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Evaluating the Influence of Genotypic Mixtures on Field Pea Productivity and Competitive Ability

by

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DEDICATION

To my parents (*Abdelhadi and Fahmiah Darras*) for teaching me how to farm and grow things. To my wife (*Tahani*) for her continuous love, support and patience. To my son (*Hadi*) for making my life full of joy and laughter!

ABSTRACT

This study was conducted to determine whether two-way genotypic mixtures could improve field pea productivity and competitive ability and whether genetic relatedness affects the mixing ability of genotypes. Genotypes were chosen on the basis of pedigree: two sister lines (CDC 1987-3 and CDC 1897-14), a common parent (Eclipse), and a distantly related genotype (Midas). Although the results showed that most mixtures performed similar to their components in monocultures, CDC1897-3 x Eclipse was found to reduce pseudo-weed (barley) seed production by 47% and 61% at Lethbridge in 2010 and 2011, respectively. The same mixture also significantly reduced the pseudo-weed biomass by 61% at St. Albert in 2010 and 41% at Lethbridge in 2010 and produced more above-ground biomass than its components in the greenhouse. Therefore, mixtures have potential to improve field pea productivity and competitive ability when combining poorly and strongly competitive genotypes; however, mixtures potential should be evaluated on a case-by-case basis.

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List of Abbreviations

a.e	Acid Equivalent
a.i	Active Ingredient
C	Competition
ºC	Degree Celsius
dS	Deci Siemens
E.C	Electrical Conductivity
G	Genotypic Composition
g	Gram
ha	Hectare
K	Potassium
Kg	Kilogram
L	Liter
m	Meter
Mha	Million Hectare
mg	Milligram
N	Nitrogen
NH_3	Ammonia
NS	Not Significant
P	Phosphorus
RY	Relative Yield
RYT	Relative Yield Total
S	Sulfur
SY	Site-Year
TSW	Thousand Seed Weight
VL	Vine Length
Wt.	Weight
Diff.	Difference
yr	Year
%	Percent
µmol	Micromole

CHAPTER 1: INTRODUCTION

1.1 Background

Field pea is grown worldwide for its nutritional value and used for human and animal consumption. The nutritional value of field pea and its importance to agroecosystems have been extensively studied around the world. In addition, field pea has the ability to fix nitrogen, which makes it one of the most important rotational crops. Hence, field pea production practices have been investigated thoroughly to improve crop yield and productivity, reduce input materials and production costs, and ease the environmental impacts caused by traditional agricultural pesticides and fertilizers.

Weed competition in field pea is one of the primary concerns limiting its cultivation. Field pea's poor competitive ability with weeds can reduce crop yield significantly (Harker et al., 2001; Lemerle et al., 2006; Strydhorst et al., 2008). Although field pea breeding programs have been successful in improving plant standability and disease resistance, limited success has been achieved with regard to improving field pea competitive ability. For that reason, field pea cultivation depends heavily on the chemical treatment of weeds and thus, finding a practical solution to improve field pea's competitive ability is imperative to increasing the crop's profitability and acreage.

Cultivar mixtures have been studied extensively in many cereal crops such as barley, wheat and oat crops and used as an alternative to conventional cropping systems (Kaut et al., 2008; Sarandon & Sarandon, 1995). Many researches have suggested that growing cultivar mixtures comprised of varied genetic material may offer yield advantages and better control of weeds, disease and insect infestations when compared to cultivars grown in monocultures (Helland & Holland, 2001; Jedel et al. ,1998; Kiaer et al., 2009; Smithson & Lenne, 1996).

However, no work has been done to examine growing field pea genotypes in mixtures. Therefore, information about the mixing ability of field pea genotypes that differ in their genetic relatedness or whether field pea genotypic mixtures can offer any productivity and competitive ability advantages has not been reported in the literature.

