Enhancing the competitive ability of oat (*Avena sativa* L.) cropping systems

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By

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Abstract

Ecological based weed management strategies are imperative in cropping systems when herbicide use is limited or prohibited. Herbicides are not applicable in controlling wild oat (*Avena fatua* L.) in oat (*Avena sativa* L.) cropping systems, as they are closely related. Moreover, herbicide use is prohibited in organic oat cultivation, resulting in a need for developing alternative weed management strategies. Enhancing the crop competitive ability (CA) can be an essential strategy in managing weeds in such instances. Two studies were carried with the objectives to: 1) evaluate newly developed oat genotypes for their CA against wild oat; and 2) develop a competitive organic oat cropping system integrating mechanical and cultural weed control practices. In the first study, seven oat lines deliberately bred for enhanced CA and their two parental cultivars were evaluated for the CA with wild oat. The genotypes yielded similarly in the presence and in the absence of wild oat competition. The tall oat line SA050479 with greater seedling leaf size was more wild oat suppressive among all lines. Moreover, SA050479 had greater yield potential and grain quality; thus, it has the potential to be developed as a commercial wild oat suppressive cultivar. The second study used two contrasting levels of genotype, row spacing, crop density and a post-emergence harrowing and a non-harrowed control in two organic oat fields to develop an integrated weed management system. High crop density and harrowing increased the grain yield by 11% and 13% respectively. The competitive cultivar CDC Baler and high crop density (500 plants m^{-2}) reduced weed biomass by 22% and 52% respectively. Harrowing reduced weed density by more than 50% in three site-years. The cultural and mechanical weed control practices when combined were additive in increasing grain yield and reducing weed biomass. Oat seed yields were increased by 25% when high crop density planting and harrowing were combined. Similarly, the combined effect of competitive cultivar, high crop density, and post-emergence harrowing were greater as weed biomass was reduced by 71%. The outcome of this project implies the importance of enhancing the crop CA by means of crop breeding and integrating cultural and mechanical weed control strategies. Furthermore, this study was able to identify the importance of ecological based weed management strategies in order to overcome the constraints in weed management in present oat cropping systems.

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Dedication

I would like to dedicate this thesis to my late mother Priyani De Silva and to my father Ranjith De Silva for their love, inspiration, and guidance. In addition, I would like to dedicate this thesis to my wife Indika Benaragama for the love and support.

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List of Abbreviations

ANOVA	Analysis of Variance
CA	Competitive Ability
CDC	Crop Development Center
CD	Crop Density
FLL	Flag Leaf Length
FLW	Flag Leaf Width
FLA	Flag Leaf Area
G	Genotype
H	Harrowing
HT	Height
IWM	Integrated Weed Management
LA	Leaf Area
LAI	Leaf Area Index
LI	Light Interception
PAR	Photosynthetically Active Radiation
SP	Spacing
SLA	Specific Leaf Area
STLA	Seedling Total Leaf Area
TLA	Third Leaf Area
TLW	Third Leaf Width
TLL	Third Leaf Length
TKW	Thousand Kernel Weight
TW	Test Weight
WSA	Weed Suppressive Ability

1.0 Introduction

Oat (*Avena sativa* L.) is an important cereal crop in Canada, where it is cultivated on about 1.1 million hectares of land (Statistics Canada 2011). It represents 6% of production and exports among cereals and oilseed crops in Canada (Agriculture and Agri-Food Canada 2010). On a global scale, Canada is one of the major oat producers of the world and accounts for 45 to 50% of the world oat exports (Agriculture and Agri-Food Canada 2010). Oat is grown throughout Canada, and the major growing areas are in the western Prairie Provinces (i.e., Saskatchewan, Alberta, and Manitoba). Saskatchewan is the largest producer of oats, with approximately 0.75 million hectares of cultivated crop (Statistics Canada 2009). Oat is mostly harvested for grain and in some regions is cut for fodder. Although world oat production has been stable for the last five years, the demand for oat as a food has risen because of the recognized nutritive value of the oat grain (Agriculture and Agri-Food Canada 2010).

Yield loss due to weed competition is thought to be one of the main causes of lower productivity in many agricultural crops. In Canada, the estimated cost of yield loss due to weed competition in field crops is $639 million, and among the main cereal crops grown in Saskatchewan, the yield loss is estimated to be 11%, 10%, and 8% in oat, wheat, and barley respectively (Swanton et al. 1993). Herbicides are currently the primary and most widely used method of weed control throughout the world (Liebman 2001). However, there are many repercussions of widespread use of herbicides. For instance, weeds are becoming increasingly resistant to herbicides, requiring a reassessment of current weed management tactics (McDonald et al. 2009). In addition, herbicide use has known environmental impacts (Richards et al. 1987), demanding sustainable weed management approaches (Entz et al. 2001; Weiner et al. 2001). Sustainable weed management practices should minimize weed emergence, growth, fecundity, and interference with crops (Lovette and Knights 1996; Blackshaw 2008). Therefore, in long-term weed management perspectives, we need to shift from simply using in-crop herbicides to redesigning cropping systems to manage weeds at all stages of their life cycle.

Crop competitive ability (CA), the ability of a crop to compete against weeds, is a key ecological concept that can be used to manage weeds in cropping systems (Jordan 1993;

Mohler 2001). Enhancing crop CA can be an inexpensive tool in weed management that complements other weed control methods (Huel and Hucl 1996). Crop CA can be manipulated by growing competitive cultivars (Lemerle et al. 1996; Fischer et al. 2001) and by manipulating cultural practices (Champion et al. 1998; Anderson 2005; Harker et al. 2009). Growing competitive crop cultivars has been identified as an important strategy in managing weeds in cereals (Konesky et al. 1989; Whiting et al. 1990; O' Donovan et al. 2000; Fischer et al. 2001).

Competitive crop cultivars can be highly beneficial in situations where weeds are difficult to control by herbicides (Gibson et al. 2003), such as wild oat (*Avena fatua* L.) control in oat and red rice (*Oryza sativa* L. var. sylvatica) control in rice (*Oryza sativa* L.). In oat cropping systems, wild oat control is an abiding problem faced by farmers. The genetic similarity between wild oat and oat precludes the use of herbicides in oat cultivations. Breeding and selecting oat cultivars that are competitive with wild oat could be an alternative strategy in managing wild oat in oat. Wildeman (2004) identified genotypic differences for CA among commonly grown oat cultivars in Western Canada. However, the competitive cultivar CDC Bell identified by Wildeman (2004) is not desirable as a grain crop because of its low grain yield potential. Therefore, there is value in breeding and evaluating competitive oat cultivars with high yield potential in order to mitigate wild oat competition in oat.

Enhancing crop CA can be a vital strategy for managing weeds in cropping systems where herbicide use is prohibited. Increasing trend in organic crop production in the Western Canada requires effective weed control alternatives to replace herbicides. Organic farming generally relies on cultural and physical methods to control weeds. Cultural practices such as high-density planting (Koscelny et al. 1990; Evans et al. 1991) and narrow row spacing (Murphy et al. 1986; Putnam et al. 1992; Weiner et al. 2001) enhance crop CA and thereby suppress weeds. Mechanical weed control is also an essential tool in organic cropping systems (Hanson et al. 2007). Post-emergence harrowing is an effective mechanical weed control tactic in controlling weeds in many cereal crops (Cirujeda et al. 2003; Velykis 2009). However, the use of a single cultural or mechanical weed control strategy may not deliver a substantial level of weed control in organic cropping systems (Malik et al. 1993; Anderson 1997; Mertens and Jansen 2002); thus, farmers must integrate several weed control measures for the most benefit. Even though the effect of individual cultural and mechanical strategies on weed control has been widely studied, the integrated approach of cultural and mechanical weed control has not been explored to a great extent.

The focus of this thesis is to apply ecological-based weed control strategies to manage weeds in oat cropping systems where herbicide use is limited or prohibited. The main hypothesis is that enhancing crop CA by crop breeding and integrating cultural and mechanical weed control practices will aid in managing weeds in conventional and organic oat cropping systems. The two main objectives of this thesis are to: 1) evaluate newly developed oat genotypes for their competitive ability against wild oat and their potential to suppress wild oat in conventional oat cropping systems, and 2) develop an integrated weed management system for organic oat cropping systems using both cultural and mechanical weed control methods.

The outcome of this study will enable the exploration of the potential for ecological weed management tactics to achieve more sustainable crop production systems, particularly managing weeds where herbicides are not applicable. The results of this project will benefit both conventional and organic oat farmers to overcome present weed management challenges, to redesign crop production systems in an ecologically sound way in order to minimize economic loss due to weed competition.

2.0 Literature Review

2.1 Plant competition in ecosystems

Plants rarely grow in isolation, whether in natural or agricultural ecosystems. Every plant is a member of a community of plants, interacting with each other through different mechanisms. When plants grow close to each other, they interact by altering their immediate environment in which they acquire resources such as light, water, and nutrients (Zimdahl 2004). The plant's ability to acquire resources and the availability of resources in the immediate surroundings depends on the type and the magnitude of these interactions. The ultimate result of plant-plant interaction is reduction of plant growth and changes in morphology and reproduction of individuals (McDonald et al. 2009).

In natural or agricultural ecosystems, there are numerous interactions amongst organisms. Plants interact with many other organisms (i.e., animals, insects, fungi, and bacteria) in the surrounding environment and these interactions can be classified as competition, mutualism, commensalism, amensalism, and herbivory (Williamson 1972). Among these, the most abundant plant-plant interaction is competition. Although competition is the most widely observed plant-plant interaction, there is no general agreement on the best definition of competition; however, competition can be simply defined as a reciprocal negative interaction between organisms (Connell 1990). According to Crawly (1986), plant competition involves either direct interference (allelopathy) or direct competition for shared resources (i.e., light, water, and nutrients). Moreover, there are mechanisms that indirectly cause reciprocal negative interactions between organisms known as apparent competition (Holt 1977), which differs from direct competition. The presence of many mechanisms in a community may cause difficulties identifying which type of competitive mechanisms exists between plants. Plant-plant competition is common but not universal in natural ecosystems; but weed-crop competition is abundant, natural and undesirable in agricultural plant communities (Zimdahl 2004).

2.2 Crop competitive ability

In agricultural ecosystems, crops often interact with weeds. Crop competitive ability (CA) is the ability of the crop to compete against weeds. Crop CA has two mechanisms. First, the crop interference (Harper 1977) or net competitive effect (Goldberg 1990), is the ability of the crop to suppress weeds (weed suppressive ability). Weed suppressive ability (WSA) of a crop can described in terms of reduced weed seed production, weed emergence, and reduced weed biomass (Jordan 1993). The second mechanism, the crop competitive response, or crop tolerance to weed competition, occurs when the crop is able to tolerate the weed effect on crop emergence, biomass, and yield (Jordan 1993). Therefore, plants can be superior competitors either by rapidly depleting a resource or resources or by being able to continue growing under limited resource conditions (Goldberg 1990).

Weed competition greatly affects crop yield. Similarly, weed attributes (size, number, and fecundity) are also influenced by crop abundance, size, and proximity, which determine crop CA (Radosevich et al. 1997). Hence, any attempt to alter the competitive balance in favour of the crop could help to maximize yield in cropping systems. Crop CA can be enhanced by both genetic (Lemerle et al. 1995; Huel and Hucl 1996) and agronomic (Koscelny et al. 1990; Mohler 2001) measures, which together may provide a greater advantage in a given environment.

2.3 Crop genotype and crop competitive ability

Differences in crop CA against weeds have been widely demonstrated in many crop species. Pavlychenko and Harrington (1934) ranked crops in Western Canada for their CA against wild oat (*Avena fatua* L.) as barley (*Hordium vulgare* L.) > spring rye (*Secale cereale* L.) > wheat (*Triticum aestivum* L.) > flax (*Linum usitatissimum* L.). Similarly, Bell and Nalewaja (1968) and O'Donovan et al. (1985) noted that barley was more competitive than wheat against wild oat. In most circumstances, barley has a greater CA than wheat (Fischer et al. 2000). Nevertheless, the magnitude of crop CA can vary among different environmental conditions and the type of weed (Cousens and Mokhtari 1998). For instance, Lemerle et al. (1995) ranked the crop competitive ability against ryegrass (*Lolium rigidum* L.) in Australia as; oat > cereal rye > triticale (x *Triticoscale*) > oilseed rape (*Brassica napus* L.) > spring wheat > spring barley > field pea (*Pissum sativum* L.). Therefore, under Australian conditions, barley has less CA than wheat depending on cultivar and seasonal conditions. In Denmark, Melander (1993) ranked peas and oilseed rape as less competitive against weeds than winter rye, wheat, and barley. In the UK, oat was found to be more competitive in terms of reducing ryegrass biomass followed by barley and then wheat (Seavers and Wright 1999). All these studies demonstrate the variability of CA among crops under different environmental conditions.

Crop cultivars often differ in CA against weeds. Differences for CA among cereal crop cultivars were identified for wheat (Blackshaw 1994; Huel and Hucl 1996; Lemerle et al. 1996; Acciaresi et al. 2001), barley (Christensen 1995; O'Donovan et al. 2000; Paynter and Hills 2009), rice (Suzuki et al. 2002; Estorninos et al. 2005; Zhao et al. 2006), sorghum (Walker et al. 2008), and oat (Wildeman 2004; Schaedler et al. 2009). The winter wheat cultivar Turkey was found to be more competitive than cultivar Centurk 78 against downy brome (*Bromus tectorum*) (Challaiah et al. 1986). Among five winter wheat cultivars tested, WH-147 and HD-2285 were found to be more competitive (Balyan et al. 1991). Among three spring wheat cultivars, Neepawa (hard red spring wheat), HY320, and HY355 (Canada prairie spring wheat), the genotype Neepawa was found to be more weed suppressive (Kirkland and Hunter 1991). Among sorghum cultivars tested, MR Goldrush and Bonus MR were identified to be more competitive than six other most widely used sorghum cultivars (Walker et al. 2008). Among 25 rice cultivars tested, weed biomass of the five most competitive cultivars were 75% lower than the five least competitive cultivars (Garrity et al. 1992). Similarly, differences for wild oat suppression were identified among barley cultivars. O'Donovan et al. (2000) reported that among the six barley cultivars tested, there was 25% less weed biomass in plots where the cultivars Seebe, AC Lacombe, and Harrington were grown compared to less competitive cultivars. In a study with seven barley cultivars, Christensen (1995) identified that cultivar Ida had 48% less weed biomass than the mean biomass of all other cultivars tested.

2.4 Traits associated with crop competitive ability

Differences in CA among crop species and crop cultivars can be attributed to differences in morphological, physiological, and phenological traits (Lemerle et al. 2001b). Any trait that enables the crop to rapidly use the immediate supply of resources and to increase its area of ground cover in which it competes against its neighbor, is vital to its CA (Donald 1968). These traits include early vigour, fast growth rate, high nutrient acquisition, nutrient use efficiency, tolerance to abiotic stresses, and chemical defense mechanisms through mycorrhizae and allelopathy (Grace 1990).

Crop competitive traits can be differentiated by above-ground and below-ground traits because crop weed competition exists for both above-ground and below-ground resources. Crop emergence rate, seedling growth rate, crop relative growth rate, leaf area expansion rate, leaf angle, canopy development rate, plant height, and above ground biomass are the main plant traits associated with above ground CA (Gaudet and Keddy 1988; Jordan 1993; Huel and Hucl 1996; Lemerle et al. 1996; Acciaresi et al. 2001). Among below-ground traits, root size, distribution and uptake capacity per unit size (Dunbabin 2007), root density and surface area (Casper and Jackson 1997) are important for crop CA. Although below-ground competition is important, it has received less attention because it is difficult to study below-ground competition. Moreover, Satorre and Snaydon (1992) reported that although below-ground competition is greater than above-ground competition, cereals (wheat, barley, and oat) and their cultivars were only slightly different in root CA. However, crop cultivars often differ in above-ground competitive traits and have received more attention. Most of these competitive plant traits are genetically regulated and can be passed to the next generations; therefore enabling plant breeders to use these traits to develop competitive crop cultivars.

2.4.1 Crop height and competitive ability

Plant height is the trait most associated with crop CA against weeds. Plant height plays a major role in a community because individuals constantly compete for light. The taller crop cultivars have their leaves higher in the canopy, thereby maximizing the use of incoming radiation, and receiving more light than shorter, competing weeds (Wicks et al. 1986). Many cereal cultivars with high CA are taller than their neighbours with horizontal leaves and extensive leaf display (Donald and Hamblin 1976; Lemerle et al. 2001a). Even if the crop is not as tall as the competing weed, more elevated distribution of leaf area can enable greater interception of light (Mohler 2001).

Tall wheat cultivars are able to intercept a greater proportion of photosynthetically active radiation (PAR) and suppress weed growth compared to short cultivars with less light interception (Wicks et al. 1986; Champion et al. 1998). Accordingly, many studies revealed that wheat crop height and CA were positively correlated (Wicks et al. 1986; Balyan et al. 1991; Seefeldt et al. 1999; Huel and Hucl 1996; Cosser et al. 1997; Lemerle et al. 2001b). Among 29 barley cultivars commonly grown in Canadian Prairies, semi-dwarf cultivars are less competitive with oat (Watson et al. 2006). Differences among rice cultivar CA against red rice (*Oryza sativa* var. *sylvatica*) have been identified in relation to plant height (Kwon et al. 1991). They reported that Newbonnet, a conventional tall (115 cm) rice cultivar was more competitive than the semi-dwarf (92 cm) cultivar, Lement. Furthermore, among upland rice cultivars tested, plant height was the most significant character negatively correlated ($r = 0.77 – 0.88$) with weed biomass (Garrity et al. 1992).

Crop height is indispensable to both crop tolerance and weed suppression. Among Canadian spring wheat cultivars, the shortest cultivars experienced the largest yield reduction and the greatest weed growth (Huel and Hucl 1996). Seefeldt et al. (1999) found that the tallest wheat isoline was able to reduce jointed goatgrass (*Aegilops cylindrica*) seed production and maintain its yield under weed competition.

Tall cereal crop cultivars may not necessarily be competitive with all weeds. The type of weed, weed density, and environmental conditions can influence the association between crop height and cultivar CA (Lemerle et al. 2001a). In Alberta, O'Donovan et al. (2000) found that semi-dwarf barley cultivars Falcon and CDC Earl were approximately 18% shorter than other cultivars resulting in higher wild oat shoot biomass. In contrast, Watson et al. (2006) found that CDC Earl was not inferior in CA among the rest of the cultivars. Using near isogenic wheat lines, Seefeldt et al. (1999) showed that although weed seed production decreased linearly with incremental crop height, the relationship between wheat height and yield (crop tolerance) was not linear. Murphy et al. (2008) reported that plant height was negatively correlated with weed biomass in 63 wheat cultivars tested in the USA, but only accounted for 7% of total variation in weed suppressive ability. Watson et al. (2006) observed that the tallest hull-less barley cultivar Hawkeye was the poorest competitor amongst tall cultivars, while the short hulled cultivar AC Ranger was highly competitive. Furthermore, crop height at maturity does not reflect differences in sorghum CA. For instance, of six sorghum cultivars tested the tallest cultivar 85G83 was the least competitive. (Walker et al.

