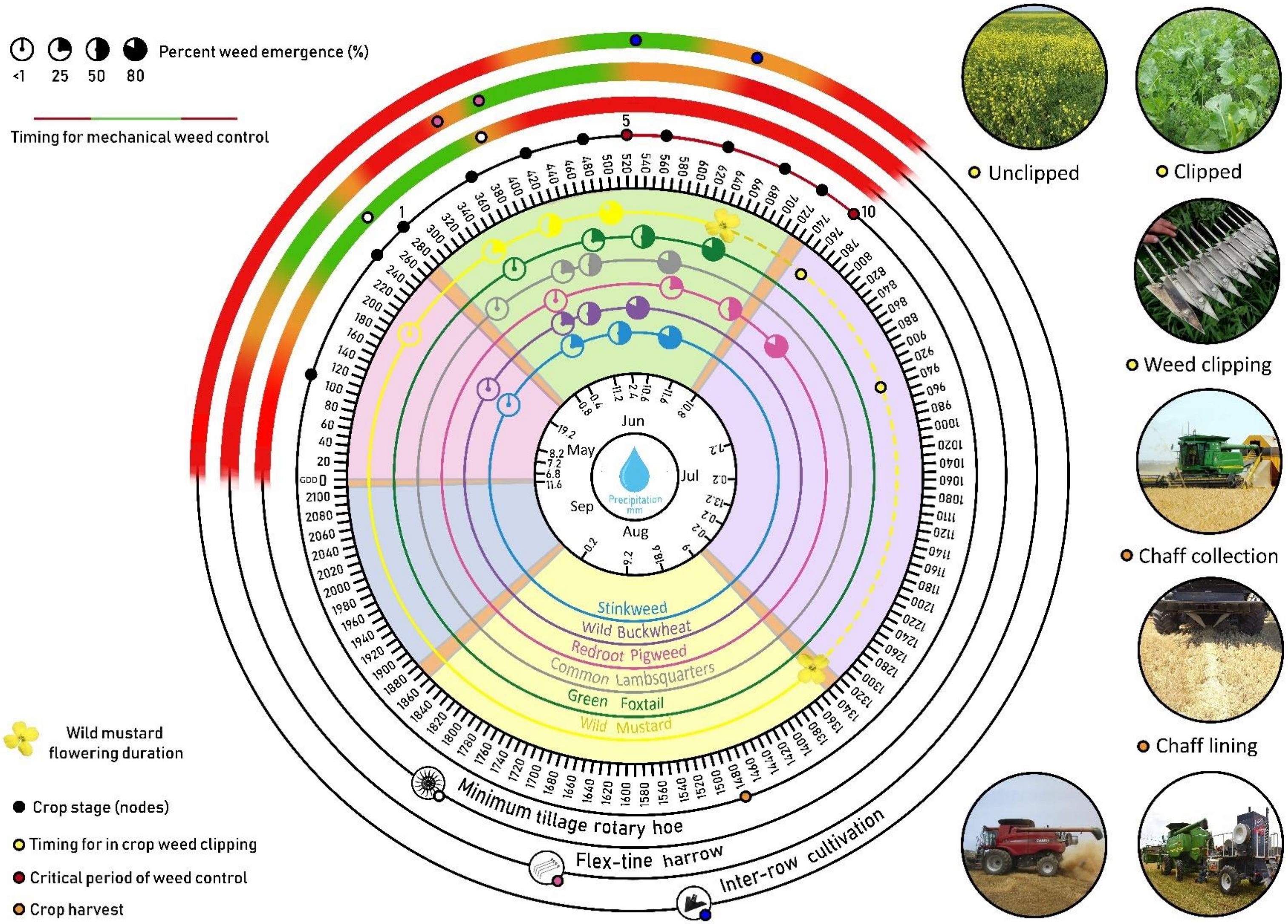


Figure 5.2: Concentric circular concept for organic weed management in field pea

5.3 Future Research

Future organic weed management would require tailoring weed control practices to better accommodate differences in spatial weed distribution, community compostion and emergence periodicity. Weed control efficiency achieved in our study may vary from site to site due to differences in weed community structure and composition (Liebman et al., 2016), soil type and environmental conditions (Cordeau et al., 2017). Therefore, there is a need to develop varieties better adapted to local environmental conditions (Carkner and Entz, 2017), while maintaining high weed suppressive ability and market quality requirements (Osman et al., 2016). Along with this, there is a need for designing specific crop rotations, cover cropping, intercropping and MWC (Liebman, 1989, Melander et al., 2017).