The focus of this project was to investigate the benefits of growing field pea in two-way genotypic mixtures in which mixtures consist of component genotypes that vary in their relatedness. This project addressed and investigated the following areas:

- The effect of growing field pea in two-way genotypic mixtures on biomass and seed yield, as well as the crop's competitive ability against weeds.
- The effect of genetic relatedness on genotype mixing ability.

This thesis reports two runs of a field experiment conducted at two locations (St. Albert and Lethbridge, Alberta.) for two years (2010, 2011), and two runs of a greenhouse experiment (spring and fall of 2011). We hope that the information and the knowledge derived and presented in this thesis will provide a better understanding of the benefits and the feasibility of growing field peas in mixtures in western Canada.

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CHAPTER 2: LITERATURE REVIEW

2.1 Field Pea (*Pisum sativum* L.) Production

Field pea (*Pisum sativum* L.) is a cool season pulse crop that belongs to the Leguminosae family. Pulses are the edible seeds of legumes such as field peas, beans, lentils, and chick pea (Alberta Agriculture, Food and Rural Development, 2010). The area sown to field peas worldwide in 2011 was estimated to be 6 to 6.6 million ha (FAOSTAT, 2011). It is also one of the most commonly grown pulses in Canada, accounting for 23% of total grain legume production in 2007 (Strydhorst, 2008). Field peas are native to the Middle East, and have been cultivated in Europe for several thousands of years (Agriculture and Agri-Food Canada, 2008).

Field pea is a high-yielding crop and it is considered a major crop in both organic and conventional farming systems (Larsen & Andreasen, 2004). The seed is rich in protein (contains 20-25% crude protein) and it is also considered an excellent source of fibre, carbohydrates, vitamins and minerals. The seed and the biomass of the plant are also used as a protein component of animal feed (Strydhorst et al., 2008a). Vegetative growth of field pea contains high levels of nitrogen, and decomposes quickly relative to other pulse crops, thus releasing nitrogen into the soil (Strydhorst, 2008). As a result, field pea is also grown as a green manure to improve the soil structure, increase the soil organic matter content and to provide nitrogen for the subsequent crop (McCartney & Fraser, 2010).

Field pea plants are of two main types: leafy and semi-leafless (Alberta Agriculture, Food and Rural Development, 2010). The semi-leafless trait tends to improve yield, canopy air and light penetration and resists lodging when compared to leafy type (Wang et al., 2003). Field pea plants normally have a single main stem, although under stressful conditions they may develop several stems, a tap root and a shallow root system. It is estimated that 77 to 85% of the root growth in field pea is located in the 0 to 40 cm depth (Gan et al., 2009), and about 47% of the root biomass is located in the 0 to 10 cm depth (Liu et al., 2011). The majority of the vegetative growth in field peas occurs under cool humid conditions (French, 2004). Although field peas can tolerate low moisture (Agriculture and Agri-Food Canada, 2008), they are very sensitive to drought and high temperatures during the flowering period (Mahieu et al., 2009).

2.1.1 Field Pea in Canada

Field pea production in western Canada has been increasing in the last 30 years (Agriculture and Agri-Food Canada, 2008). In 2009, the area sown to field pea in western Canada increased to1.5 Mha (Statistics Canada, 2010) compared to 1.1 Mha in 2003 (Pulse Canada, 2007). In Alberta, field peas were sown on 323,700 ha in 2009 (Alberta Agriculture and Rural Development, 2010). This rapid growth in field pea area was stimulated by the move towards increasing diversity in cropping systems (Olson et al., 2001) as well as favorable markets (Agriculture and Agri-Food Canada, 2008). Domestic consumption of field peas in Canada was 846,000 tonnes of field pea seed, with significant amounts (1.97 million tonnes of field pea seed) exported to different markets around the world (Pulse Canada, 2007). The largest markets for Canadian field peas are South Asian countries such as India, Bangladesh, and Sri Lanka as well as South and

Central American countries (Pulse Canada, 2007). Canada exported more than $778 million worth of field peas in 2006. The domestic market utilizes approximately 550,000 tonnes of field peas as animal feed, with the rest of the quantity produced is exported to Europe, which is the largest feed market for Canadian field peas (Pulse Canada, 2007).