2008). Crop height alone may not always contribute to greater CA. In Nebraska, Wicks et al. (1986) found that among 20 winter wheat cultivars, cultivars taller than 83 cm intercepted more light and reduced weed growth more than short cultivars; however, two short lines NE 78742 (75 cm) and NE 78743 (72 cm), were better competitors with weeds. Therefore, these studies revealed that there could be crop traits other than crop height associated with CA.

2.4.2 Early seedling vigour and crop competitive ability

Early season competition determines most of the outcome of crop-weed competition in many environments (Lemerle et al. 2001a). Therefore, plant traits that enhance efficient resource capture at early growth stages can be important to crop CA. Early crop vigour can be determined by high rate of emergence, high relative growth rate or large seedling size (Lemerle et al. 2001a). Early seedling vigour obtained by greater seed size, early emergence, biomass accumulation, and leaf area development can contribute to greater CA (Lemerle et al. 1996; Seavers and Wright 1999; Willenborg et al. 2005a). Weeds that emerge prior to the crop have a greater CA (O'Donovan et al. 1985; Willenborg et al. 2005b); therefore, selecting cultivars with high rates of early emergence could be an useful strategy to enhance CA.

Rapid acquisition of available resources and biomass accumulation are important in determining early crop CA. Lemerle et al. (1996) found that wheat and durum wheat (*Triticum durum* Desf) cultivars that were strongly competitive with ryegrass had high early PAR (photosynthetically active radiation) interception and early biomass accumulation. Similarly, Zerner et al. (2008) found that traits associated with early vigour such as length and width of seedling leaves, early plant biomass, and leaf area index (LAI) were important traits associated with wheat CA. Early vigour in terms of seedling leaf development and stem characters can help distinguish phenotypically strong and weak competitive plant types (Jennings and Aquino 1968). Among Australian wheat cultivars, length and the width of the first leaf and seedling dry matter were negatively correlated with yield loss and ryegrass dry matter (Lemerle et al. 1996). In sorghum, rapid emergence and seedling growth were associated with weed suppression. Moreover, the length and width of the first leaf and seedling dry matter are negatively correlated with sorghum yield loss and weed dry matter (Guneyli et al. 1969). In barley, wheat, and oat, width of the first and second seedling leaf is strongly correlated with early vigour (López-Castañeda and Richards 1996). Hence, first and the second leaf width could be used effectively to select for early vigour, which are important traits in crop CA (Rebetzke and Richards 1999).

2.4.3 Crop canopy development and competitive ability

Crop canopy development and leaf area have been associated with cultivar CA in wheat, barley, oat, and corn (Seavers and Wright 1999; Acciaresi et al. 2001; Gail et al. 2004). Jennings and Aquino (1968) found that strong rice competitors had more tillers, long leaves, LAI, greater height, and greater biomass; hence, they defined a competitive plant as being larger and more spreading than a weaker competitor. In spring wheat, the crop yield loss and weed dry matter is negatively correlated with crop dry matter, tiller number, PAR, height, and leaf habit (Lemerle et al. 1996). Among bread wheat and durum wheat near isogenic lines, Zerner et al. (2008) found that as well as plant height and early vigour, greater LAI at early tillering stage was an indispensable trait for preventing crop yield loss and suppressing weeds. Seavers and Wright (1999) reported that between two wheat cultivars, Spark (upright growth, tall) and Avalon (recurved leaves, short, rapid canopy development), significant differences were identified between the two with Avalon being more competitive than Spark.

Cultivar CA is not an absolute characteristic, but is the outcome of different combinations of physiological traits (Korres and Froud-Williams 2002). Spring wheat cultivar CA is negatively correlated with crop height, ground cover, biomass production, and flag leaf length (Huel and Hucl 1996). In rice, cultivar competitiveness is associated with its ability to intercept light (Fischer et al. 2001) as LAI, number of tillers and PAR interception of rice cultivars are negatively correlated with weed biomass. Johnson et al. (1998) reported that the most competitive rice cultivar had a larger leaf weight, a greater specific leaf area, and earlier tiller production than less competitive cultivars. Larger leaf weight and large canopy-specific leaf area reduce the amount of photosynthates needed to produce a given leaf area for light capture and have been identified as the main strategy for improving competitiveness in tropical upland rice (Dingkuhn et al. 1999). Although numerous studies indicate that rice CA is highly determined by early vigour, Kawano et al. (1966) argued that the high early growth rate can cause low grain yields. They showed that early increase in plant weight can lead to mutual shading, increased respiration, leaf deterioration, and decreased LAI and photosynthetic capacity at later growth stages.

2.5 Crop breeding for competitive ability

2.5.1 Challenges in breeding for crop competitive ability

The concept of CA of crops has been widely studied over the years, but the importance and use of CA in weed management has been minimal due to the wide use of herbicides and other weed control strategies. Initial work on crop weed competition and breeding for competitive crops has been hindered by the dominance of herbicides as the main weed control strategy (Paolini et al. 2008). Still, competitive crop cultivars are essential components in sustainable weed management strategies. At present, scientists are trying to identify the variability that exists in CA among crop cultivars, characterize the traits associated with crop CA, heritability of competitive traits, and to develop new competitive crop cultivars (Lemerle et al. 2001a). Modern cultivars of most crops may have lost their CA due to plant breeding for various other traits such as high yields, high grain quality, and resistance to pests and diseases. In contrast to the progress obtained in breeding for other traits, only few attempts and developments have been made in crop breeding for CA against weeds (Olofsdotter and Anderson 2004). Even though developing competitive crop cultivars is possible, identifying of crop traits strongly associated with CA is a challenging task. The traits should have a reasonable level of genetic control (high heritability) and the incorporation of genes for CA should not negatively affect crop yield and quality (Lemerle et al. 2001a).

Traits associated with CA can be highly diverse because they occur for different growth resources, times in the life cycle, and vary with the species with which the plant is competing (Cousens et al. 2003). This wide variability of traits associated with crop CA can be an impediment in developing competitive crop cultivars. For instance, a trait imperative in early crop growth stage may not be important for CA at later growth stages. Similarly a particular competitive crop trait may not be useful in all environments. The potential use of tall wheat cultivars has been identified in many studies (Challaiah et al. 1986; Blackshaw 1994; Lemerle et al. 1996; Seefeldt et al. 1999), but, Reeves and Brooke (1977) and Wicks et al. (1986) were unable to find any association with wheat crop height and CA. The low heritability of competitive traits due to genotype and environment interaction (Coleman et al. 2001) is a further hindrance in developing competitive cultivars. Crop traits associated with CA are both qualitative and quantitative in nature, and quantitative traits have less heritability because they depend on environmental factors (Pester et al. 1999). Therefore, in order to establish well-defined crop breeding objectives, the ideal target traits should strongly reveal competitive ability. The research challenge in understanding the inheritance of competitive traits is solely due to the complexity of understanding the genetics of these traits.

2.5.2 Crop competitive ability and grain yield

Crop traits associated with CA may hinder grain yield potential. This negative correlation between CA and grain yield could be one of the main constraints in the selection and breeding of competitive crops. According to Jennings and Aquino (1968), rice yield is negatively correlated with CA; hence, crop CA is not considered as a feasible weed management option in rice. Similarly, many other studies have found that crop CA is associated with low weed free grain yields (Challaiah et al. 1986; Fischer and Quail 1990; Seefeldt et al. 1999). Among the competitive traits, mature crop height is thought to be the most prominent trait correlated with grain yield under weedy conditions. However, taller plants have often been associated with lower yields due to low harvest index and susceptibility to lodging (Lemerle et al. 2001a). Similarly, many studies revealed a grain yield cost associated with increasing plant height (Challaiah et al. 1986; Seefeldt et al. 1999). In cereals, the growing stem is an important sink for assimilates during elongation and competes with the spike for assimilates. A reduced supply of assimilates can reduce spikelet formation and ultimately reduce the number of grains (Fischer and Quail 1990; Miralles and Slafer 1995; Miralles and Slafer 1997). Therefore, tall cultivars tend to have lower grain yields than short cultivars (Miralles and Slafer 1997). Tall, highly competitive wheat (Challaiah et al. 1986) and oat (Wildeman 2004) cultivars are not widely grown because they tend to have lower grain yields.

The negative correlation between yield and CA is not clearly understood (Lemerle et al. 2001a). For instance, Johnson et al. (1998) identified the possibility to enhance CA in rice without compromising yield potential. Lemerle et al. (2001b) found no negative correlation with crop tolerance and weed-free grain yield in spring wheat with ryegrass. Furthermore, the trade-off between CA and yield is always magnified in experiments where tall and semi-dwarf varieties were compared. This may not be an obstacle, as modern cereal cultivars do not have a great range of plant height. Moreover, Lanning et al. (1997) showed that high yield is not always incompatible with high CA, as significant variation among genotypes for CA can be detected even among short genotypes. Overall, these studies suggest the importance of developing competitive short crop cultivars.

2.6 Crop tolerance and weed suppressive ability in crop breeding

The competitive ability of a crop can be enhanced either by increasing crop tolerance or by increasing weed suppression ability (WSA). Either one of these two mechanisms can determine crop CA and may not always occur together (Lemerle et al. 2001a). Therefore, Pester et al. (1999) argued that plant breeding should focus on developing crop cultivars that are genetically superior competitors to weeds, either through crop interference (WSA) or by crop tolerance. Both mechanisms could be important in selecting and developing competitive crops, but in long-term preventive perspectives, crop interference may be more useful (Jorden 1993). Nevertheless, Callaway and Forcella (1993) argued the importance of both these aspects of CA in terms of breeding for high yielding cultivars in the presence of weeds. However, there can be instances where both these aspects are observed in one genotype. For instance, studies have found that crop tolerance and WSA are correlated in wheat (Challaiah et al. 1986; Lemerle et al. 1996). Still, no one has successfully distinguished crop traits associated with each aspect of CA. Therefore, attempts to breed competitive crops should be directed to consider both aspects of CA even though CA is studied and understood separately in relation to crop tolerance and WSA.

2.7 Cultural practices and crop competitive ability

2.7.1 Crop density

Plant population density is often used to describe the plants in a crop or weed stand within a unit area (Radosevich et al. 1997). As population density increases to a certain level, competition occurs among neighbouring plants. High plant density in a plant community can cause competition for limited resources such as light, space, moisture, and nutrients. The ultimate outcome of competition is the alterations to the plant population, including reduced growth, mortality, and decline in reproductive output (Harper 1977). Increasing the population density of a particular species in a community can cause both interspecific and intraspecific competition. Crop-weed competition for some growth resources is often size asymmetric as larger individual acquiring majority of resources compared to a smaller individual. The degree of size asymmetry in competition increases with increasing density of individuals (Schwinning and Weiner 1998). However, Mohler (2001) argued that even if competition is size symmetric, increasing the crop density would decrease weed biomass. Therefore, increasing crop density is an essential tool in weed management in most cropping systems (Weiner et al. 2001).

Weed biomass and other measures of weed abundance usually decrease as the crop density increases (Wax and Pendelton 1968; Evans et al. 1991; Weiner et al. 2001; Olsen et al. 2004). Carlson and Hill (1985) used different wild oat and wheat densities to study crop density effect on weed suppression. In their study, wild oat infestation of 5.5 plants m^{-2} resulted in 20% grain yield reduction in a poor crop stand of 100 plants m^{-2}. When the crop stand was 700 plants m^{-2}, 38 wild oat plants m^{-2} were needed to cause the same degree of yield reduction. Similarly, Xue and Stougaard (2002) identified that increasing the planting density of spring wheat from 175 to 280 plants m^{-2} increased competitive ability by reducing wild oat panicle number from 352 to 323 panicles m^{-2}. Weed biomass generally decreases with increasing crop density for many weed species (Olsen et al. 2006). In a study conducted using natural weed flora, it was observed that the vegetative traits (dry weight and leaf area) and reproductive structures of many weed species were affected by enhanced wheat density (Froud-Williams and Korres 2001). Increasing the crop density of oat from 250 plants m^{-2} to 500 plants m^{-2} reduced wild oat biomass and wild oat seed production (Wildeman 2004).

Increasing crop density can increase intraspecific competition and thereby reduce grain yield and quality; hence, high crop densities can suppress weeds but reduce crop yield. Effective weed suppression by increased crop density should occur at densities lower than those which may result in substantial crop yield losses (Weiner et al. 2001). Under weedy conditions, crop yield can be improved with the use of higher seeding rates (Mohler 2001). Barton et al. (1992) found that barley grain yield was greatest when seeded at higher rates (134 kg ha^{-1} or 201 kg ha^{-1} compared to 67 kg ha^{-1}) due to decline of wild oat competition with higher seeding rates. In the presence of weeds, crops generally respond to high crop density with increased grain yield. O'Donovan et al. (1999) found that barley yield decreased with increasing crop density, but this negative effect was minimized when high weed densities were present.

The response to PAR interception, above-ground biomass, radiation-use efficiency, harvest index, and grain yield increases asymptotically with increasing seed rate in wheat (Gooding et al. 2002). Koscelny et al. (1990) identified that wheat seeded at 530 seeds m^{-2} produced 15% more grain yield and suppressed rye brome (*Bromus secalinus*) seed production by 25% more than when seeded at 265 seeds m^{-2}. Mason et al. (2007a) conducted a comprehensive study in organic fields using nine hard spring wheat and two spring barley cultivars. They found that on average, doubling the crop density from 300 seeds m^{-2} to 600 seeds m^{-2} increased grain yield by 10% in the presence of weeds. Overall, the natural weed biomass was reduced by 28%. Earlier studies revealed that increasing the crop density often increased grain yield whether in the presence or absence of weeds (Roberts et al. 2001; Mennan and Zandstra 2005).

The benefit of enhancing the crop density is not cultivar specific; hence, Mason et al. (2007b) suggested that increasing the crop density could be a more viable strategy than growing competitive genotypes. Champion et al. (1998**)** found that when both competitive wheat cultivars and increased crop densities were used, the reduction in weed biomass caused by high crop density occurred at early growth stages; therefore, they argued that increasing the crop density is more useful during the establishment and early growth stages, while cultivar competitive traits more important at later growth stages. Furthermore, increasing seeding rate can be a quick method to suppress weeds; whereas identifying and developing cultivars for CA is a long-term approach.

2.7.2 Crop row spacing

Crop planting pattern can substantially influence the competitive balance between the crop and weeds (Mohler 2001). Crops can be grown in a wide range of planting patterns with a variety of inter-row and intra-row spacings. Changing the number of plants within rows (crop density) and changing the distance between two crop rows (row spacing) can alter the planting pattern. Generally, crop rows are considered to be very narrow clumps of plants (Olsen et al. 2004); the density is very high within rows and low between rows. Theoretically, reducing the inter-row distance (narrow row planting) can make the two-dimensional pattern less clumped (Weiner et al. 2001) and decrease the rectangularity (ratio between crop row spacing and within row plant spacing) (Fischer and Miles 1973). In the absence of weeds, the morphological plasticity allows the crop to grow towards the space between rows where resource availability is high, thereby reducing intraspecific competition (Ballare et al. 1994).

In weedy conditions, crop plants distributed in a clumped pattern have less capacity to suppress weeds than in a uniform pattern (Weiner et al. 2001). In a uniform planting pattern, crop canopy cover development is faster and light penetration through the canopy is minimized (Teasdale and Frank 1983; Murphy et al. 1996). Therefore, narrower row planting often results in decreased weed biomass and higher grain yields (Murphy et al. 1996; Putnam et al. 1992; Teich et al. 1993). Begna et al. (2001) studied corn (*Zea mays*) hybrids with two row spacings (38 cm and 76 cm) and found that the respective weed biomass was reduced by 29% and 20% in both years tested; this reduction was due to narrow row spacing. When Olsen et al. (2004) planted wheat in normal, random, and uniform patterns, they found that weed biomass was lower and crop biomass was higher in random and uniform patterns than for the normal pattern.

In the presence of weeds, narrow row spacing often increases crop yield (Mohler 2001). Hence, the yield advantage of narrow row planting can be due to either greater weed suppression or more efficient use of resources. Narrow row spacing either equals or increases yield due to greater ground cover and reduced weed incidence (Peters et al. 1965; Sharratt and McWilliams 2005). In wheat, narrow row spacing results in greater yield than wide row spacings, attributed to more resource use when the crop plants grow closer to each other (Champion et al. 1998). In a study with soybean, decreasing row spacing from 75 cm to 25 cm increased the yield by 10% to 20% (Wax 1968). Increased yield in soybean grown in narrow spacing could be due to the crop acquiring more of the limited resources than what weeds acquired (Puricelli et al. 2003). Similarly, high yields were observed in maize in narrow row planting, and the increased yield was attributed to greater radiation interception (Mashingaidze et al. 2009).

The yield advantage of narrow row spacing is greater at high crop densities (Champion et al. 1998). When maize plants were grown in higher density and narrow row spacing, light interception increased from 3% to 5% (Begna et al. 2001). However, in some situations, narrow row spacing results in yield reductions. Fanadzo et al. (2007) found that maize yield was significantly reduced in 60-cm and 70-cm row spacing compared to 90-cm row spacing.

The reason for yield reduction was mainly attributed to resource limitation in the growing environment and increased intraspecific competition.

2.7.3 Mechanical weed control

Physical removal of weeds by disturbing the soil is one of the oldest methods of weed control in crops (Mohler 2001). Tillage, harrowing, hoeing, and hand weeding are the main mechanical weed control techniques used. Mechanical weed control using tillage and cultivation controls weeds in three distinct ways: first, they uproot and bury growing weeds and dormant structures; second, they inhibit the germination of weed seeds and third, they redistribute weed seeds vertically and horizontally thereby reducing the probability of seedling emergence and survival (Mohler 2001). The use of mechanical weed control in current agriculture is limited because herbicides are more attractive to farmers. However, the growing awareness of organic farming and the environmental impacts of herbicides are creating more interest in mechanical weed control (Lundkvist 2009).

In-crop mechanical weed control is often practiced using several types of tillage instruments. Most of these implements physically remove weeds either by cutting or uprooting and are generally known as cultivators. Some implements remove weeds between crop rows and are known as inter-row cultivators. In-row cultivators control weeds within the crop row. Furthermore, full-field implements, such as weeding harrows and rotary hoes, control weeds both within and between crop rows and are used effectively to control weeds in narrow-row planted crops like cereals (Mohler 2001).

In organically grown spring cereals, pre- and post-emergence weed harrowing are key weed control strategies (Hansen et al. 2007). The effectiveness of harrowing on weed control is a combined effect of uprooting weeds, burial with soil, and their ability to re-grow (Kirkland 1995; Rasmussen 1991; Kurstjens and Kropff 2001). Cirujeda et al. (2003) reported that harrowing in winter wheat reduced weed biomass from 40% to 60%. Velykis et al. (2009) showed that in organically grown spring oat and field pea, harrowing the crop at the two to three-leaf stage resulted in a 62% reduction in weed density. Similarly, in organically grown spring barley, two to three harrowing passes were able to reduce weed density by 76% to 82% (Auskalnis and Auskalniene 2008). Harrowing improves yield not only because it suppresses weeds but also because it enhances soil physical and chemical properties such as soil aeration, moisture conservation, and mineralization of organic matter (Velykis et al. 2009). Nevertheless, intensive harrowing also has negative effects leading into deterioration of soil structure and nitrogen leaching (Bond and Grundy 2001; Steinmann 2002).