Conventional producers may benefit from integrating physical and chemical weed control practices. For instance, RH and H may be used for incorporation of soil-applied herbicides. In fact, in our study on average weed biomass was at least two-fold lower following single MWC operation. Hence, conventional producers may utilize reduced herbicide rates in combination with mechanical and cultural weed control practices, without sacrificing weed control efficacy (Mulder and Doll, 1993; Redlick et al., 2017).

The rapid growth of precision agriculture sector has promising potential for introduction of robotic (Young and Meyer, 2012; Fennimore et al., 2016) and sensor-based laser (Universität Bonn, 2017) weed management allowing to identify potential weed control problems and rapidly react to them. Among weed control precision and selectivity, there is a need to improve soil disturbance caused by IT cultivation, by optimizing shovel design (Melander et al., 2015; Kunz et al., 2017; Znova et al., 2018). For areas with significant weed spatial variability and high weed community density higher intensity of H or IT might provide more consistent weed control. Harrowing weed control intensity can be enhanced by adjusting aggressiveness of tines according to weed density present in the field (Rueda-Ayala et al., 2015). While for the inter-row cultivation it can be suggested that adding vibrators to shovels might improve the intensity of cultivation without increasing cultivation depth. It can be hypothesized that adding vibration elements to the inter-row cultivator would result in breaking and uprooting more weeds in areas with higher weed densities. Although, vibration should not cause variation in cultivation depth since it might increase variation in weed seed recruitment depth which therefore might increase the periodicity of weed seedling emergence

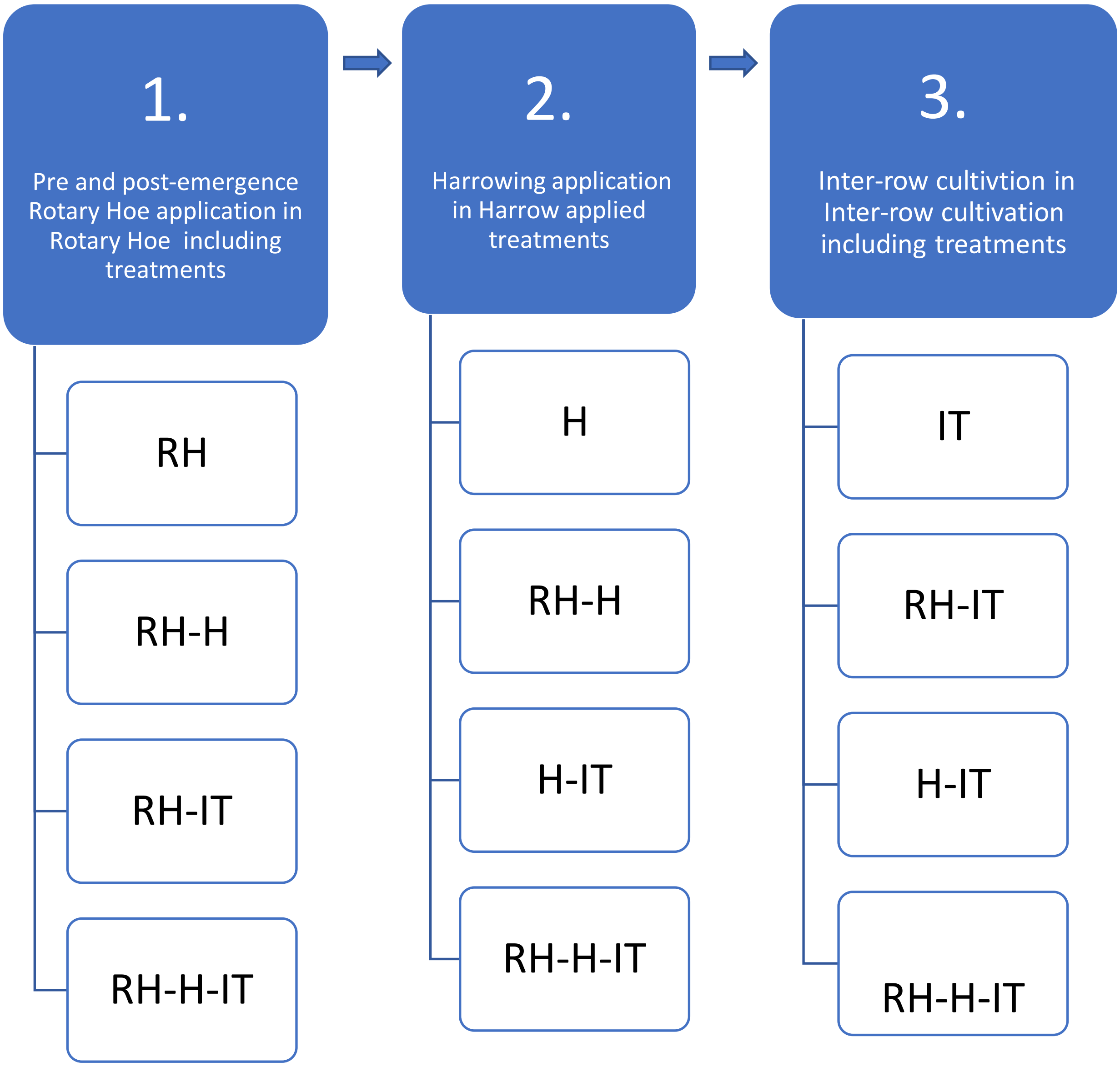
(Zimdahl, 1993). Hence, it is critical to avoid undesirable horizontal and vertical soil movement, if weed seed bank depletion is not the primary weed control goal.