2.2 The Importance of Field Pea to the Agroecosystem

2.2.1 Field Pea Nitrogen Fixation

One of the significant benefits of growing field peas is that they can add nitrogen, an essential element for plant growth, to the soil. Field peas fix nitrogen by symbiotic nitrogen fixation, which is a relationship between field pea plants and nitrogen-fixing bacteria (*Rhizobium*) in which atmospheric nitrogen (N_2) is reduced to plant available ammonium (NH_3) (Corre-Hellou & Crozat, 2005; Downie, 2005; Heldt & Piechulla, 2011; Rascio & La Rocca, 2008). Some of the nitrogen fixed can be utilized by field peas and the rest can be recycled for the benefit of the subsequent crop in the rotation (Lupwayi & Kennedy, 2007; Soon & Lupwayi, 2008; Stevenson & Van Kessel, 1996; Strydhorst et al., 2008b). Field pea plants have the potential to reduce the use of chemical nitrogen fertilizer because field peas were estimated by Strydhorst (2008) to add between 33 to 246 kg N ha^{-1} yr^{-1}. Maidl et al. (1996) also reported that field peas can add between 215 and 246 kg N ha^{-1} yr^{-1}.

The symbiotic relationship starts when field pea roots excrete flavonoid compounds such as lectin (a galactosamine- binding protein consisting of carbohydrate-binding protein that serves as a source of energy to rhizobium bacteria) under nitrogen-starved conditions (Diaz et al., 1989; Rascio & La Rocca, 2008). Particular forms of lectin compounds attract host-specific rhizobium bacteria. The attracted bacteria infect field pea plant roots that host them, forming nodules where nitrogen fixation occurs (Diaz et al., 1989; D'haeseleer et al., 2010). Mahieu et al. (2009) demonstrated that nodulation is affected significantly by moisture stress. The authors reported that moisture stress caused a reduction in nodule biomass, and a 65% reduction in their nitrogen content.

Nitrogen fixation in field peas is an aerobic process and therefore, oxygen is a key component of the N fixation process (Rascio & La Rocca, 2008). Delivering oxygen to the rhizobium in the nodules is the responsibility of leghemoglobin (Downie, 2005; Rascio & Rocca, 2008). Leghemoglobin (legume hemoglobin) is an oxygen-binding protein that is synthesized in the cytoplasm cells of the field pea plant (Downie, 2005; Rascio & La Rocca, 2008). The formation of leghemoglobin is triggered by the rhizobium located in the legume plant roots (Downie, 2005; Rascio & La Rocca, 2008).

Active nitrogen-fixing nodules in field peas can be recognized when digging up the roots and cutting into one of the nodules to find the red colored protein (leghaemoglobin) (Downie, 2005; Virtanen & Laine, 1946). However, when the color of the protein is green or brown, the nodules are no longer fixing nitrogen (Virtanen & Laine, 1946). This usually happens at the end of the flowering stage in field peas or when field pea plants are suffering from adverse conditions such as drought, disease, or intense weed competition (Virtanen & Laine, 1946).

Several different strains of rhizobium bacteria are found in soils and their populations are usually heterogeneous. Thus, inoculation is recommended to apply the specific strain of rhizobium (*Rhizobium leguminosarum* bivar *viceae*) for optimal field pea N fixation (Rascio & La Rocca, 2008). Rhizobium inoculants are available commercially in different forms including liquid, peat and granular (Clayton et al., 2004). The most commonly used is the granular formulation because it has active rhizobium that can be applied directly to the seeds at seeding time (McVicar et al., 2009). Granular inoculants are also less affected by a dry seedbed or seed treatment fungicides when compared to other forms of inoculants.