The use and the efficiency of harrowing is determined by several factors, including type of crop, weed species, development stage of crop and weeds, soil type, environmental conditions, and harrow type (Mohler 2001; Hansen et al. 2007). Harrowing can be implemented at either the pre- or post-emergence crop stages. Implementing at either stage has its own disadvantages. Pre-emergence harrowing can enhance weed seed germination, and post-emergence harrowing can damage the crop as well as the weed (Rasmussen et al. 2008). In an experiment in Sweden, Lundkvist (2009) found that the best weed control in spring cereals and peas was obtained by a combination of pre- and post-emergence harrowing.

Weed harrowing can often result in unacceptable crop injury (Lafond and Kattler 1992). If the weeds are larger than crop plants at the time of harrowing, the selectivity (Rasmussen 1992) which is the ratio between the positive weed control effect and the negative effect of crop covering by soil, will decrease (Rasmussen 1991). Crops differ in their ability to resist (ability to avoid soil covering) and tolerate (resistance and crop ability to recover from burying) post-emergence harrowing. Oat was found to have a greater resistance than wheat, barley and triticale; however, triticale was the most tolerant followed by wheat, oat and barley (Rasmussen et al. 2009). Significant cultivar differences can be observed in crop tolerance to harrowing. Hansen et al. (2007) found that among barley cultivars, harrowing had less effect on the yield of the cultivar Otira than the cultivar Brazil. In addition, they observed that plant height at harrowing was correlated to tolerance to harrowing. However, according to Rasmussen et al. (2009) crop species differences are greater than the cultivar differences in tolerance to harrowing.

Crop injury due to harrowing can be due to prevailing environmental conditions (Kirkland 1995). Moreover, the negative impact on yield due to harrowing can depend on the time of application. Lundkvist (2009) observed yield reduction in spring wheat and oat in relation to time of harrowing. In late pre-emergence and post-emergence harrowing treatments, the yield loss was 6% and 14% respectively. This reduction was minimized in early pre-emergence and post-emergence harrowing where the yield losses were 2% in spring wheat and 5% in oat. Harrowing cereal crops does not consistently improve grain yield (Rasmussen and Svenningsen 1995; Velykis et al. 2009); therefore, the use of harrowing in cereals is debatable (Mohler 2001). Still, harrowing could be a viable option to reduce weed pressure and minimize weed seed bank in the long term.

2.8 Integrated weed management

Integrated weed management (IWM) uses an ecological framework to combine several weed control tactics. Before the widespread use of herbicides, farmers integrated crop CA, crop rotation, selective tillage and hand weeding to manage weeds (Parish 1990). At present, herbicides are the primary and most widely used method for weed control throughout the world (Liebman 2001). However, the rise of herbicide resistance among weeds has led to reassess the current weed management tactics used (McDonald et al. 2009). Moreover, the importance of ecological-based integrated weed management approaches have been inflated due to the growing interest in organic and sustainable agriculture.

Integrated weed management is a multi-disciplinary approach (Sanyal et al. 2008) that involves chemical, physical, biological, and cultural methods of weed management. There is no single universal method of achieving an ecological based weed management cropping system because it relies on a combination of weed management strategies. As described by McDonald et al. (2009), IWM reduces the weed burden by depleting the weed seed bank, reducing the weed population by minimizing weed germination, and finally reduces the competitiveness of weeds by enhancing the crop CA. Integrated weed management involves the use of physical and cultural techniques such as crop rotation, cover crops, mulching, and mechanical weeding. Integrated weed management systems consists of zero tillage, crop rotation, competitive crop cultivars, high seeding rates, crop fertilization, and cover crops in the Canadian Prairies (Blackshaw et al. 2008). These strategies should be complementary to each other and should be easily integrated to the existing production systems (Swanton et al. 2008). Research directed towards weed population management has identified valuable aspects of population equilibrium, density dependent mortality and life stages that are important in regulating population size (Mortensen et al. 2000). Therefore, these insights into weed ecology and biology have significantly improved current IWM strategies.

Crop CA is a key ecological phenomenon that can be used to manage weeds in many cropping systems. Crop CA can be enhanced by integrating several cultural weed management strategies. Integrating competitive cultivars and improved cultural practices can enhance crop CA (Pester et al. 1999). Cultural practices such as increasing crop density, optimizing timing of planting and planting in narrow rows are key components in integrated weed management systems (Malik et al. 1993; Buhler and Gunsolus 1996). Harker et al. (2003**)** found that combining competitive cultivars with high seeding rate and early weed removal reduced weed biomass and increased barley yield by 41%. Shrestha et al. (2001) achieved lower weed biomass with integration of narrow-row crop planting with high crop density; than with wide-row planting with low crop density in maize. Malik et al. (1993) found that competitive crop cultivars suppressed weeds better when crops were grown in narrow rows as compared to traditional wide rows. Furthermore, Anderson (1997) found that the tall wheat cultivars grown with higher crop density reduced weed seed production by 40% to 45% as compared to conventional systems. Anderson (2005) reported that in sunflower, cultural tactics such as narrow row spacing, increased plant density and delayed planting reduced weed biomass by 5% to 10% when used alone. When two of the three practices were combined weed biomass was reduced by 20% to 25%, and when all the three practices were combined weed biomass was reduced by up to 90%. Similarly, in proso millet (*Panicum miliacum*), planting of tall competitive cultivars with high crop density increased weed suppression by 60% compared to shorter, less competitive cultivar with low crop density (Anderson 2000).

Maximum outcome of mechanical weed control could be achieved by combining it with cultural practices. Mechanical weeding does not uproot and bury all the weeds within a crop; weeds can escape or re-grow after mechanical weeding. Therefore, enhancing the crop competitiveness against the surviving or partially controlled weeds is highly useful to obtain better weed control (Melander et al. 2005). Moreover, the weed removal from mechanical weed control could be more effective with wide-row spacing (Rasmussen 2004). In rye and barley, mechanical weed control efficacy was greater at wide-row spacing (24 cm) than at narrow-row spacing (12 cm), but yield losses were high in barley (9% to 12%) and rye (4% to 6%) with wide-row spacing (Melander et al. 2001). Mertens and Jansen (2002) investigated weed seed production in different wheat cropping systems with different row spacings (10, 20 and 30 cm) and planting densities (140 and 180 kg ha^{-1}) after mechanical weed control treatments (hoeing and harrowing). Among surviving plants, average seed production was low in narrow spacing (10 cm) and high density (180 kg ha^{-1}) planting treatments; hence, this study shows the importance of applying cultural practices along with mechanical weed control techniques for better weed management. As all these studies imply, the additive or synergistic effects of combining several weed management strategies are the main objectives to be achieved in any IWM program.

3.0 Competitive oat (*Avena sativa* L.) genotypes to manage wild oat (*Avena fatua* L.) competition

3.1 Introduction

Wild oat (*Avena fatua* L.) is one of the world's worst weeds with a wide adaptability to various farming systems in Europe, America and Australia (Berville et al. 2005). It is a common annual grass weed found in many temperate grain producing areas, and considered as the most troublesome annual weed in field crops in Western Canada (O'Donovan et al. 2000). In weed surveys done on the Canadian Prairies, wild oat was found in 56% of all fields (Thomas et al. 1998), in 50% of crop fields and in 44% of oat (*Avena sativa* L.) fields (Leeson et al. 2005). However, due to the difficulty of distinguishing wild oat from oat at early growth stages, the occurrence of wild oat in oat cultivations is likely even higher than reported.

Wild oat infestations can reduce grain yield and quality in many crops (O'Donovan et al. 1985; Kirkland 1993; Wildeman 2004). Wild oat is a troublesome weed in oat where densities of 60 to 180 plants m^2 can reduce oat yield by 3 to 22% (Wildeman 2004). Because wild oat is closely related to tame oat (in the same genera), herbicides cannot be used to selectively control wild oat from oat. In the past, oat growers used late planting to control wild oat, which allowed them to control emerging weeds by chemical and mechanical means before sowing oat, but resulted in reduced grain yield and grain quality (Humphreys et al. 1994; May et al. 2004). An alternative to late planting is to use herbicide-resistant oat cultivars that would allow use of herbicides to control wild oat. At present no such cultivars have been developed due to the ability of oat to outcross with wild oat, consequently it could create a large opportunity for gene flow and subsequent development of herbicide-resistance in wild oat populations (Berville et al. 2005). Therefore, it is vital to develop more sustainable alternatives of controlling wild oat in oat cultivations.

Enhancing crop competitive ability (CA) is identified as one of the key ecological weed management strategies in cropping systems (Jordan 1993; Mohler 2001; Zerner et al. 2008). Genotypic differences in crop CA have been identified in many cereal crops including rice (*Oryza sativa* L.), barley (*Hordium vulgare* L.), wheat (*Triticum aestivum* L.), and oat (*Avena sativa* L.) (Siddiqi et al. 1985; Dhaliwal et al. 1993; Fischer et al. 2001; Wildeman 2004).

Crop traits such as early emergence, early vigour, plant height, tillering capacity, canopy structure, and flag leaf length have been identified as the main traits associated with crop CA (Gonzalez-Ponce 1987; Huel and Hucl 1996; Lemerle et al. 1996). Over the years, many researchers attempted to screen existing crop cultivars for better CA and identify the traits associated with CA. Few researchers attempted to breed crop cultivars to be competitive against weeds (Olofsdotter and Anderson 2004). Callaway and Forcella (1993) concluded that soybean (*Glycine max* L.) can be deliberately bred for CA. Although studies have shown that wheat cultivars can potentially be bred for CA as plant traits associated with CA have been identified, the genetic control of these traits and the potential yield loss is not clearly understood (Lemerle et al. 2001a). Therefore, limited progress has been made in developing competitive wheat cultivars.

The apparent complex nature of CA in crops and the negative correlation with grain yield and quality (Challaiah et al. 1986; Fischer and Quail 1990; Seefeldt et al. 1999; Wildman 2004), make selecting and breeding for competitive crops less attainable. Substantial work was carried out in the USA in order to develop competitive rice cultivars using the competitive allelopathic rice line PI312777 (Dilday et al. 2001; Mattice et al. 2001) developed by IRRI as it lacks the milling and cooking quality and is susceptible to lodging under USA conditions (Gealy et al. 2003). However, none of the progeny lines developed from numerous crosses demonstrated substantial CA (Gealy and Moldenhauer 2006). Conversely, the possibility of developing competitive high yielding crop cultivars still exists as the findings of Lanning et al. (1997) and Johnson et al. (1998) revealed that the crop CA could be achieved without compromising the yield potential.

Breeding new crop cultivars for CA is vital as most of cereal cultivars screened for CA lack high grain yield potential as compared to commonly cultivated cultivars. Development of commercial competitive crop cultivars can be highly beneficial for situations where weed control using herbicides is inapplicable (Gibson et al. 2003), such as wild oat control in oat cultivation and red rice (*Oryza sativa* L. var. sylvatica) control in cultivated rice (*Oryza sativa* L.). Despite the importance of competitive cultivars for oat cropping systems to control wild oat, limited attempts have been made to breed for competitive oat cultivars. Wildeman (2004) identified cultivar differences in CA among oat against wild oat and found that the tall, forage-type cultivar CDC Bell was highly competitive among the genotypes tested against wild oat competition. Still, CDC Bell cannot be used as a grain crop because it has a low grain yield potential (Wildeman 2004).

Breeding for competitive oat cultivars with high yield potential can be identified as a valuable strategy for managing wild oat competition in oat cropping systems. Scientists at Crop Development Centre (CDC), University of Saskatchewan, developed new oat lines with the goal of incorporating CA, high grain yield, and high seed quality. CDC Baler (Rossnagel and Scoles 1998) a phenotypically similar sister line to CDC Bell with better seed quality was crossed with Ronald, a high yielding semi-dwarf type oat cultivar (Menzies et al. 2003) in order to obtain a progeny with high yields, better seed quality and greater CA. Therefore, the present study was conducted to evaluate these newly developed oat genotypes for their CA against wild oat. This study hypothesizes that these newly bred oat cultivars will differ in CA with wild oat and also have high grain yield potential and could be effectively used to manage wild oat competition in oat cropping systems. The primary objective of this experiment was to evaluate newly developed oat genotypes for their CA against wild oat and their potential to control wild oat in conventional oat cropping systems. The secondary objective was to identify the crop traits associated with enhanced CA of newly developed oat genotypes against wild oat.

3.2 Materials and methods

3.2.1 Experimental location and design

Field experiments were conducted in 2008 and 2009 at two locations, the Kernen Crop Research Farm (KCRF) (52^{O} 09′ N, 106^{O} 33′ W) and at the Goodale Research Farm (GRF) (52^{O} 03′ N, 106^{O} 29′ W) both near Saskatoon, SK. The KCRF site is located on Black Chernozemic loam soil with a pH of 7.5 and GRF site was located on Dark Brown Chernozemic loamy soil with a pH of 6.5. The treatments were nine oat genotypes and two weed levels (presence and absence of wild oat). The experimental layout was a randomized complete block design with four replicates. Each replicate consisted of 18 treatments with a 2 x 6 m plot size.

3.2.2 Experimental treatments and establishment

Nine oat genotypes were used in this experiment to evaluate their competitive ability against wild oat. Seven new oat breeding lines were developed by crossing the oat cultivars CDC Baler and Ronald. The seven lines SA050040, SA050044, SA050045, SA050049, SA050051, SA050479, and SA050498 were F_4-derived F_8 selection and were selected for divergent short and tall plant height with leaf characteristics similar to CDC Baler. These lines were further selected for better grain yield and superior grain characteristics. The seven lines and the two parental cultivars (altogether nine genotypes) were seeded with and without wild oat into wheat stubble. In 2008, the crop and wild oat were seeded on May 08th at Kernen, and on June 16th at Goodale. In 2009, both sites were seeded on May 18th. Seed was obtained from the CDC's oat breeding program. Oat was seeded at a target population of 250 plants m^{-2} and seeded in 23 cm rows using a disc cone seeder. The seeding rate for each genotype was adjusted based on 1000 kernel weight, germination percentage, and a 5% mortality rate. At the same time, wild oat was seeded into oat seeded plots for the treatments that oat genotypes were established with wild oat competition. Wild oat was seeded at a target population density of 250 plants m^{-2} in alternate rows with oat. Nitrogen and phosphorous fertilizers were applied at the time of seeding at each location based on spring soil test recommendations. Pre-emergence weed control was achieved by applying glyphosate at 450 g a. i. ha^{-1}. Post-emergence broadleaf weeds were controlled by applying bromoxynil at 276.6 g a. i. ha^{-1}.

3.2.3 Data collection

Following seeding, oat and wild oat seedling emergence was monitored every other day on two 1-m rows on the front and back of each plot. Each plant on the selected row was marked daily with a coloured paper clip to distinguish it from the subsequent emerging plant. Plant emergence was monitored for six to seven days following seeding until the majority of the seedlings were emerged. After all the seedlings were emerged, plant counts were obtained using 0.25 m^2 quadrats placed randomly at the front and back of each plot. Quadrats were placed parallel to the crop row to include three crop rows within the quadrat. When seedlings were at the three-leaf stage, five plants from each treatment from the wild oat-free plots were randomly uprooted, bagged and bought to the laboratory. The leaves from each plant were separated from the stem. The width and the length of the third leaf were measured with a ruler. Thereafter, all the leaves were passed through a leaf area meter model LI-COR 3100 (LI-COR Biosciences Lincoln, NE) and total leaf area was recorded. All shoots of the five plants from each plot were bagged and dried in an oven at 60 ^{O}C for two days to obtain dry weights. The specific leaf area (SLA) was calculated using the following equation.

$$\text{Specific leaf area (SLA)} = \frac{\text{Total leaf area of the sample}}{\text{Total leaf dry weight}}$$

At the flag leaf stage (Zadoks 39), percentage intercepted radiation was measured in wild oat-free plots using a line quantum sensor model LI-COR 189 (LI-COR Biosciences Lincoln, NE) with a probe length of 1 m. The sensor was first held horizontally over the top of the canopy (full sun light) to measure the incoming radiation. Immediately afterward, it was placed under the canopy both perpendicularly and parallel to the rows to measure transmitted radiation. All data was recorded under clear sky conditions (1000 h to 1400 h). Intercepted radiation percentage was calculated with averaged transmitted radiation of perpendicular and parallel crop row measurements using the following equation.

$$\text{\% Intercepted radiation} = \frac{\text{Incoming radiation-Transmitted radiation}}{\text{Incoming radiation}} \times 100$$

In 2009, at both sites, canopy leaf area index was measured (Zadoks 39) using a AccuPAR PAR/LAI ceptometer model LP-80 (Decagon) and at Zadoks stage 42, flag leaf length and width were measured. After panicle emergence was complete (Zadoks 59), plant height was measured in all the genotypes from the ground to the top of the main culm . All the above measurements were made in wild oat-free plots. At the soft dough stage (Zadoks 85), oat and wild oat shoot biomass were sampled from 0.25m^2 quadrats at the front and back of every plot. Oat and wild oat biomass were separated and all samples were oven dried for 48 hours at 60^{O}C to obtain shoot dry weights.

In 2009, the Goodale and Kernen crops were treated with Reglone^{TM} at 414 g a.i. ha^{-1} to obtain even maturity before harvest. Prior to harvesting, plot size was reduced to a length of 6 m to minimize edge effects. At maturity (Zadoks 90), the crop was harvested using a 1.6 m wide small plot combine harvester. Harvested grains were air dried for 2 to 3 days until they reached a constant moisture content. Each harvested grain sample was cleaned using a dockage tester (Carter Day International, Inc.). Cleaned samples were weighed and yield per plot was recorded. A 1 kg representative grain sample from each plot was stored in a paper bag for subsequent evaluation. The percentage of wild oat seed in the oat grain sample was measured by hand removal of wild oat seeds from a 400 g sub-sample taken from the 1 kg sample. Wild oat-free oat grain yield was calculated accounting for percentage of wild oat seed.

Grain quality parameters, test weight, thousand kernel weight, percentage thin kernels, and percentage plump kernels were determined from the 400 g sub-sample. Thousand kernel weight was measured by weighing a sample of 200 seeds and multiplying by five. Test weight was determined by the specifications of the Canadian Grain Commission's Official Grain Grading Guide (2009). The percentage of plump kernels was determined by the proportion of grain sample retained after sieving through a 2.15 mm x 8.33 mm slotted sieve, and the percentage of thin kernels were the proportion that passed through a 1.95 mm x 8.33 mm sieve.

3.2.4 Data analysis

A combined analysis of all the data from four site-years was performed using Analysis of Variance (ANOVA) using SAS Mixed models (SAS Institute 2008). Genotype and weed treatment were considered fixed effects, while block within site-year, site-year and site-year by fixed effect interactions were considered random effects. Depending on the site-year by fixed effect interaction ($P < 0.05$) it was determined whether the data needed to be analyzed combined or by individual site-year. To obtain the best simple model, model simplification was carried out by removing non-significant covariance parameters based on the Akaike's Information Criterion (AIC) values (Littell et al. 2005). Oat biomass and weed biomass data were $\log_{10}$ and square root transformed respectively based on the Levene's test for homogeneity of variance and by observing residuals when necessary. Means were separated using Fisher's protected Least Significant Difference (LSD) at $P < 0.05$. A priori orthogonal contrasts were used to compare the means between Ronald, CDC Baler and all breeding lines. Correlation analysis was conducted to identify the associations between crop traits and the competitive parameters measured.