Alternatively, implements as in-crop weed clipping (Johnson and Hultgreen, 2002) and post-harvest weed seed destructor (Walsh et al., 2013) can also be integrated into weed management strategy to deplete weeds present in the seed bank. Nevertheless, the benefits of more diverse weed control systems, labor requirements can be a greater barrier to adoption despite profit opportunities being similar to less diverse systems, less reliance on herbicides, and improved energy efficiencies (Davis et al., 2012; Liebman et al. 2008). Since crop production in North America is mostly profit oriented (Owen, 2016), direct profitability comparison between organic and conventional systems is required to encourage the adoption of more diverse weed management.

5.4 Final Remarks

Results of this study demonstrate that physical weed control in organic systems can be used as a reliable alternative to chemical weed control in conventional systems. Integrated weed management has several benefits for conventional producers. First, it lowers herbicide inputs (Mulder and Doll, 1993; Kunz, 2017). Second, it maintains weeds control efficiency comparable to single herbicidal approach (Blackshaw, 2008, Redlick et al., 2017). Finally, inclusion of in-crop MWC into chemical weed control strategy would facilitate herbicide-resistant weeds management (Harper, 1956; Powles, 2008; Mortensen et al., 2012,) thus resulting in a more robust weed control (Swanton and Murphy, 1996; Booth and Swanton, 2002; Ryan et al., 2010; Owen, 2016). Absence of weed control in our study resulted in yield losses of 50% and 55% in field pea and lentil when compared to hand weeded control respectively. The presence of MWC increased yield up to 50% and up to 40% in field pea and lentil respectively. Thus, we strongly believe that crop rotation (Liebman and Dyck, 1993), increased crop competitive ability (Willenborg, 2004; Benaragama and Shirtliffe, 2013), elevated crop SR (Baird et al., 2009a, 2009b), CPWC (Fedoruk et al., 2011) and in-crop MWC (Johnson and Holm, 2010; Shirtliffe and Johnson, 2012; Stanley et al., 2017) are essential elements of ecologically based pest management. Hence, removal of cooperation "filters" between weed scientists, engineers, economist, sociologists, policymakers and farmers focusing on weed control within their farm and agroecosystem is required to amplify the adoption of ecologically sustainable weed management (Liebman et al., 2016).

Appendix: Scheme of mechanical weed control treatment application.



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