2.2.2 Field Pea Improves the Diversity of Crop Rotations

Studies have shown that using diverse crop rotations offers higher crop productivity and more stable farm incomes (Green, 1997; Smith et al., 2008; Zentner et al., 2002). Basic agronomy should be considered carefully when selecting crops for a successful rotation. For example, crops should be assessed for their fertilizer requirements, moisture use efficiency, insect and disease susceptibilities and competitive ability against weeds (Mertens et al., 2002; Zegada-Lizarazu & Monti, 2011).Well-planned crop rotations can help to improve crop productivity, enhance soil fertility and structure, and increase soil beneficial biota (Green, 1997). They can also help overcome some of the problems associated with monocultures (including disease, insect and weed population shifts) by exhibiting diverse life cycles (Zegada-Lizarazu & Monti, 2011). Studies have shown that the maximum benefit of crop rotation was achieved when species diversity increased and the same species in succession was avoided (Smith et al., 2008). Weed populations can be managed by crop rotation by preventing them from becoming uncontrollably large (Bullock, 1992). Managing weed populations by crop rotation can be achieved by crop rotation schemes that make continuous changes to the weed populations and seedbank communities (Blackshaw et al., 2005). Crop rotations are also used as a means to vary the mode of action of herbicides (Jordan & Donaldson, 1996) and consequently, prevent weeds from developing herbicide resistance, which occurs when using the same herbicide mode of action on the same crop (Smith et al., 2008).

Field pea is an important rotational pulse crop in western Canada. Field peas recently have been getting a lot of attention on the Canadian Prairies as farmers who have traditionally used monoculture-based cereal-fallow cropping systems search for alternatives. Farmers are now gradually shifting to legume-based rotations (Lupwayi & Kennedy, 2007; Zentner et al., 2002). This change in the cropping system is motivated by the desire to improve crop productivity and reduce chemical fertilizer input costs and thus, field pea has become a major rotational crop in western Canada (Lupwayi & Kennedy, 2007; Zentner et al., 2002).

Incorporating field peas into crop rotations benefits the subsequent crop in the rotation and consequently, increases yield. For example, in Saskatchewan, the grain yield of wheat in a field pea-wheat-oilseed rotation was 43% greater than in a wheat-wheat-oilseed rotation (Stevenson & Van Kessel, 1996). Only 8% of the yield increase was attributed to nitrogen benefits, with the other 92% attributed to disease and weed suppression. Similarly, grain yield of wheat in Saskatchewan increased by 25% when it was grown on field pea stubble compared to growing wheat on wheat (Miller et al., 2002). Yet another study reported that the grain yield of wheat increased in two of three years (2000 and 2001) by 15.3% and 1.7%, respectively, when grown on field pea stubble compared when grown on its own (Johnston et al., 2005). Miller et al. (2002) reported that field pea increased soil nitrogen by 30-39 kg ha^{-1} at two of the three sites. The same study also reported that the grain yield of wheat following midseason field pea harvest (at early bloom of field pea) was 12% greater than the chemical fallow control. In Germany, winter wheat following field peas also yielded 43% more grain than when it followed oats (Maidl et al., 1996).

One of the rotational non-nitrogen benefits of a field pea crop is reserving moisture for the subsequent crop in the rotation. An Alberta study reported that field pea extraction of soil moisture was normally concentrated between 0 to 0.6 m deep (McKenzie et al., 2004). The moisture deeper than 0.6 m was reserved for the subsequent crop in the rotation. The post-harvest soil moisture content of field pea stubble from 60-120 cm deep was reported to hold 7 mm of water more than that of wheat (Miller et al., 2002).

In spite of the proven benefits of diverse crop rotations, rotations in Alberta have fewer crop components compared to Saskatchewan. Approximately 95% of the seeded land in Alberta in 2011 was occupied by three major crop components: cereals, canola, and tame hay, which accounted for 45.2%, 25.0% and 25.1%, respectively. However, the seeded land in Saskatchewan in 2011 had more component crops included (cereals for 42.5%, canola for 28%, tame hay for

14.6, lentils for 7%, field peas accounted for 4.5% and flaxseed for 1.5%) and more diversified rotations (Statistics Canada, 2011). Increasing crop components in Alberta is essential for better cropping systems and that can be achieved by incorporating more pulse crops like field peas.