3.3 Results and discussion

3.3.1 Plant emergence

Wild oat plant densities were not different ($P > 0.05$) among wild oat seeded plots, indicating uniform emergence among treatments. Average wild oat densities obtained were 36 and 160 plants m^{-2} at Kernen in 2008 and 2009 respectively, and 93 and 115 plants m^{-2} at Goodale in 2008 and 2009, respectively. Relatively dry weather conditions (Table 3.1) could be the reason for low weed density in 2008. The oat genotypes did not differ ($P > 0.05$) in rate of emergence indicating that none of the genotypes had an advantage of early competition. However, oat genotype (Wildeman 2004) has been identified as an important determinant of rate of germination.

TABLE 3.1 Monthly rainfall (mm) and mean daily temperature (°C) for Saskatoon, Saskatchewan from May until September in 2008 and 2009 and climate normals (30-yr average).

Month	Rainfall			Temperature		
	2008	2009	Normal†	2008	2009	Normal†
	mm			°C		
May	22.2	12.0	41.5	15.9	18.2	11.8
June	69.6	43.0	60.5	22.0	22.7	16.0
July	55.8	60.5	57.3	21.7	24.5	18.3
August	44.2	97.0	35.4	22.1	25.2	17.6
September	1.2	17.5	28.9	23.5	18.7	11.5
Total	193.0	230.0	223.6	_	_	_

† 1970-2000 Canadian climate normals obtained from Environment Canada (2010).

3.3.2 Seedling leaf size

Genotypes differed in seedling leaf size as measured by width and the area of the third seedling leaf (Table 3.2). Seedling third leaf width (TLW) was different ($P < 0.001$) among genotypes. Third leaf width was greatest for genotypes SA050479, SA050044, SA050498, and Ronald (Figure 3.1). The narrowest TLW was observed for SA050049 which was 22% narrower than line SA050479, which had the widest seedling leaf. Among the parent cultivars, CDC Baler unexpectedly had significantly narrower third leaf than Ronald (Table 3.2). CDC Baler has wider leaves at maturity compared to Ronald; therefore it was expected that CDC Baler would have greater seedling leaf width than Ronald. In many studies the length and the width of seedling leaves have been found to be associated with CA. For instance, in wheat, width of the first and second seedling leaf was associated with crop CA (Zerner et al. 2008).

The seedling third leaf length (TLL) did not differ among genotypes (Table 3.2). However, approximated leaf area (length x width) of the third leaf significantly differed among genotypes (Table 3.2). Genotypes SA050045 and SA050051 had the lowest third leaf area (TLA). Genotypes CDC Baler, SA050040, SA050479, SA050044 and Ronald tend to have a large seedling TLA (Figure 3.1).

Seedling total leaf area (STLA) differed ($P < 0.05$) among genotypes. Seedling total leaf area tends to be greater in SA050479, SA050498, and Ronald. Breeding lines SA05045, SA050049, and SA050051 had low STLA (Figure 3.1). This is consistent with the results of the seedling third leaf size as these three lines were similar in ranking. The STLA can be considered as a measure of early ground cover, which is essential in early crop CA (Huel and Hucl 1996). Cultivar CDC Baler which is considered to be competitive had a modest STLA but was not significantly different from SA050479, SA050498, and Ronald. However, oat genotypes did not show any difference in SLA measured at the seedling stage (Table 3.2).

Larger seedling leaf size is associated with early crop vigour (Zerner et al. 2008). Similarly, in many crop species like barley, wheat, rye, and oat, width of the seedling leaves is strongly correlated with early vigour, and could be used effectively to select for early vigour (López-Castañeda and Richards 1996). Early crop vigour has been identified as an important trait for crop CA (Cousens 1996; Lemerle et al. 1996). In this study, early vigour was evaluated based on the seedling leaf size. Overall, SA050479, SA050498, and Ronald tend to be greater in early vigour.

TABLE 3.2 ANOVA for crop competitive traits as affected by genotype assessed in Kernen and Goodale in 2008 and 2009.

Source	TLL	TLW	TLA	STLA	SLA†	FLL†	FWD†	FLA†	HT	LAI†	LI
	cm	cm	cm^2	cm^2	cm^2g^{-1}	cm	cm	cm^2	cm		µmol $m^{-2}s^{-2}$
Site-year	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Site-year x Genotype	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Genotype	NS	***	**	**	NS	***	***	**	***	NS	NS
CDC Baler vs. Ronald	NS	*	NS	NS	NS	**	***	**	***	*	NS
CDC Baler vs. all others	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS
Ronald vs. all others	NS	**	NS	NS	NS	***	**	***	***	*	NS
CDC Baler vs. all lines	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Ronald vs. all lines	NS	NS	NS	NS	NS	***	**	***	***	*	NS

*,**,*** denote significant at the 0.05, 0.01 and 0.001 probability levels respectively.

† Data were analyzed from Kernen and Goodale in 2009.

TLL- Third leaf length
TLW- Third leaf width
TLA- Third leaf area
STLA-Seedling total leaf area
SLA- Specific leaf area
HT- Height

FLL- Flag leaf length
FWD- Flag leaf width
FLA- Flag leaf area
LAI- Leaf area index
LI- Light interception

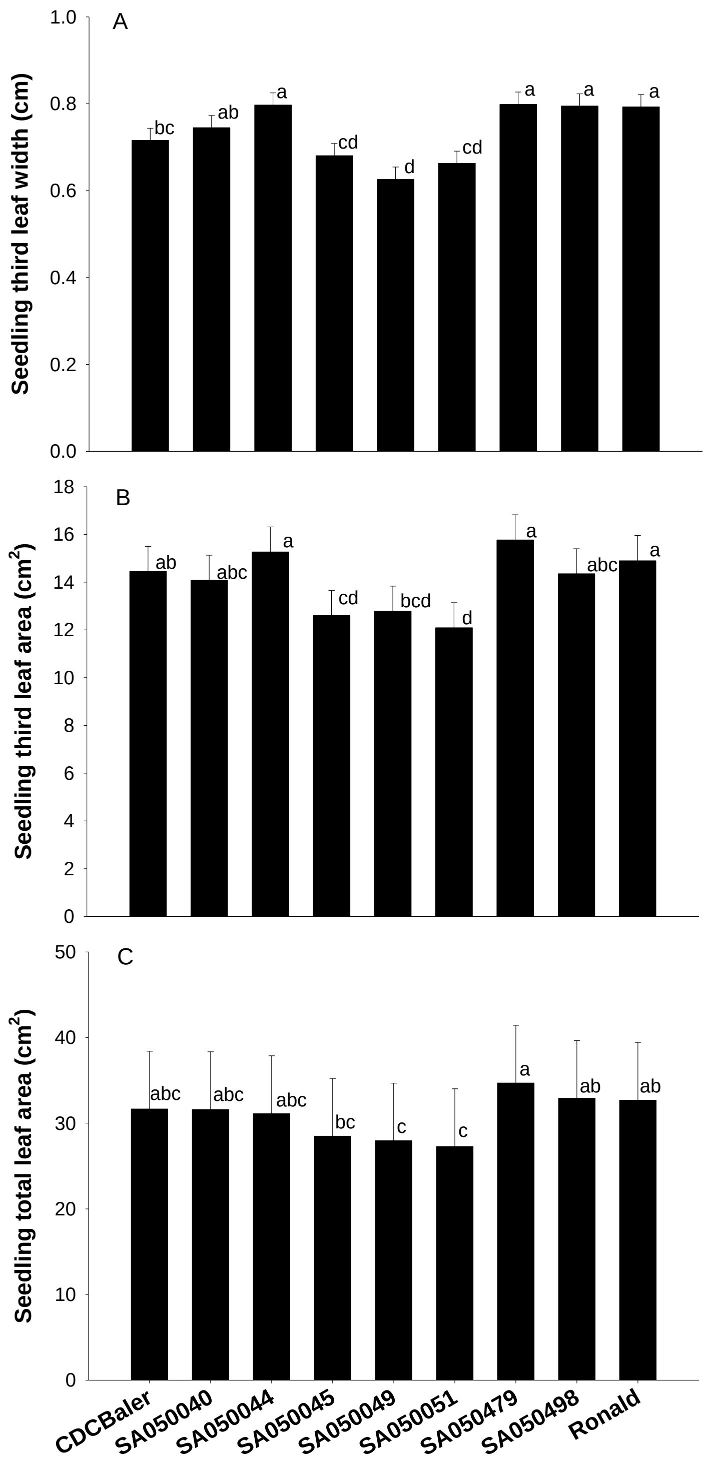

FIGURE 3.1 Effect of genotype on seedling: A. third leaf width, B. third leaf area and C. total leaf area assessed in Kernen and Goodale in 2008 and 2009. Error bars represent the standard errors of the least squares mean. Comparisons made between genotypes with similar letters indicate no significant difference at LSD $_{0.05.}$

3.3.3 Late competitive traits

3.3.3.1 Flag leaf size

Genotypes exhibited differences in flag leaf width (FLW) (Table 3.2) with genotypes SA050498 and SA050051 having widest flag leaves (Figure 3.2). CDC Baler had intermediate FLW and the narrowest flag leaf was observed for Ronald. Furthermore, differences ($P < 0.001$) were identified for flag leaf length (FLL) among the genotypes (Table 3.2). Flag leaf length was greater in SA050049, SA050051, and SA050498 (Figure 3.2).

Ronald had the smallest flag leaf width, length, and approximate leaf area (length x width) compared to all genotypes (Figure 3.2). CDC Baler was not different in FLA compared to all breeding lines but was greater than cultivar Ronald (Table 3.2). According to Huel and Hucl (1996) and Lemerle et al. (1996), greater FLL and FLA are often associated with crop CA.

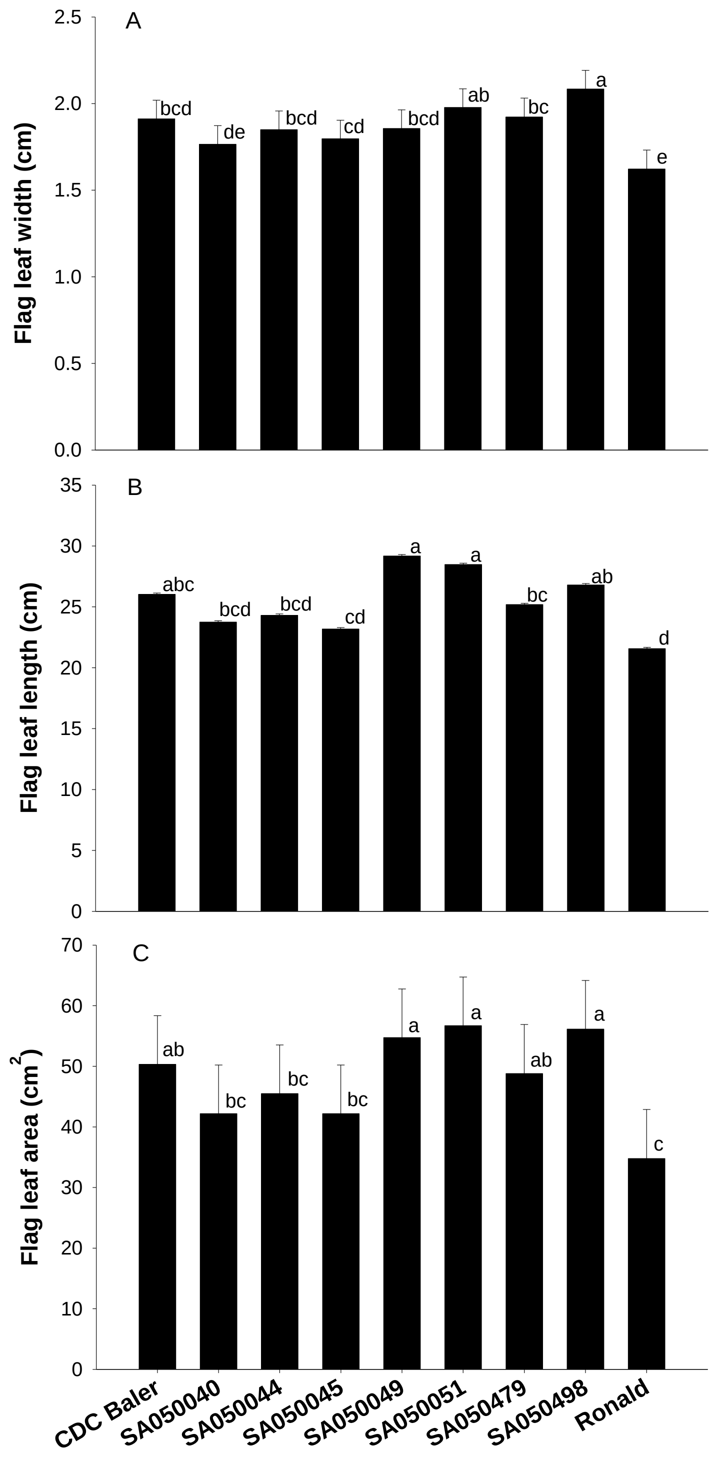

FIGURE 3.2 Effect of oat genotype on flag leaf: A. width, B. length, and C. area assessed in Kernen and Goodale in 2009. Error bars represent the standard errors of the least squares mean. Comparisons made between genotypes with similar letters indicate no significant difference at LSD $_{0.05.}$

3.3.3.2 Plant height

Oat genotypes differed (*P* < 0.001) in mature plant height (Table 3.2). Plant height at maturity is the trait most associated with crop CA (Lemerle et al. 1996; O'Donovan et al. 2000). Although CDC Baler was expected to be the tallest genotype, breeding line SA050479 was taller. Overall, CDC Baler did not differ in plant height compared to the breeding lines combined (Table 3.2). As expected, Ronald was the shortest cultivar among and was significantly shorter than CDC Baler. The tallest genotype, SA050479 was 22% taller than the shortest genotype, Ronald (Figure 3.3). These results showed that the progeny of short cultivar Ronald and tall cultivar CDC Baler had a wide range of plant heights.

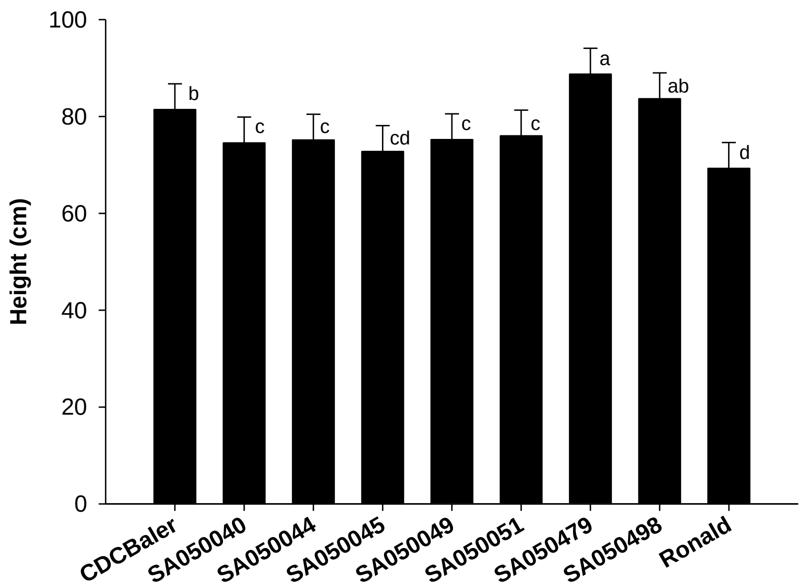

FIGURE 3.3 Effect of oat genotype on plant height assessed in Kernen and Goodale in 2008 and 2009. Error bars represent the standard errors of the least squares mean. Comparisons made between genotypes with similar letters indicate no significant difference at LSD $_{0.05.}$

3.3.3.3 Canopy traits

Genotypes did not differ in leaf area index (LAI) (Table 3.2); however, CDC Baler had a higher LAI than Ronald. Although CDC Baler and Ronald differed in LAI, the progeny did not differ in LAI. This may be because plant height is governed by major genes and can be qualitative in nature; thus, heritability is high compared to other quantitative traits such as LAI, canopy establishment and yield (Pester et al.1999). The differences in canopy height among the genotypes were not reflected in light interception (LI) as the genotypes had similar LI. Conceivably, differences could not be detected as LI was measured at the canopy-closed stage and not at early tillering stage. Fischer et al. (2001) suggested that modern cereal cultivars have erect leaves that allow light to penetrate; thus, there could not be any variability in LI with height as could be observed among genotypes with leafier canopies and lax leaves. In the present study, during the breeding programme, the genotypes were selected based on visual observations for their plant architecture; hence, it is not known that these genotypes really differ in leaf angles.

Overall, the genotypes evaluated in this study had wide variability in competitive traits measured. Genotypes differed in plant height, seedling leaf size and flag leaf size. Tallest genotypes were SA050479, SA050498 and CDC Baler. Among these genotypes, SA050479 and SA050498 had seedling traits believed to enhance CA such as greater width and leaf area of the third seedling leaf and greater seedling total leaf area. CDC Baler had intermediate seedling leaf size and intermediate flag leaf length and flag leaf area. Genotypes with intermediate plant height (i.e., SA050040, SA050044, SA050049, and SA050051) did not have competitive seedling characteristics; however, SA050049 and SA050051 had larger flag leaf area. The shortest genotype Ronald had a small flag leaf area but was among the genotypes with a large seedling leaf area.

3.3.4 Competitive ability of oat genotypes

3.3.4.1 Grain yield

The presence of wild oat reduced ($P < 0.05$) oat grain yield by 22% (data not shown) compared to grain yield without wild oat competition. There was no wild oat presence by genotype interaction (Table 3.3). Therefore, the hypothesis that the newly developed oat genotypes will vary in yield differently with the presence and the absence of wild oat competition is rejected. However, in wheat, Huel and Hucl (1996) found that the highest yielding wheat genotypes under weed-free conditions were not necessarily the highest yielding under weedy conditions. Even though the oat genotypes evaluated showed differences in competitive traits such as seedling size, flag leaf size and plant height, none of these differences were influential in weedy or weed-free grain yield. The inability to detect differences among genotypes may be because both the parents, CDC Baler (5229 kg ha^{-1}) and Ronald (5142 kg ha^{-1}) had high weed-free yield potential and therefore the progeny were high yielding lines without significant variation between them (data not shown). The weed-free grain yield of all the genotypes only varied from 4200 to 5200 kg ha^{-1} indicating similarities in yield potential.

Genotypes differed ($P < 0.001$) in grain yield when data were pooled across weedy and weed-free treatments (averaged yield) (Table 3.3). Highest yielding genotypes were CDC Baler and SA050040 (Figure 3.4). CDC Baler had 20% higher grain yield than the lowest yielding genotype SA050049 (Figure 3.4). In addition, CDC Baler had high yield compared to all the progeny lines (Table 3.3). However, there is a trend that breeding lines SA050479 and SA050498 are also high yielding and was not different from CDC Baler. Although Ronald was thought to be a less competitive cultivar due to its short stature, it had an average higher grain yield under both weedy and weed-free conditions compared to other short genotypes. Similarly Bussan et al. (1997) observed that modern soybean cultivars with high weed free yield potential and rapid establishment can be superior weed competitors in terms of grain yield.

TABLE 3.3 ANOVA for yield, yield loss, oat biomass and wild oat biomass as affected by genotype and wild oat competition (Weed) assessed in Kernen and Goodale 2008 and 2009.