2.3 Field Pea Competitive Ability

2.3.1 Crop-Weed Competition

Interference and competition are the most commonly used terms to describe interactions between plants and their neighbors. Most often these two terms are used interchangeably. Interference is defined as the response of plants to presence of neighboring plants (McDonald & Gill, 2009). However, competition is a subset of interference and is defined as the ability of a plant to capture the essential resources for growth such as water, nutrients, and light. It is a measure of how efficiently a plant can convert resources into growth material (McDonald & Gill, 2009). Most plant competition studies focus on negative interference or competition because it describes the competition between plants, which usually causes losses in yield and quality. Competitive ability can be classified into: 1) competitive effect, which is the ability to suppress neighbor growth, and 2) competitive response, or the ability to withstand neighbor suppression (Zhang & Lamb, 2012). The authors also suggested that competitive effect is a general quality of a certain species, but competitive response is a reaction to growth conditions, availability of resources, and the identity of the neighbor plant.

Many studies have attempted to understand plant competition. Scientists have tried to correlate specific traits such as specific leaf area, height, early vigor, seed mass and maturity to plants that are competitive with weeds (Goldberg & Landa, 1991; Jedel et al., 1998; McDonald, 2003; McDonald & Gill, 2009; McPhee & Aarssen, 2001; Monteith, 1977; Westoby, 1998). Plant characteristics like resource acquisition, capturing, and converting ability were also found to influence a plant's ability to compete with weeds (Goldberg & Landa, 1991). Despite strong correlations between these traits and plant's competitive abilities, scientists have found that the interaction between plants and environmental conditions is very significant (Baker, 1977; Jedel et al., 1998; Juskiw et al., 2001; Smithson & Lenne, 1996). For example, water stress and nutrient deficiencies increase competition between plants and can cause considerable changes in competition dynamics.

Competitiveness is often assessed by weed seed and biomass production (above-ground and below ground) relative to crop yield (Aminpanah & Javadi, 2011; Hoad et al., 2008; Mcdonald, 2003; Pridham et al. 2007). When competition is present, there is a consistent inverse relationship between crop and weed yields and thus, stands of poorly competitive crops have more weeds. Pridham et al. (2007) assessed the competitive ability of wheat cultivar mixtures of heritage and modern wheat in Manitoba. The results showed that the weed biomass in competitive cultivar stands was lower than the weed biomass in poorly competitive cultivar stands. Likewise, a study that examined rice competition reported that the cultivar that had the strongest competitive ability (Deylamani) also reduced barnyard grass biomass production significantly (Aminpanah &

Javadi, 2011). Thus, the outcome of competition is that one or both of the plants tends to reduce either the grain yield and /or biomass yield of the other plant.

2.3.2 Field Pea Yield Losses due to Weeds

One of the key challenges that faces field pea production is its poor competitiveness against weeds (Blackshaw et al., 2005; Derksen et al., 2002; Goodwin, 2009; Harker, 2001; Johnston et al., 2002; Johnson & Holm, 2010; Larsen & Andreasen , 2004; Lemerle et al., 2006; McDonald, 2003; Spies et al., 2011; Strydhorst et al., 2008b). In Alberta, field pea crops were found to be associated with several weeds such as chickweed, wild oat, stinkweed, wild buckwheat, Canada thistle, shepherd's purse, cleavers, lambs quarters, field horsetail and hemp nettle (Thomas et al., 1998). When yield losses to weed competition were compared between field pea, barley, oat and canola in Alberta, the reduction in yield of field pea was the greatest of all (Harker et al., 2001). Yield reductions were found in 67% of the sites with field pea compared to 40% of the barley and 27 % of the canola sites (Harker, 2001). It is estimated that field pea yield losses were between 40-70% after full season weed competition (Harker et al., 2001). Similarly, when field pea was grown at 75 plants m^{-2} with barley planted as pseudo-weed at 37 plants m^{-2}, the reduction in yield was 27% (Strydhorst et al., 2008b). Blackshaw et al. (2008) also reported that volunteer barley competition in a field pea crop reduced the yield from 30 to 85%. In Australia, yield losses in field pea competing with ryegrass were estimated to be between 90 to 40 % at the plant densities 10 to 40 field pea plants m^{-2} respectively (Lemerle et al., 2006).

Increasing plant density in field pea is used to improve the crop's competitive ability and as well as to increase yields (Townley-Smith & Wright, 1994). This approach has been proven to be successful by many studies. For example, the results of a study of six, two year field experiments in Alberta from 2004 to 2006 showed a 59% reduction in weed biomass (barley) when field pea density was increased by 2X the recommended planting rate (75 plants m^{-2}) compared with 0.5X (Strydhorst et al., 2008b). In Australia, when the plant density of field pea increased from 10 to 60 plants m^{-2} the losses in yield from annual ryegrass competition were reduced from 70 to 80% to 5 to 50%, respectively (Lemerle et al., 2006). Likewise, a study conducted between 1998 and 2001 in Lacombe, Alberta showed a reduction in weed biomass in 2 of 4 years in both barley and field pea crops when crop target densities were increased (Blackshaw et al., 2005). However, it is critical to choose a field pea planting density that provides better competitive ability with weeds (interspecific competition) without allowing field pea plants to compete with each other for limited resources (intraspecific competition). The optimal plant density usually differs according to the environmental conditions and availability of resources. For example, the recommended field pea plant density is 75 plants m^{-2} in Alberta (Alberta Agriculture and Rural Development, 2010). However, in Saskatchewan it is 88 plants m^{-2} (Saskatchewan Pulse Growers, 2000), while in south Australia the optimal plant densities range from 60 to 100 plants m^{-2} depending on growing season rainfall (McMurray, 2003).

Although increasing field pea plant density can improve the crop's competitive ability, this approach is still not enough to overcome the crop's poor competitive ability and field pea growers are still required to rely heavily on herbicide applications for the crop to be successful (Alberta Agriculture and Rural Development, 2010).

2.3.3 Traits Associated with the Competitive Ability of Field Pea

Understanding the relationship between field pea competitive ability and weeds can benefit growers by improving their ability to control weeds. Scientists have been trying to understand which traits are responsible for /or correlated with field pea competitive ability. Identifying these traits will help plant breeders focus on selecting these traits to produce cultivars with improved competitive abilities and thus, better productivity. This will also give scientists, agronomists and growers a tool to build integrated weed management strategies for better and more successful weed control in the future.

Field pea leaf type

Field pea cultivars have been studied extensively in an attempt to find a relationship between certain traits and competitive ability. For example, a greenhouse experiment in the U.K. was carried out to assess the competitive ability of leafy and semi-leafless field pea cultivars (Semere & Froud-Williams, 2001). The two cultivars were grown with forage maize under two watering regimes: water stress (15% of field capacity) and no water stress (70% of field capacity). The results showed that the leafy field pea was more competitive than the semi-leafless under both watering regimes. In contrast, Martin et al. (1994)

reported that the semi-leafless cultivars are not always weak competitors and competitive ability of field peas is not affected by the semi-leafless structure. Likewise, McDonald (2003) also reported that leaf-type has no effect on field pea's ability to compete with weeds. The field pea root depth of the leafy and semi-leafless cultivars was also studied to assess their ability to root deeper in the soil and capture moisture under drought conditions (Martin et al., 1994). The study showed that the root depths of both field pea types were not significantly different and both the leafy and the semi-leafless roots could not capture soil moisture located below 70 cm, which caused considerable grain yield loss. In addition, field pea competitive ability was not always found to be affected by the plant leaf types.