Source	df	Yield	Yield Loss	Oat Biomass†	Wild oat Biomass‡
		kg ha^{-1}	%	kg ha^{-1}	kg ha^{-1}
Site-year	3	NS	NS	NS	NS
Site-year x Genotype	24	NS	*	NS	NS
Site-year x Weed	3	NS	NA	NS	NA
Site-year x Genotype x Weed	24	NS	NA	***	NA
Genotype	8	*	NS	NS	*
Weed	1	*	NA	**	NA
Genotype x Weed	8	NS	NA	NS	NA
CDC Baler vs. Ronald		NS	NS	NS	NS
CDC Baler vs. all others		**	*	NS	*
Ronald vs. all others		NS	NS	NS	NS
CDC Baler vs. all lines		**	NS	NS	*
Ronald vs. all lines		*	NS	NS	NS

*,**,*** denote significant at 0.05, 0.01 and 0.001 levels respectively.
† Data were log_{10} transformed.
‡ Data were square root transformed.
NA- denotes not applicable.
NS- denotes not significant.

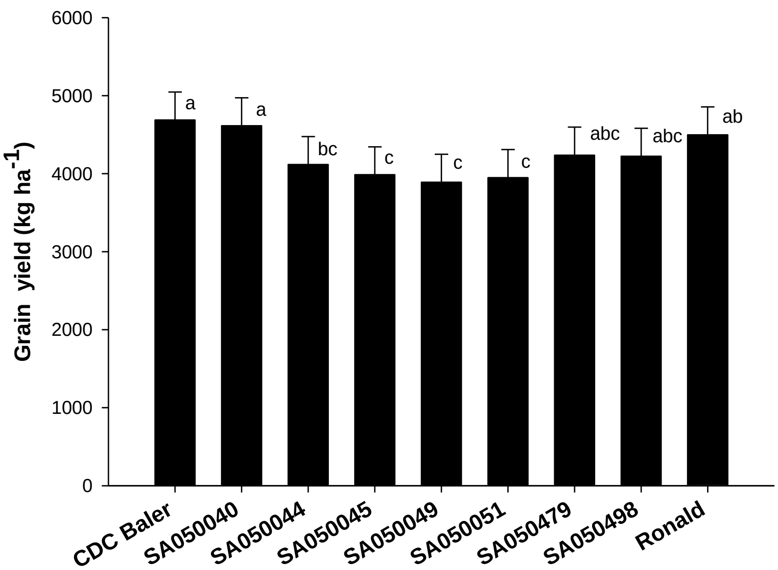

FIGURE 3.4 Effect of oat genotype on grain yield (pooled across weedy and weed-free conditions) assessed in Kernen and Goodale 2008 and 2009. Error bars represent the standard errors of the least squares mean. Comparisons made between genotypes with similar letters indicate no significant difference at LSD $_{0.05}$.

There was no correlation between plant height with averaged grain yield (Table 3.4) or weed-free grain yield (data not shown). However, many studies with different crop species revealed that although tall cultivars lack attractive weed-free yields, they were often higher yielding than short cultivars under weedy conditions (Kwon et al. 1991; Mason et al. 2008). In contrast, Wildeman (2004) identified that the tall competitive forage-type oat cultivar CDC Bell was the lowest yielding cultivar among the six cultivars tested. In the present study, both the tall (CDC Baler, SA050498, and SA050479) and short (SA050040 and Ronald) genotypes had high average grain yield under weed-free and weedy conditions. The lack of association between grain yield and plant height in the present study could be because these genotypes differ in other traits that affect grain yield. Since these oat genotypes are not isogenic lines, identifying traits associated with grain yield can be a difficult task. Correlation analysis indicated that none of the traits measured was associated with crop yield except STLA which showed a significant (P = 0.07) positive correlation (r = 0.62) (Table 3.4). Accordingly, genotypes SA050049 and SA050051 which had the smallest STLA had the lowest grain yield.

TABLE 3.4 Pearson's correlation coefficients (*r*) between oat crop traits and competitive parameters.

Crop traits	Yield	Yield Loss	Wild oat Biomass
	kg ha^{-1}	%	kg ha^{-1}
Seedling traits			
Third leaf width	(0.47)NS	(0.21) NS	(-0.61)†
Third leaf length	(0.08)NS	(-0.24)NS	(-0.17)NS
Third leaf area	(0.54)NS	(0.07)NS	(-0.73)*
Total leaf area	(0.62)†	(0.03)NS	(-0.86)**
Mature crop traits			
Flag leaf width	(-0.29)NS	(-0.45)NS	(-0.24)NS
Flag leaf length	(-0.48)NS	(-0.50)NS	(0.20) NS
Flag leaf area	(0.15)NS	(-0.52)NS	(0.02) NS
LAI	(-0.37)NS	(-0.27)NS	(0.18)NS
LI	(0.03)NS	(-0.31)NS	(0.09)NS
Plant height	(0.08)NS	(-0.27)NS	(-0.76)*

*,** denote significant at the 0.05 and 0.01 probability levels respectively.
† denotes significant at the 0.1 probability level.
NS - denotes not significant.

There was no significant genotype effect on percentage yield loss (Table 3.3). However, there was a site-year by genotype interaction identified for percentage yield loss (Table 3.3). Genotypes differed in yield loss at Kernen 2008, Kernen 2009 and Goodale 2009 with (P = 0.07, 0.07, and 0.04) respectively, indicating differences in crop tolerance. CDC Baler was the most tolerant oat genotype to wild oat competition (Figure 3.5). Similarly, Wildeman (2004) determined that CDC Bell (sister line of CDC Baler) was the most tolerant to wild oat competition in two site-years out of four. Due to the presence of site-year by genotype interaction, the magnitude of percentage yield loss was highly variable across environments. No genotype except CDC Baler was consistent for low percentage yield loss. Similarly, Cousens and Mokhtari (1998) found that wheat cultivar tolerance to weeds was highly variable depending on the environment. The yield loss of CDC Baler was 13%, 18% and 7.5% at Kernen 2008, Kernen 2009 and in Goodale 2009 respectively. This variability of yield loss can be mainly attributed to differing wild oat densities among site-years and the varying environmental conditions that prevailed.

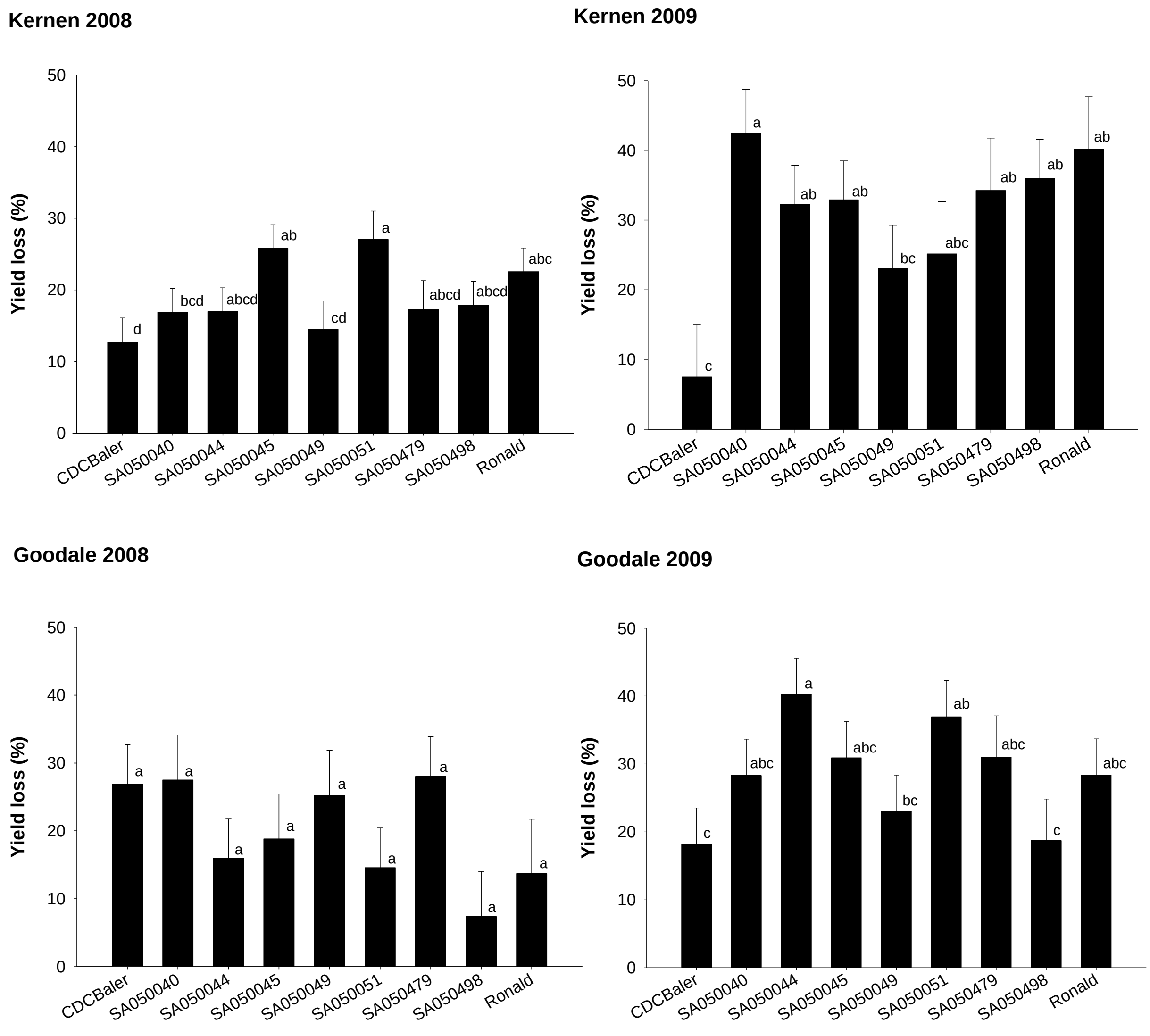

FIGURE 3.5 Percentage grain yield loss affected by genotype assessed in Kernen and Goodale in 2008 and 2009. Error bars represent the standard errors of the least squares mean. Comparisons made between genotypes with similar letters indicate no significant difference at LSD $_{0.05}$.

None of the measured crop traits including plant height were correlated with percentage yield loss. Although taller genotypes were expected to be more competitive with wild oat, the correlation analysis indicated that crop height was not associated with crop yield loss (crop tolerance) (Table 3.4). In contrast, other studies showed that increasing plant height was associated with the crop's ability to tolerate weed competition (Huel and Hucl 1996; Seefeldt et al. 1999; Zerner et al. 2008). Coleman et al. (2001) found that wheat lines with genetically longer seedling leaves, larger flag leaves, and tall mature height had more crop tolerance as evidenced by less yield loss when grown with ryegrass. However, most of the previous studies evaluated a wide range of crop genotypes and not only two parents with their progeny.

3.3.4.2 Oat biomass

There was no genotype effect on oat biomass (Table 3.3). Oat biomass was reduced ($P < 0.01$) by 23% due to wild oat competition (Table 3.3). There was no genotype by weed interaction; indicating that there were no differences among genotypes for oat biomass in the presence or absence of wild oat competition.

3.3.4.3 Wild oat biomass

The ability of the oat genotypes to suppress wild oat biomass differed among genotypes (Table 3.3). Genotypes SA050045, SA050049 and SA050051 demonstrated highest wild oat biomass indicating less weed suppressive ability (WSA) (Figure 3.6). CDC Baler and SA050479 had lower wild oat biomass and therefore were the cultivars with greatest WSA, while SA050498 and Ronald tend to have intermediate wild oat biomass. The most wild oat suppressive line SA050479 had 32% less wild oat biomass compared to least suppressive line SA050049.

Crop height may have contributed to the higher WSA of SA050479, CDC Baler, and SA050498. The correlation analysis indicated that crop height was negatively correlated with wild oat biomass ($r = -0.76$, $P < 0.05$) (Figure 3.7). Similarly, the tallest cultivar CDC Bell was found to be the most competitive with wild oat (Wildeman 2004). Taller crop cultivars are able to intercept more light than their competing weeds (Wicks et al. 1986) and are more competitive than short cultivars (Champion et al. 1998). However, in the present study, the shortest cultivar Ronald also had intermediate wild oat suppressive ability, suggesting that other plant traits may have also contributed to crop WSA.

Oat seedling total leaf area and third leaf area was strongly negatively correlated with wild oat biomass (Figure 3.7). Third leaf width was slightly correlated with wild oat biomass (Table 3.4). Accordingly, the most wild oat suppressive genotype SA0500479 had greater STLA, TLW and STLA. These results are in accordance with Lopez-Castaneda and Richards (1996), Seavers and

Wright (1999) and Zhao et al. (2006) who all found that seedling leaf area was an important crop trait associated with crop CA.

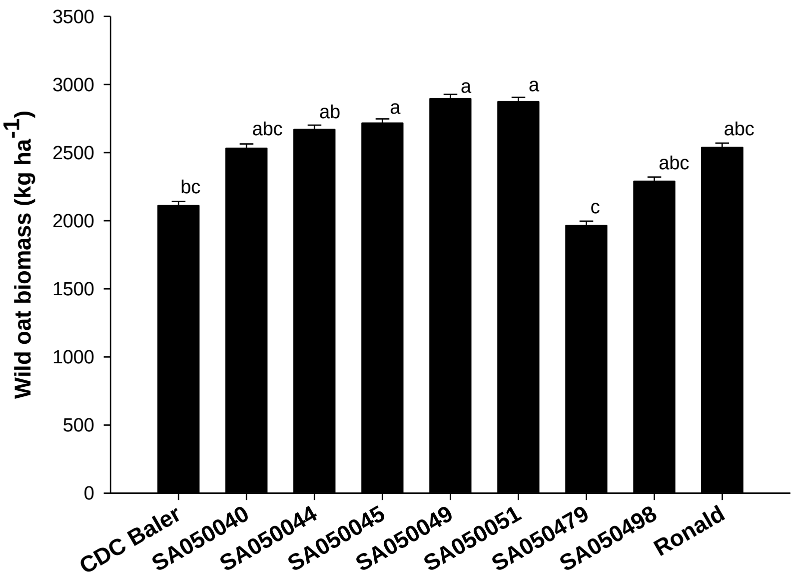

FIGURE 3.6 Wild oat biomass as affected by oat genotypes assessed in Kernen and Goodale in 2008 and 2009. Means are back transformed. Error bars represent the standard errors of the least squares mean. Comparisons made between genotypes with the same letter indicate no significant difference at LSD $_{0.05}$.

The greater seedling leaf size in Ronald may have compensated for its reduced height and thereby acquired greater CA. Since SA050479 was the tallest line and had the highest STLA and larger third leaf size, it is likely the combination of crop height and greater seedling size that influence the CA of this oat genotype. Accordingly, the least wild oat suppressive cultivars SA050045, SA050049, and SA050051 were short and had small seedling size. Furthermore, line SA050040, with an intermediate height and intermediate competitive seedling traits, was intermediate for wild oat suppression. Our study concurs with several others (i.e., Guneyli et al. 1969; Huel and Hucl 1996; Lemerle et al. 1996) and strongly suggests that seedling leaf size and crop height are the main attributes for crop CA. Furthermore, all these studies confirm that selection for seedling leaf size at early growth stage can be an effective screening tool when breeding for competitive crop cultivars.

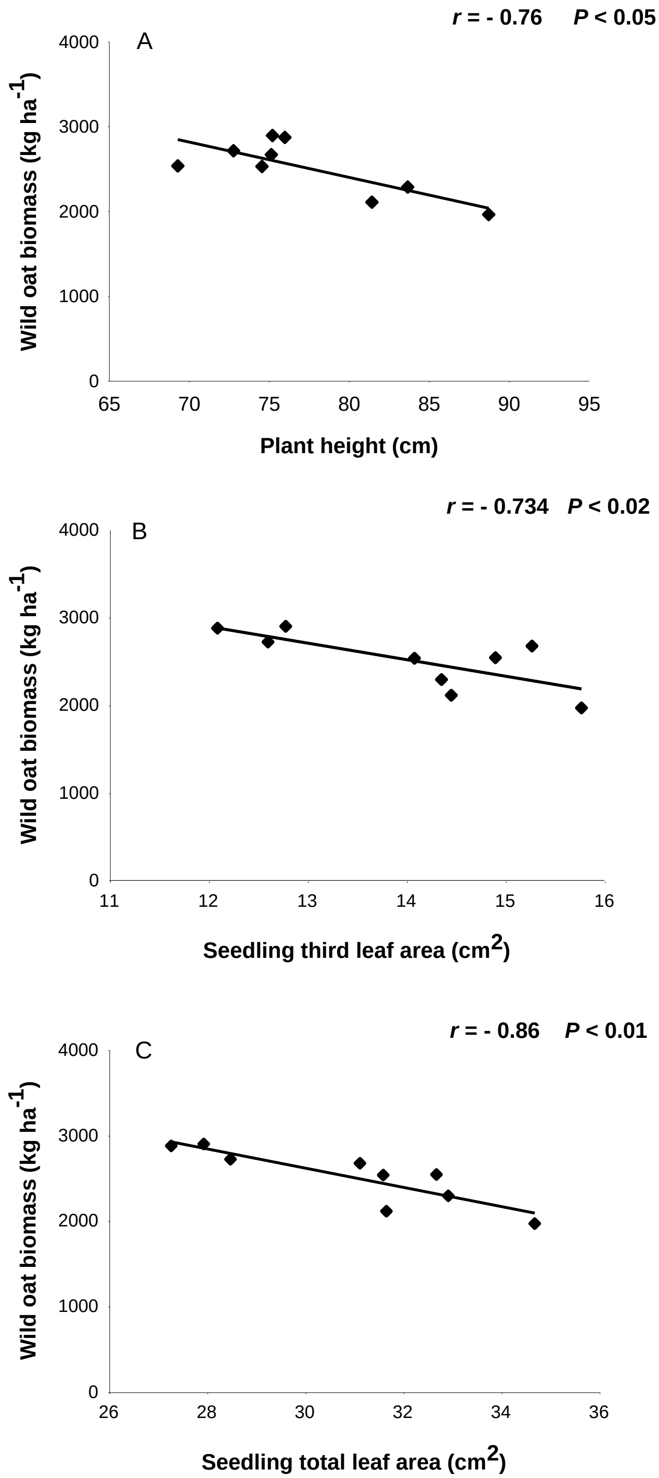

FIGURE 3.7 Association of wild oat biomass with: A. plant height, B. seedling third leaf area, and C. seedling total leaf area averaged in Kernen and Goodale in 2008 and 2009.

Crop canopy traits such as LAI, LI, and flag leaf size were not associated with wild oat biomass. In contrast to the present study, Fischer et al. (2001) and Zerner et al. (2008) found that crop canopy traits such as LAI, LI, and flag leaf size were correlated with weed suppression.

3.3.5 Grain quality

3.3.5.1 Wild oat contamination

In the presence of wild oat, the oat seed contamination with wild oat was significantly (P = 0.007) higher. Weed-free plots had an average of 0.03% contamination with wild oat seed and weedy plots had 2.5% wild oat seed. However, wild oat contamination was not affected by the crop genotype at $P > 0.05$ (results not shown).

3.3.5.2 Grain physical quality

There was no genotype by weed interaction for the percentage of plump and thin kernels (Table 3.5). Similarly, Wildeman (2004) found that wild oat competition did not affect the percentage of plump kernel of the oat cultivars tested. When averaged over weedy and weed-free treatments, genotypes showed differences for percentage plump and thin kernels (Table 3.5). Higher percentage of plump kernels and lower percentage of thin kernels indicate better grain quality. Lines SA050498 and SA050479 had higher percentage of plump kernels compared to the rest of the genotypes (Table 3.6). Similarly, these two lines had lower percentage of thin kernels, indicating better quality compared to all other genotypes. Ronald, SA050040 and SA050051 demonstrated poorest grain quality in respect to percentage plump and thin kernels.

There was no interaction between genotype and weed competition for test weight (TW) and thousand kernel weight (TKW) (Table 3.5). The presence of wild oat had a significant ($P < 0.05$) effect on test weight (Table 3.5). Wild oat competition increased the test weight slightly (0.9%) from 273.6 g 0.5 L^{-1} to 276.3 g 0.5 L^{-1}. The minimum test weight standard for Canadian western NO.1 grade is 260 g 0.5 L^{-1} (Canadian Grain Commission 2009). Genotypes differed in TW and TKW ($P < 0.001$) when averaged across weedy and weed-free treatments (Table 3.5). All the genotypes in this experiment were above the minimum standard for TW including CDC Baler, a forage type cultivar, with a test weight of 270 g 0.5 L^{-1}. Ronald, SA050479 and SA050498 had highest test weights (Table 3.6). Thousand Kernel weight in CDC Baler was higher than Ronald. Lines SA050045, SA050049, SA050498, and SA050479 had higher TKW compared to the rest of the genotypes (Table 3.6). When all the genotypes were considered for grain quality parameters, the two parental genotypes had intermediate grain quality; Ronald had higher percentage of plump kernels and lower percentage of thin kernels, CDC Baler had higher TKW. Importantly, the most wild oat suppressive line SA050479 had good grain quality in terms of all parameters measured. Based on the grain yield and grain quality evaluations the competitive oat line SA050479 could be identified as a potential wild oat suppressive cultivar.

TABLE 3.5 ANOVA for oat percentage plump and thin kernels, test weight (TW), and thousand kernel weight (TKW) as affected by oat genotype and wild oat competition assessed in Kernen and Goodale in 2008 and 2009.

Source	Plumps	Thins	TW	TKW
	%	%	g 0.5L^{-1}	g
Site-year	NS	NS	NS	NS
Site-year x Genotype	**	**	**	*
Site-year x Weed	NS	NS	NS	NA
Site-year x Genotype x Weed	NS	NS	NS	NA
Genotype	***	***	***	***
Weed	NS	NS	*	NS
Genotype x Weed	NS	NS	NS	NS
CDC Baler vs. Ronald	***	***	***	***
CDC Baler vs. all others	***	***	***	***
Ronald vs. all others	***	***	***	***
CDC Baler vs. all lines	NS	NS	*	NS
Ronald vs. all lines	***	***	***	***

*,**,*** denote significant at the 0.05, 0.01 and 0.001 levels respectively.
NA- denotes non significant random effects that were removed to improve the AIC of the model.

TABLE 3.6 Oat percentage plump and thin kernels, test weight (TW), and thousand kernel weight (TKW) as affected by oat genotype in averaged weed-free and weedy treatments assessed in Kernen and Goodale in 2008 and 2009.

Treatments	Plumps	Thins	TW	TKW
	%	%	g $0.5L^{-1}$	g
CDC Baler	95.7abc	3.0cde	269.9c	44.0b
Ronald	88.6e	7.8a	285.5a	39.5c
SA050040	92.2d	5.5b	277.8b	40.3c
SA050044	95.8abc	2.5cde	269.2c	44.5b
SA050045	94.5bcd	3.2cd	270.7c	47.8a
SA050049	93.8cd	3.9bc	271.4c	47.9a
SA050051	91.8d	6.0ab	270.7c	40.4c
SA050479	97.1ab	1.7de	281.8ab	46.3a
SA050498	97.5a	0.9e	277.7b	47.5a

†Means within a column with the same letters are not significantly different at $LSD_{0.05.}$

3.3.6 Conclusions

The oat genotypes used in this study differed in phenotypic traits such as seedling leaf size, flag leaf size, and mature plant height. However, genotypes did not show differences in grain yield in the presence or absence of wild oat competition. Genotypes differed in mean grain yield (both weedy and weed-free), with SA050040, SA050498, SA05079, Ronald and CDC Baler having greater yield. Genotypes SA050479 and CDC Baler were the most wild oat suppressive. Crop traits such as seedling total leaf area, seedling third leaf width, seedling third leaf area, and plant height were strongly associated with the crop's ability to suppress wild oat. The most weed suppressive line SA050479 did not demonstrate greater crop tolerance. However, CDC Baler showed better crop tolerance (less percentage yield loss) compared to the rest of the genotypes used. Wild oat suppressive line SA050479 had a greater yield potential both under weed-free and weedy conditions and had better grain quality. The results confirmed that the limitations identified in yield and grain quality in competitive oat cultivar CDC Bell have been overcome by this newly developed oat line. Furthermore, the results of this study confirmed that the development of new oat cultivars with greater crop competitive ability and high yield potential is possible and can be useful in mitigating wild oat competition in oat cropping systems.

4.0 Integration of cultural practices to enhance the competitive ability of organic oat (*Avena sativa* L.) cropping systems

4.1 Introduction

Modern agriculture depends on the use of synthetic herbicides to control weeds. Alternative farming strategies are being developed due to increased risk of overuse of synthetic pesticides and fertilizers and their effect on the environment (Mason et al. 2007b). Organic farming is one form of sustainable agriculture where crop production occurs without the use of synthetic inputs such as fertilizers and pesticides. Of all the organic field crops grown in Canada, oat has the second highest acreage next to wheat. Saskatchewan has the largest organic crop production in Canada accounting for 54% of cultivated organic land (Canadian Organic Growers 2010). Due to many challenges, organic crop production is less attractive among farmers. Low grain yields compared to conventional systems (Kitchen et al. 2003; Ryan et al. 2004) can be the main reason for low adoption of organic crop production. The greater abundance of weeds compared to conventional systems (Leeson et al. 2000; Entz et al. 2001), and lack of efficient weed control strategies (Leeson et al. 2000; Bond and Grundy 2001; Entz et al. 2001) may be responsible for low yields.

In sustainable weed management, an ideal weed management system should minimize weed emergence, reduce growth and fecundity, and finally minimize crop interference (Lovette and Knights 1996; Blackshaw 2008). Therefore, in organic cropping systems, weed management tactics consist of long term strategies such as crop rotations, cover crops, green manure crops as well as short term cultural and mechanical weed management strategies such as high density planting, growing competitive genotypes, narrow row planting, harrowing and hoeing.

Crop competitive ability (CA) is one of the factors that determine the density, biomass, and fecundity of weeds, and it can be manipulated by different cultural practices (Mohler 2001). The primary goal of cultural weed control is to reduce weed competition through the enhancement of crop CA (Melander et al. 2005). Crop CA can be enhanced by numerous cultural methods, such as competitive genotypes (Lemerle et al. 1996; Mason et al. 2007a), narrow crop row spacing (Koscelny et al. 1990; Fanadzo et al. 2007) and high crop seeding rates (O'Donovan et al. 1999;

Olsen et al. 2004). Mechanical weed control reduces weed density and weed biomass, and thereby, providing a competitive advantage for the crop. In-crop mechanical weed control such as harrowing and hoeing are the most widely used direct weed control methods in organic crop production (Rasmussen 2004). Specifically, post-emergence harrowing is effective in controlling weeds in cereals (Kirkland 1995; Velykis 2009).

Multi-tactic approaches that prevent weed seed germination, enhance crop competition, and control weeds can be more important than single tactics (Rasmussen et al. 2000). Therefore, integration of cultural and mechanical weed control methods is valuable as it provides both preventive and therapeutic measures in weed management (Jordan 1993). Post-emergence harrowing provided better results when it was a part of a weed management system that included cultural weed control methods such as fertilizer management, high seeding rate, and competitive crop genotypes (Melander et al. 2005). Combining competitive genotypes with high seeding rates and early weed removal reduced weed biomass and increased yield by 41% (Harker et al. 2003). Similarly, Anderson (2005) reported the use of narrow row spacing, increased plant density, and delayed planting in sunflower reduced weed biomass by only 5-10% when used individually. When two and three of these practices were combined, weed biomass was reduced by 20-25%, and up to 90%, respectively.

Combining several weed control strategies may not always provide additive weed control as they may interact with each other. In spring wheat, genotypes that have greater CA at low crop densities may not be competitive when seeded at high densities (Weiner et al. 2001). Similarly, the effect of narrow row planting on weed biomass in wheat was reduced at high crop density (Olsen et al. 2004). Furthermore, the effectiveness of each cultural method and their additive or synergistic effect varies depending on the growing environmental conditions (O’Donovan et al. 1999; Rasmussen et al. 2009).

Most attempts to integrate weed control tactics were conducted in conventional cropping systems with herbicides as a weed control option (Harker et al. 2003; Anderson 2005; Harker et al. 2009). Interactions and additive effects from combining cultural and mechanical weed control methods are less known in organic cropping systems. Therefore, this study hypothesizes that integrating cultural and mechanical weed control strategies could enhance crop CA and thereby enhance weed control in organic cropping systems. The objective of this study was to determine the individual and combined effect of crop genotype, crop density, row spacing, and post-emergence harrowing on weed biomass, weed density as well as crop yield under organic conditions. To do this we used organic oat production as a model system.

4.2 Materials and methods

4.2.1 Experimental design and location

Field experiments were carried out at two locations; the Kernen Crop Research Farm (KCRF) (52° 09' N, 106° 33' W) Saskatoon, SK, and a commercial organic farm (52°19' N, 106° 05' W) near Vonda SK. The KCRF and Vonda farms were under organic for 19 and 14 years respectively. Both sites are on Black Chernozemic clay loam soil.

The experiment was a factorial design with four levels (oat genotype, crop density, row spacing and post-emergence harrowing), each having two treatments. The field layout was a randomized complete block design with four replicates and a plot size of 4 x 6 m. The oat genotypes were Ronald (Mitchell et al. 2003) and CDC Baler (Rossnagel and Scoles 1998). Ronald is a high yielding semi-dwarf type oat genotype expected to be low in competitive ability. CDC Baler is a tall broad leaved competitive genotype (Wildeman 2004). Two crop densities used were 250 plants m^{-2} (recommended) and 500 plants m^{-2} (2X recommended). The two row spacings were 11.5 cm (narrow) and 23 cm (standard). Mechanical weed control treatments were post-emergence harrowing and a non-harrowed control.

4.2.2 Experimental procedure

Oat seed was obtained from Crop Development Centre Saskatchewan. Seeding rates were calculated based on the targeted planting density by using thousand kernel weight, germination percentage, and estimated mortality (5%) for each genotype. Seeding took place on 21st May in Vonda and 23rd May in Kernen 2008. In 2009, Vonda was seeded 11th May and Kernen was seeded 18th May.

The post-emergence harrowing treatment was applied when oat seedlings were at 2-3 leaf stage. An Einbock spring tine weed harrower (Einbock) was used with a standard tine setting of 7 mm x 490 mm long and 4 m overall width. One pass was done along the crop row over the selected plots with a driving speed of approximately 6 km h^{-1}. At locations with high weed density, two passes were carried out sequentially. Plant counts were taken for crop and weeds at the 2-3 leaf crop stage. A $0.25 m^2$ quadrat was placed in random positions on both the front and back of each plot. Quadrats were placed parallel to the crop row to include three crop rows within the quadrat. The number of weeds within the quadrat was recorded by species.

Oat shoot biomass and weed shoot biomass were taken by clipping all plants in a 0.25 m^2 quadrat from both the front and back of every plot at the soft dough stage (Zadoks 85) of the crop. Oats and weeds were separated and the samples were oven dried in paper bags for 48 hours at 60 ^oC. At maturity (Zadoks 90), crop was harvested using a plot combine harvester with 1.6 m width. Length of the harvested plot was reduced to 6 m and edges of either side of the plot were kept un-harvested to reduce edge effects. Harvested grain samples were air dried for 2-3 days until a constant moisture condition was reached. Each harvested grain sample was cleaned using a dockage tester (Carter Day International, Inc.). Cleaned samples were weighed and yield per plot was recorded. A 1 kg of sample was taken and stored in paper bags for subsequent quality evaluation.

Grain quality parameters test weight (TW), thousand kernel weight (TKW), percentage of thin kernels and percentage of plump kernels were determined using a 400 g sub-sample. Thousand kernel weight was measured by weighing 200 seeds and multiplying by five. The TW was determined by the specifications of the Canadian Grain Commission’s Official Grain Grading Guide (2009). The percentage of plump kernels was determined by the proportion of grain sample retained after sieving through a slotted sieve of 2.15 mm x 8.33 mm, and the thins were that proportion passed through a 1.95 mm x 8.33 mm sieve.

4.2.3 Data analysis

All data for the four site-years were combined, and analysis of all the data was performed using Analysis of Variance (ANOVA) with SAS Mixed models (SAS Institute Inc., 2008).

Treatments were considered fixed effects while replicates (blocks) and environment (site-year) and all the site-year by treatment interactions were considered random. Non-significant covariance parameters were eliminated from the model according to AIC values for better model fit (Littell et al. 2005). Preliminary analysis of variance indicated a high degree of variation in naturally occurring weeds in Vonda 2008; therefore, a spatial covariance analysis was conducted when the data were analyzed by site-year, to eliminate the spatial variability of weed density in Vonda 2008. Before analysis, weed density and weed biomass data were $\log_{10}$ and square root transformed respectively based on the Levenes test for homogeneity of variance and inspecting residuals. Means were separated using Fisher's protected Least Significant Difference (LSD) at $P < 0.05$.

4.3 Results and discussion

4.3.1 Crop and weed density

Crop emergence was uniform across site-years. At the target crop density of 250 plants m^{-2} the actual mean density was 193 plants m^{-2}, and it was 329 plants m^{-2} when the targeted density was 500 plants m^{-2}.

Weed density was highly variable across locations and seasons. At Kernen 2008, average weed density was low (Table 4.1). Weed densities were high at Vonda 2008, Kernen 2009, and Vonda 2009 with 320, 223 and 290 plants m^{-2}, respectively. Variability of weed density across site-years could be due to different rainfall among site-years. Vonda was relatively dry during 2008 and 2009 compared to Kernen receiving only 3.7 and 4.5 mm average rainfall (Table 4.2). A diversity of weed species was observed among the four site-years. The main species identified were wild oat (*Avena fatua* L.), wild mustard (*Sinapsis arvensis* L.), wild buckwheat (*Polygonum convolvulus* L.), green foxtail (*Setaria viridis* L.), common lambsquarters (*Chenopodium album* L.), and kochia (*Kochia Scoparia* L.). Different species were dominant in different environments. In Vonda 2008, the majority of the weeds were wild oat and wild mustard. Wild mustard dominated the community at Kernen 2009, while green foxtail dominated at Vonda 2009.

TABLE 4.1 Mean weed species density (plants m^{-2}) assessed in each site-year.

Species	Kernen 2008	Vonda 2008	Kernen 2009	Vonda 2009
Wild oat	NA	114	4	4
Wild mustard	5	126.	264	121
Wild buckwheat	2	NA	6	13
Green foxtail	NA	NA	30	477
Lambsquarters	3	NA	NA	NA

NA- denotes species absent or very low density.

4.3.2 Grain yield

There was no significant genotype effect on grain yield ($P > 0.05$) (Table 4.3), indicating that there was no difference between CDC Baler and Ronald. These results mirror those observed in the previous experiment (Chapter 3) where CDC Baler and Ronald had similar grain yield in the conventional system. However, average grain yield varied from a high of 4540 kg ha^{-1} at Kernen 2008 and to a low of 1380 kg ha^{-1} at Vonda in 2008 (data not shown). The low weed density at Kernen in 2008 and the high weed density at Vonda in 2008 (Table 4.1) is probably the main reason for the yield difference.

Increasing crop density increased grain yield ($P < 0.01$) (Table 4.3). Oat planted at higher crop density (500 plants m^{-2}) had 11% greater yield compared to normal crop density (250 plants m^{-2}) (Figure 4.1). Similarly, May et al. (2009) found that increasing oat seeding rate from 150 seeds m^2 to 350 seeds m^2 increased oat grain yield. Mason et al. (2007a) observed a similar yield increase by doubling the seeding rate in organic wheat and barley. Crop density did not interact with other cultural practices; thus, increasing crop density always increased grain yield independent of other treatments used in this study. In general, increased seeding rate is often associated with increase in grain yield in most cereals such as wheat (Lemerle 2004), barley (Barton et al. 1992), and oat (Peltonen-Sainio and Jarvinen 1995) in conventional cropping systems.

TABLE 4.2 Monthly rainfall (mm) and mean daily temperature (°C) for Saskatoon and Vonda from May until September in 2008 and 2009 and climate normals (30-year average).

		Rainfall			Temperature		
Location	Month	2008	2009	Normal†	2008	2009	Normal†
			mm			°C	
Saskatoon	May	22.2	12	41.5	15.9	18.2	11.8
	June	69.6	43	60.5	22	22.7	16
	July	55.8	60.5	57.3	21.7	24.5	18.3
	Aug	44.2	97	35.4	22.1	25.2	17.6
	Sep	1.2	17.5	28.9	23.5	18.7	11.5
	Total	193	230	223.6	_	_	_
Vonda	May	0.3	0.6	_	13.9	8.5	_
	June	1.6	0.9	_	15.2	15.4	_
	July	0.9	1.5	_	17.3	15.6	_
	Aug	0.6	0.6	_	17.8	15.4	_
	Sep	0.3	0.8	_	10.4	16.1	_
	Total	3.7	4.5	_	_	_	_

† 1970-2000 Canadian Climate Normals for Saskatoon obtained from Environment Canada (2009).

No row spacing effect observed for grain yield (P = 0.18) indicating that reducing crop row spacing from 23 cm to 11.5 cm does not increase grain yield. Previous studies suggest that the row spacing effect on grain yield was inconsistent. Solomon et al. (1991) and Koscelny et al. (1990) found that grain yield increased with decreasing row spacing when weeds were present in wheat. In contrast, other studies revealed that a reduction in row spacing had no effect on grain yield (Kolb et al. 2010), had an inconsistent effect (Puricelli et al. 2003), or resulted in reduced grain yield (Fanadzo et al. 2007).

TABLE 4.3 ANOVA for grain yield, oat biomass, weed density, and weed biomass as affected by genotype (G), Crop density (CD), Spacing (SP) and Harrowing (H) assessed in Kernen and Vonda in 2008 and 2009.

Source	Yield‡	Oat Biomass	Weed Density§	Weed Biomass‡
	kg ha^{-1}	kg ha^{-1}	Plants m^{-2}	kg ha^{-1}
Genotype (G)	0.4665	0.0988†	0.7607	0.0452*
Crop Density (CD)	0.0104*	0.0225*	0.2387	0.0001***
Spacing (SP)	0.1827	0.2427	0.6558	0.1713
Harrowing (H)	0.0028**	0.155	0.1301	0.4516
G x CD	0.9406	0.9357	0.2052	0.9645
G x SP	0.4588	0.1875	0.3332	0.1103
CD x SP	0.3287	0.4165	0.3265	0.7706
SP x H	0.3324	0.1713	0.0253*	0.1643
G x H	0.7981	0.2304	0.6924	0.8537
CD x H	0.6149	0.8118	0.2835	0.0952†
G x CD x H	0.8485	0.4868	0.7158	0.6059
G x CD x SP	0.2086	0.4548	0.8572	0.997
G x SP x H	0.9595	0.5151	0.763	0.9841
CD x SP x H	0.7455	0.4293	0.9121	0.9155
G x CD x SP x H	0.9938	0.766	0.257	0.2359

*,**,***, denote significant at the 0.05,0.01,0.001 probability levels respectively.
† denotes significant at 0.1 level.
‡ Data were square root transformed for analysis.
§ Data were $\log_{10}$ transformed for analysis.

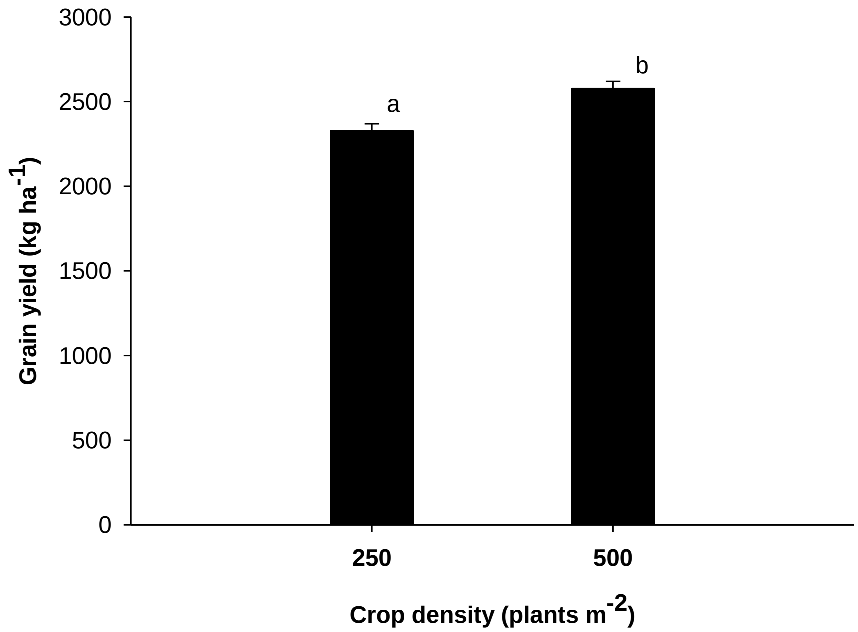

FIGURE 4.1 Effect of crop density on grain yield assessed in Kernen and Vonda in 2008 and 2009. Least squares means are back transformed. Error bars represent the standard errors of the least squares mean. Comparisons made between treatments with similar letters indicate no significant difference at LSD $_{0.05.}$

Post-emergence harrowing resulted in a 13% increase in grain yield compared to the non-harrowed treatment (Figure 4.2). However, previous studies revealed no consistent yield increase in cereals with harrowing (Rasmussen and Svenningsen 1995; Rydberg 1994). Yield advantage of harrowing can be obtained if the predominant weed is sensitive to harrowing, weed density is high and the application is timely (Mohler 2001). In the present study, the yield advantage observed could be due to high weed density and timely application.

Harrowing for weed control is often associated with crop damage and can result in reduced yields if the crop injury effect is greater than the weed control effect (Kirkland 1995). The results of the present study indicated that the positive effect of controlling weeds by harrowing could be greater than the negative effect of crop damage. Despite the individual effect of harrowing and high crop density, combining these two cultural strategies were able to increase the grain yield up to 25%; indicating that these two cultural practices are additive in nature.

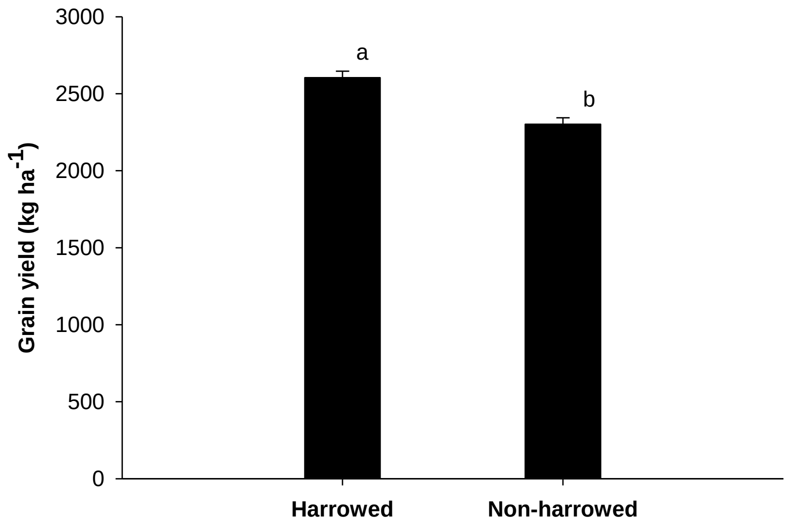

FIGURE 4.2 Effect of harrowing on grain yield assessed in Kernen and Vonda in 2008 and 2009. Least squares means are back transformed. Error bars represent the standard errors of the least squares mean. Comparisons made between treatments with similar letters indicate no significant difference at LSD $_{0.05.}$

4.3.3 Oat biomass

Oat biomass was affected by genotype ($P < 0.1$) and crop density ($P < 0.05$) (Table 4.3). CDC Baler had 22% higher shoot biomass compared to Ronald (Figure 4.3). This could be mainly because CDC Baler is a tall, leafy, forage type cultivar compared to Ronald, which is a short, grain type cultivar (Chapter 3). Oat shoot biomass was higher when the crop density was 500 plants m^{-2} compared to the density of 250 plants m^{-2} (Figure 4.4). The absence of any interaction between crop densities with other treatments indicates that oat biomass increases with crop density and was independent of row spacing, genotype or harrowing.

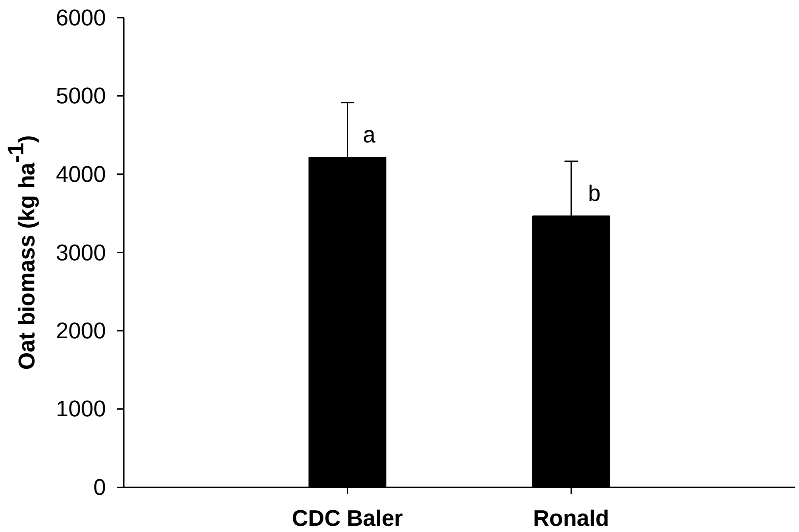

FIGURE 4.3 Effect of genotype on oat shoot biomass assessed in Kernen and Vonda in 2008 and 2009. Error bars represent the standard errors of the least squares mean. Comparisons made between treatments with similar letters indicate no significant difference at LSD $_{0.05.}$

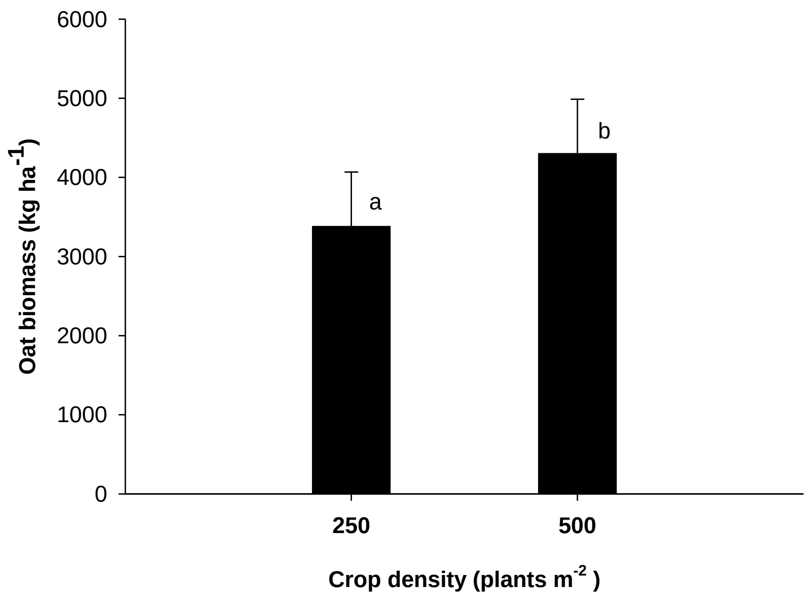

FIGURE 4.4 Effect of crop density on oat shoot biomass assessed in Kernen and Vonda in 2008 and 2009. Error bars represent the standard errors of the least squares mean. Comparisons made between treatments with similar letters indicate no significant difference at LSD $_{0.05.}$

4.3.4 Weed density

Weed density was not affected by any of the main effect treatments; however, there was a significant row spacing by harrowing interaction for weed density (Table 4.3). Overall, harrowing resulted in lower weed density at both row spacings (Figure 4.5). With no harrowing, wide row spacing had higher weed density. When harrowed, the wide row spacing had less weed density compared to narrow row spacing. However, the mean separation technique used did not detect statistically significant differences among treatments probably due to high variability in weed density across site-years.

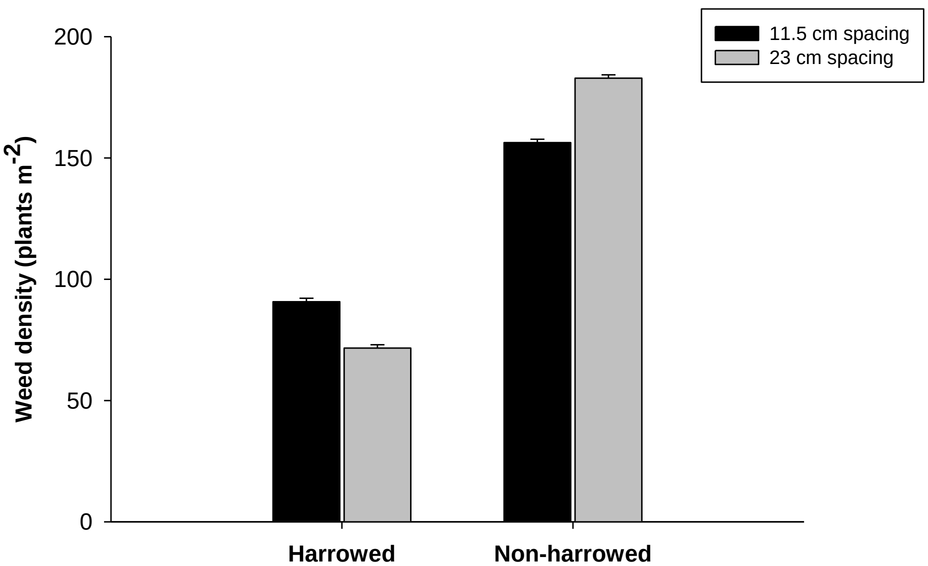

FIGURE 4.5 Interaction of harrowing and row spacing on weed density assessed in Kernen and Vonda in 2008 and 2009. Least squares means are back transformed. Error bars represent the standard errors of the least squares mean. Comparisons made between treatments indicate no significant difference at $LSD_{0.05.}$

Harrowing was effective in reducing weed density at sites with high weed densities. Even though there were no site-year by harrowing interaction, data analyzed within site-years clearly suggests that harrowing was highly effective ($P < 0.001$) in reducing weed density among three site-years out of four (Figure 4.6).

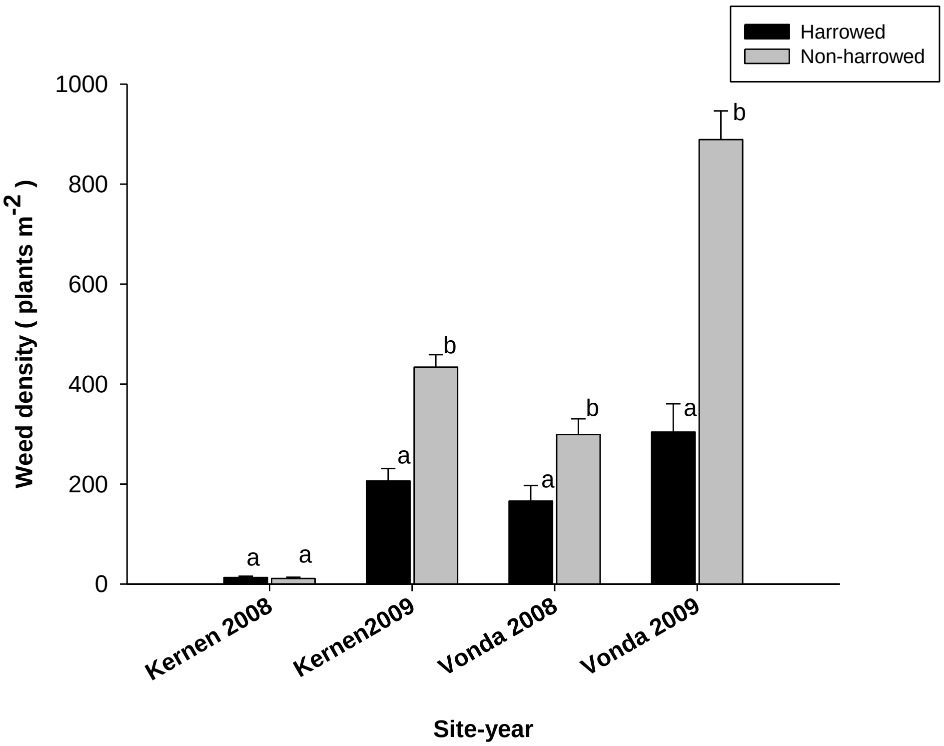

FIGURE 4.6 Effect of harrowing on weed density assessed in each individual site-year. Error bars represent the standard errors of the least squares mean. Comparisons made between treatments with similar letters indicate no significant difference at $LSD_{0.05.}$

The inability to detect the effect of harrowing on weed density at Kernen 2008 could be due to the very low weed density. Under weedy conditions, harrowing reduced weed density by 59%, 56% and 76% at Kernen 2009, Vonda 2008 and Vonda 2009 respectively. The results of Kernen 2008 suggest that harrowing in low weed conditions is not required. Therefore, post-emergence weed harrowing should be applied in situations with high weed density.

4.3.5 Weed biomass

CDC Baler treatment demonstrated less weed biomass ($P < 0.05$) than Ronald treatment (Figure 4.7); thus can be considered to be more competitive than Ronald. The higher CA of CDC Baler could be due to plant height (Chapter 3) and higher crop biomass compared to Ronald. Similarly, in winter wheat, tall genotypes were found to be more competitive than short genotypes with weeds under organic conditions (Neuhoff et al. 2009). Moreover, Mason et al. (2007b) found that plant height in wheat genotypes was the main attribute for CA in organic fields. Genotype differences in CA have often identified in conventional cropping systems

(Lemerle et al. 1996; Watson et al. 2006); however, competitive genotypes in conventional systems are not often tested under organic conditions. In this regard, the results of this study suggest that CDC Baler, a tall competitive genotype in conventional systems (Chapter 3), was also competitive in organic conditions. The results indicate that genotype competitive ability is not dependent on other cultural practices used as there was no interaction between genotype and the other treatments (Table 4.3). In contrast, Neuhoff et al. (2009) found that tall planophile cultivars were more weed suppressive when grown in wide-rows compared to narrow-rows.

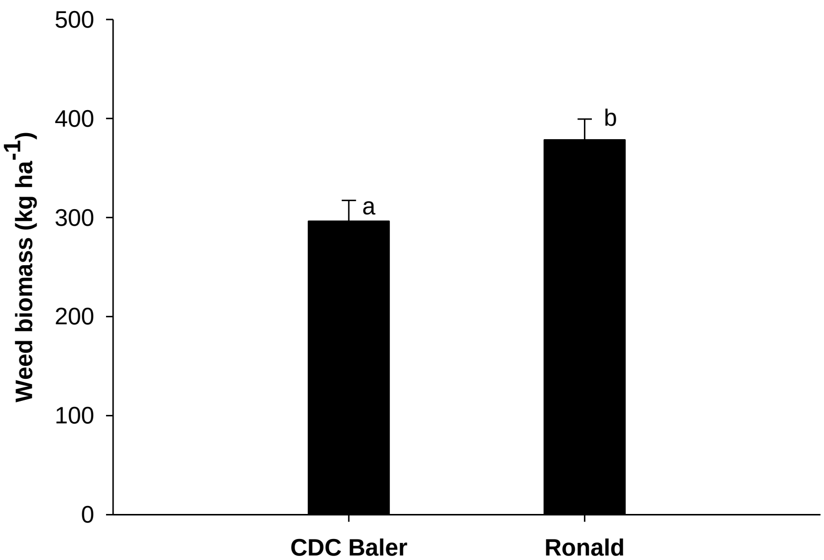

FIGURE 4.7 Effect of oat genotype on weed biomass assessed in Kernen and Vonda in 2008 and 2009. Least squares means are back transformed. Error bars represent the standard errors of the least squares mean. Comparisons made between treatments with similar letters indicate no significant difference at LSD $_{0.05.}$

Increasing crop density from 250 to 500 plants m^{-2} reduced weed biomass by 52% (Figure 4.8). Similarly, in organically grown wheat and barley, doubling the seeding rate reduced weed biomass by 28% (Mason et al. 2007a). In the present study, doubling the crop density was found to be more effective than growing competitive genotypes. This is in accordance with many other studies which revealed greater weed biomass reduction by increasing the crop density compared to other cultural practices (Scursoni and Satorre 2005; Chengci chen et al. 2008; Mason et al. 2007b; Kolb et al. 2010). Moreover, the results of the present study and that of Mason et al. (2007a) indicate that doubling the crop density does not depend on the crop genotype used.

Furthermore, crop density and crop genotype were additive in nature as the combination of competitive genotype (CDC Baler) with high cropping density (500 plants m^{-2}) reduced weed biomass by 63% compared to a non-competitive genotype (Ronald) with standard cropping density (250 plants m^{-2}).

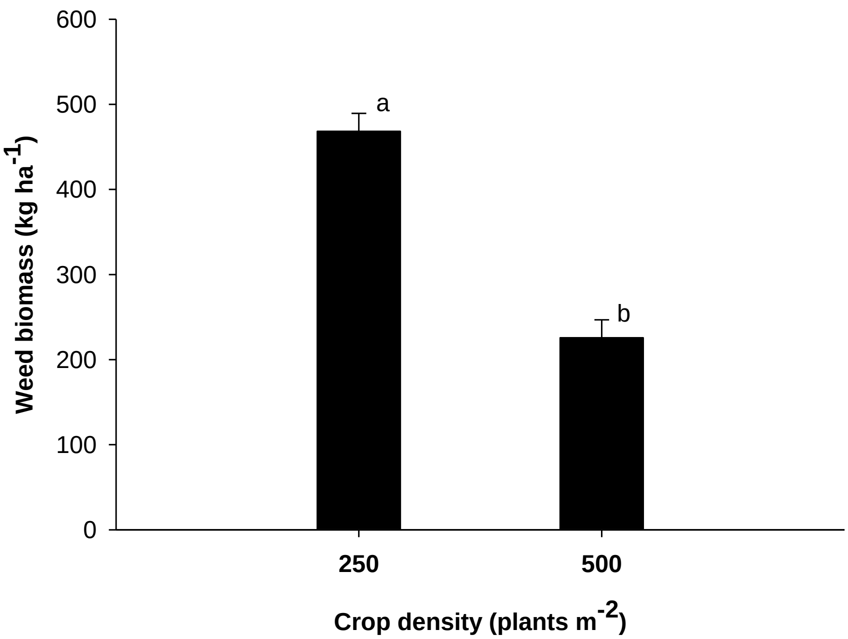

FIGURE 4.8 Effect of crop density on weed biomass assessed in Kernen and Vonda in 2008 and 2009. Least squares means are back transformed. Error bars represent the standard errors of the least squares mean. Comparisons made between treatments with similar letters indicate no significant difference at LSD $_{0.05}$.

There was a significant (*P* = 0.09) crop density by harrowing interaction for weed biomass. Harrowing for weed management was most effective when oat was planted at higher densities (Figure 4.9). There was 65% less weed biomass in the harrowed, high crop density treatment compared to that of the non-harrowed low density treatment. This interaction highlights the importance of combining the two cultural practices. Moreover, the combination of competitive genotype, high crop density, and post-emergence weed harrowing reduced weed biomass by 71 % which is far greater than the individual effects.

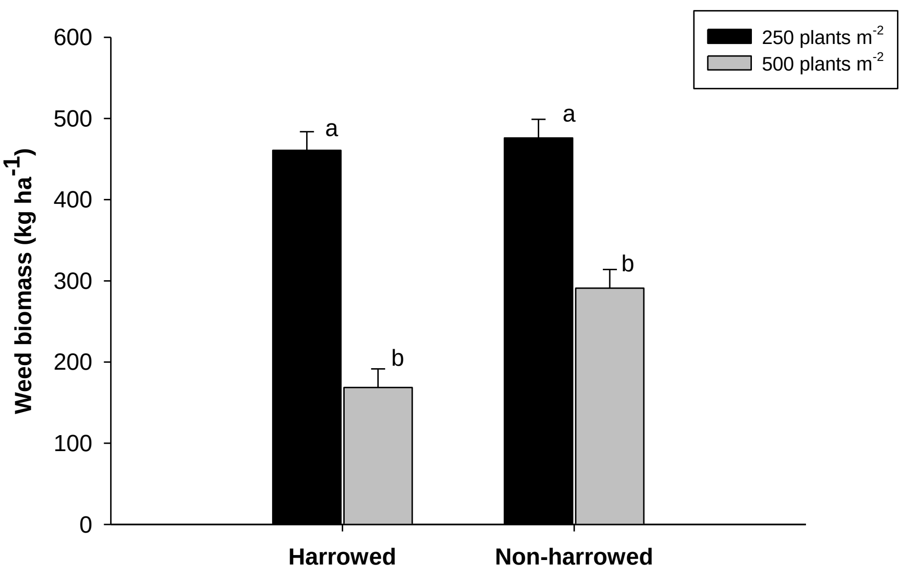

FIGURE 4.9 Interaction of harrowing and crop density on weed biomass assessed in Kernen and Vonda in 2008 and 2009. Least squares means are back transformed. Error bars represent the standard errors of the least squares mean. Comparisons made between treatments with similar letters indicate no significant difference at LSD $_{0.05.}$

4.3.6 Grain quality

As expected, the two genotypes differed significantly for grain quality parameters (Table 4.4). CDC Baler had a lower test weight (TW) of 258 g 0.5 L^{-1} and higher thousand kernel weight (TKW) compared to Ronald (Table 4.5). Increasing crop density significantly increased percentage thin kernels from 14% to 16% ($P < 0.05$) and decreased plump kernels from 86% to 73% (Table 4.5). Increasing the crop density did not affect TW or TKW (Table 4.4). The effect of increasing crop density on grain quality did not depend on other cultural practices used as there was no interaction among crop density and other treatments (Table 4.4). Since only percentage thin and plump kernels were negatively affected by increasing crop density, the benefits of this strategy on yield and weed control more than outweigh the negative effects on grain quality.

Harrowing also did not affect the grain quality parameters. Yet, there was a significant interaction observed for test weight ($P = 0.078$) and percentage thin kernels ($P = 0.056$) (Table 4.4) between spacing and harrowing. For both these parameters, the non harrowed treatment with 23 cm (standard) spacing had slightly better grain quality (data not shown).

TABLE 4.4 The ANOVA for test weight (TW), thousand kernel weight (TKW), percentage thin and plump kernels as affected by oat genotype (G), crop density (CD), spacing (SP), and harrowing (H) assessed in Kernen and Vonda in 2008 and 2009.

Source	TW	TKW	Thins	Plumps
	g 0.5 l^{-1}	g	%	%
Genotype (G)	0.0063**	0.0496*	0.0655	0.0766
Crop density (CD)	0.924	0.156	0.0178**	0.0469*
Row spacing (SP)	0.762	0.769	0.553	0.596
Harrowing (H)	0.292	0.752	0.483	0.576
G*CD	0.305	0.789	0.749	0.806
G*SP	0.870	0.633	0.690	0.935
CD*SP	0.213	0.804	0.978	0.638
G*H	0.410	0.430	0.445	0.501
CD*H	0.770	0.493	0.963	0.969
SP*H	0.078†	0.125	0.0569*	0.158
G*CD*SP	0.089	0.180	0.848	0.383
G*CD*H	0.531	0.212	0.600	0.622
G*SP*H	0.478	0.953	0.207	0.295
CD*SP*H	0.891	0.399	0.571	0.970
G*CD*SP*H	0.673	0.569	0.762	0.286

*,**,*** denote significant at the 0.05, 0.01 and 0.001 levels respectively.
† denotes significant at the 0.1 level.

TABLE 4.5 The mean effect of oat genotype (G), crop density (CD), spacing (SP), and harrowing (H) on test weight (TW), thousand kernel weight (TKW), percentage thin and plump kernels assessed in Kernen and Vonda in 2008 and 2009.

Source		TW	TKW	Thins	Plumps
		g $0.5l^{-1}$	G	%	%
Genotype (G)	CDC Baler	258.33	35.26	11.62	85.75
	Ronald	278.73	31.82	18.47	73.17
Crop Density (CD)	250 plants m^{-2}	268.45	34.01	14.26	80.72
	500 plants m^{-2}	268.60	33.07	15.84	78.21
Spacing (SP)	11.5 cm	268.72	33.47	15.20	79.17
	23 cm	68.34	33.60	14.90	79.75
Harrowing (H)	Harrowed	267.40	33.43	15.51	79.12
	Non-harrowed	269.65	33.64	14.59	79.80

4.6 Conclusions

In organic cropping systems, weed control using cultural and mechanical practices are highly effective. Increasing crop density from 250 plants m^{-2} to 500 plants m^{-2} and post-emergence weed harrowing increased oat grain yield. Genotype and row spacing did not affect grain yield. The competitive genotype, CDC Baler was able to suppress weeds better than Ronald. Increasing the crop density was the most effective individual strategy for greater weed suppression and increased grain yield. Manipulations to cultural practices from the standard practices had a minimum impact on grain quality; hence, provides more opportunities to alter them in order to achieve better yield and weed suppression. No negative interactions were observed when cultural and mechanical weed control tactics when combined; thus most of them were additive in nature. When high crop density, competitive genotype and post-emergence harrowing were combined, weed biomass was reduced by 71%. Similarly, grain yield was increased by 25%, when high crop density and harrowing was combined. Therefore, these results clearly indicate the importance of combining several cultural and mechanical weed control strategies opposed to using them in isolation for better yield and greater weed suppression.

5.0 General Discussion

5.1 Competitive oat cultivars to suppress wild oat competition

The results of this study revealed genotypic differences among newly developed oat breeding lines for their CA with wild oat. Moreover, the competitive oat lines also had high grain yield potential and acceptable quality; hence, could be recommended to farmers. Therefore, the hypothesis that newly developed oat lines differ in CA against wild oat and could be used effectively to mange wild oat competition in oat cropping systems is accepted.

Competitive oat lines developed by CDC oat breeding programme at the University of Saskatchewan had superior grain yield and grain quality. Furthermore, the results proved that it is possible to breed new cultivars with both CA and high grain yield potential. The main challenge in developing competitive crop cultivars is the negative correlation between CA and weed- free yield potential (Challaiah et al. 1986; Fischer and Quail 1990) and grain quality (Gealy et al. 2003; Wildeman 2004). According to the literature, none of the breeding efforts have been successful in developing competitive cereal crop cultivars for commercial use. Therefore, the outcome of this study is unique as it was able to demonstrate that the CDC breeding programme has overcome the challenges in developing competitive crop cultivars.

The most wild oat-suppressive breeding line SA050479 identified in the present study was among the best of all genotypes for grain yield and grain quality parameters test weight, thousand kernel weight and percentage plump kernels. The outcome of this study suggests that it is possible to develop competitive cultivars without compromising grain yield and quality. Therefore, these results and results of other studies (Fischer et al. 2001; Gibson et al. 2003) should encourage scientists to rethink of the possibilities of developing competitive high-yielding crop cultivars.

Oat breeding line SA050479 was identified as best in terms of CA as it was able to suppress wild oat biomass by more than 32% compared to the least wild oat-suppressive line. Even though line SA050479 was the most wild oat-suppressive among all lines tested, it did not differ from CDC Baler. Furthermore, the results confirmed that there are wild oat tolerant and wild oat suppressive oat cultivars.

CDC Baler was the most tolerant to wild oat competition as it had less percentage yield loss with wild oat competition in three site-years out of four. However, inconsistency in crop tolerance was observed because the genotype's ability to tolerate weed competition depended on environmental conditions. Several studies (Cousens and Mokhtari 1998; Ruiz et al. 2007) also revealed the variability of wheat cultivar tolerance depended on environmental conditions. CDC Baler had both crop tolerance and WSA compared to the rest of the genotypes. However, these results were unable to confirm a positive association between WSA and crop tolerance since oat breeding line SA050479 was not superior in crop tolerance although it was the most weed-suppressive line.

Plant traits measured in this study was unable to distinguish crop tolerance and WSA traits observed among genotypes. Similarly, no studies to date have been able to do so. The low yield loss percentage identified in CDC Baler was not associated with any of the competitive traits measured. In contrast, previous studies (Huel and Hucl 1996; Zerner et al. 2008) have indicated that crop yield loss is associated with plant height, leaf area and early vigour. These diverse results impose the complexity of understanding plant traits associated with CA and further hinders the crop improvement processes. However, WSA was genetically controlled more than crop tolerance because wild oat biomass was negatively correlated with crop height.

The short cultivar Ronald also demonstrated intermediate wild oat suppression, indicating that there could be crop traits other than plant height associated with wild oat suppression. Early vigour, demonstrated by larger seedling leaf size, could be the main determinant of wild oat suppressive ability in Ronald, as seedling leaf size was negatively correlated with wild oat biomass. These results, and results from other studies (Fischer et al. 2001; Garrity et al. 1992) confirm that tall crop varieties are not necessary to increase crop CA. Furthermore, since tall crop cultivars tend to have low harvest index and are susceptible to lodging, developing a short competitive oat cultivar is a main breeding objective of the Crop Development Centre in Saskatoon. However, none of the newly developed short oat lines were identified as superior in WSA or crop tolerance.

Oat line SA050479 may have had the greatest WSA because it was taller and had larger seedling leaf size than the other genotypes. This work and that of many others (Guneyli et al. 1969; Huel and Hucl 1996; Lemerle et al. 1996) confirm that early vigour (early ground cover, seedling growth rate, seedling size) and crop height are the main determinants for crop CA; hence, selecting for early vigour can be a promising tool in breeding for crop CA (Lemerle et al. 2001a) as it can be done at early stages of the breeding programme.

The inability to identify a single line with enhanced crop tolerance and greater WSA implies that it can be difficult to breed for a cultivar with both mechanisms to enhance crop CA. This leads to the dispute of which mechanism is important to enhance crop CA. In the short-term, cultivars with greater crop tolerance can be beneficial as they will maintain their yield under heavy weed competition. From a long-term weed management perspective, weed-suppressive cultivars are more valuable (Jordan 1993) as weed suppressive cultivars deplete the weed seed bank and thereby reduce the future weed population. Moreover, WSA could be a consistent measure of crop CA than crop tolerance (Lemerle et al. 1996; Chapter 3); hence, weed suppressive ability can be more useful in selecting crop cultivars with better CA. In conclusion, the outcome of this study suggests that the development of weed suppressive cultivars with greater yield potential could be a feasible strategy. Even though CDC Baler was the cultivar most tolerant to wild oat competition, the high grain yield potential and greater WSA of SA050479 clearly suggest that it could be preferred among the rest. In that sense, SA050479 is a promising oat line that could be developed into a cultivar recommended for farmers having difficulties managing wild oat.

5.2 Integrating cultural practices to enhance the crop competitive ability

Results of this study confirmed that integrating competitive cultivar, high crop density, and post-emergence weed harrowing were highly effective in managing weeds in organic oat cropping systems. Therefore, the hypothesis that greater weed control can be achieved by integrating both cultural and mechanical weed control tactics to enhance the crop CA against weeds is accepted.

The competitive oat cultivar CDC Baler (Chapter 3) was more able to suppress weeds more than Ronald. Selecting competitive crop cultivars is a primary and essential step to enhance the CA of a cropping system. However, competitive cultivars should posses greater yield potential. Even though CDC Baler is a forage-type cultivar, this study highlighted the importance of using competitive crop cultivars for organic cropping systems. There have been only a few attempts to develop competitive cultivars specifically for organic conditions as more than 95% of organic agriculture is based on crop cultivars bred for conventional agriculture (Lammerts van Bueren et al. in press, 2010). The outcome of the two studies in this thesis revealed that a competitive cultivar in conventional systems (Chapter 3) is also useful in organic systems (Chapter 4) as CDC Baler was competitive in both systems. In that regard, the newly developed competitive oat line SA050479 (Chapter 3) could also be useful in organic conditions. However, the competitive cultivar CDC Baler only reduced weed biomass by 22% compared to Ronald and suggests that competitive cultivars can only partially contribute to weed control in a cropping system.

The results imply that increasing crop density was the single most vital cultural weed control practice as it reduced weed biomass by 52%. Similarly, studies of Olsen et al. (2004), Mason et al. (2007), and Harker et al. (2009) revealed that increasing crop density was the most effective cultural practice to suppress weeds. Increasing crop density suppressed weeds regardless of the other cultural practices used, allowing more flexibility for farmers to incorporate into their cropping systems. High density planting, apart from its weed control effect was also able to increase grain yield by 11% which can be highly beneficial in organic cropping systems. Increased grain yield due to doubling the seeding rate could be possibly due to enhanced weed suppression rather than just increased number of plants m^{-2}; because, it was shown that in wheat, doubling the seeding rate was associated with increased grain yield in weedy conditions but not in weed-free conditions (Roberts et al. 2001). Accordingly, Beavers et al. (2008) also reported that high crop density can increase or maintain yield when weed competition is present.

Reducing row spacing from 23 cm to 11.5 cm did not have any positive effect on yield or weed suppression, suggesting that it can be unreliable in controlling weeds. There is adequate work done in different cropping systems to confirm that reducing the crop row spacing is not a very competent or consistent measure for suppressing weeds.

In general, reducing row spacing was found to be either effective (Begna et al. 2001; Weiner et al. 2001) or ineffective (Mohler et al. 2001; Rasmussen 2004) for managing weeds. Conversely, post-emergence harrowing was found to be highly effective as a weed control strategy. Harrowing increased oat grain yield by 13% and reduced weed density across three site-years compared to the non-harrowed treatment. The absence of significant interaction between harrowing and other cultural practices suggests that harrowing always increased yield regardless of crop density, genotype or row spacing.

Even though the results of this study revealed significant effects on weed suppression and grain yield by using cultural and mechanical weed control, the gain in weed control from individual strategies may not be sufficient. Limitations identified in individual weed control tactics were overcome by using multiple weed control tactics, as the additive effects by combining weed control strategies were observed. Combining high crop density and post-emergence harrowing reduced weed biomass by 65% compared to the non-harrowed, standard crop density treatment. When used alone, a competitive crop cultivar reduced weed biomass by 22%, but when a competitive cultivar and a high crop density were both used, weed biomass was reduced by 63%. Similarly, the combined effect of competitive cultivar, high crop density and post-emergence weed harrowing reduced weed biomass by as much as 71%. In addition to weed control, grain yield was enhanced by 25% when harrowing and high crop density was combined. These results confirmed that integration of competitive crop genotype, high crop density and post-emergence weed harrowing enhances the CA of organic oat cropping systems, thereby improving weed control.

Overall, the two studies in this thesis attempted to enhance the crop CA by improved crop genetics (Chapter 3) and integration of cultural and mechanical weed control practices (Chapter 4); hence, the main hypothesis of this thesis that crop competitive ability can be enhanced by both crop breeding and integrating cultural and mechanical weed control strategies is accepted.

5.3 Management implications

The outcome this thesis implies that the use of a single weed control strategy is not sufficient to manage wild oat in oat or other weeds in organic cropping systems. The oat-wild oat study revealed that competitive oat genotype accounted only for about 32% in reducing wild oat biomass, recognizing that competitive crop cultivars are not a panacea for managing weeds in cropping systems. Competitive oat cultivars, therefore, must be considered as an integral part of a combined effort to manage wild oat competition.

Integration of cultural practices could be vital for weed management in either organic or in conventional cropping systems. As identified in this study (Chapter 4), combining cultural practices such as competitive cultivars, high crop densities, and post-emergence harrowing were highly beneficial in organic systems. Even though the two experiments of this thesis were not conducted in both conventional and organic systems, the outcome and the applicability may not mutually exclusive. Hence, even in conventional fields, farmers can use an integrated approach by combining competitive cultivars, high crop density and post-emergence harrowing to control wild oat. Accordingly, the competitive oat genotype SA050479 should be established with higher crop density to augment its weed suppression ability and thereby control wild oat to a greater extent. In conclusion, this study revealed that a combination of short-term agronomic manipulations combined with long-term crop breeding effort could be the optimal scenario for wild oat management in oat cropping systems.

Results of the integrated weed management study confirm that farmers have to rely on several weed control tactics in controlling weeds in organic systems. Apart from the long-term weed management strategies (i.e., crop rotation, cover crops) that are often used, it is important to enhance the crop CA by integrating competitive cultivars, high crop density and mechanical weed control to manage weeds at ongoing level. As observed in this study, cultural and mechanical weed control strategies when combined are additive in weed suppression.

Overall, the outcome of this thesis concluded that in ecological-based weed management, integration of several strategies is needed to achieve a higher degree of weed control. Moreover, this thesis provided essential insights into the potential of ecological-based weed management strategies to address existing weed management challenges associated with different cropping systems.

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