Field pea vine length

Plant vine length in field peas was investigated in an attempt to see if it is correlated with field pea competitiveness against weeds. Wall and Townley-Smith (1996) reported that field pea genotypes with long vine lengths were more competitive with wild mustard than the short-vined genotypes. Spies et al. (2011) also reported that tall field pea cultivars were found to inhibit weed biomass more that short cultivars and noted that field pea plant vine length was associated with plant competitive ability in a three year field experiment in Saskatchewan. Vasilakoglou and Dhima (2012) reported that the field pea genotype (Olympus) with long vine length had a greater ability to suppress winter wild oat in northern Greece. Likewise, McDonald and Gill (2009) demonstrated that the yields of both tall and short field pea cultivars were found to be affected significantly by ryegrass (*Lolium rigium*) competition when assessed for two years in Australia. However, tall genotypes were estimated to lose approximately 50% of their yield to weeds compared to 70 to 80% in short genotypes. In contrast, Lemerle et al. (2006) reported that short and tall cultivars showed inconsistency in their competitive abilities. Similarly, Grevsen (2003) noted that vine length in field pea was not correlated with competitive ability against weeds.

2.4 Interspecific and Intraspecific Mixtures

Mixtures may be composed of different species (interspecific) or of different cultivars of same species (intraspecific) that vary for many characters like disease resistance, but have sufficient similarity to be grown together (Wolfe, 1985). Growing mixtures is considered a sustainable approach to growing crops, and it is an ideal method for conventional, low-input, and organic growing systems (Helland & Holland, 2001; Jedel et al., 1998; Kaut et al., 2008; Kiaer et al., 2009; Kwabiah, 2004). Mixtures have been suggested to increase biological diversity in the agroecosystem (Kaut et al., 2008; Sarandon & Sarandon, 1995; Smithson & Lenne, 1996) and thus they tend to allow the crop to adjust to varied biotic and abiotic stresses during the growing season (Juskiw et al., 2001; Wolfe, 1985). Mixtures have been also proposed as a practical and inexpensive alternative to monocultures to improve crop yield, disease resistance and competitive ability (Bing et al., 2011; Helland & Holland, 2001; Jedel et al., 1998; Kiaer et al., 2009; Wolfe, 1985). However, for mixtures to be feasible and practical to use by growers, Sage (1971) suggested that mixtures should yield at least as well as the average of the components in monoculture. Researchers have also suggested reconstituting and changing the composition of mixtures on a regular basis to accommodate grower's production needs and to address a field's environmental heterogeneity (Blijenburg & Sneep, 1975; Jedel et al., 1998; Juskiw et al., 2001).

2.4.1 Competitive Ability of Mixtures

A plant's ability to compete for available resources (water, CO_2, light, and nutrients) is a key factor that affects its productivity. For example, the ability of the plant to take up moisture and nutrients from the soil in various conditions and environments and convert these resources efficiently into growth makes them more productive and more tolerant to stress (Stutzel & Aufhammer, 1990). Thus, when a cultivar performs unexpectedly poorly under certain environmental conditions, this poor performance could be attributed to its inability to utilize resources available in the habitat (Stutzel & Aufhammer, 1990).

Crops have different competitive abilities against weeds. For example, field pea is a poor competitor (Blackshaw et al., 2005; Derksen et al., 2002; Goodwin, 2009; Harker, 2001) whereas barley is a strong competitor (Kaut et al., 2008; Harker, 2001). Not only do crops have different competitive abilities, but also cultivars of the same species may differ in their ability to compete with weeds (Kaut et al., 2008; Sarandon & Sarandon, 1995; Smithson & Lenne, 1996).

Competition in mixtures can be classified into two types, intraspecific and interspecific competition (Firbank & Watkinson, 1985; McDonald & Gill, 2009). Intraspecific competition is the competition between mixture components, whereas, interspecific competition is the competition between plant mixtures and neighboring plants such as weeds of different species. Such competition is greatly affected by plant population densities and environmental conditions (McDonald & Gill, 2009). Because plants compete for the same available resources on a per unit area basis, yield is directly affected by the availability of these resources in the habitat (Firbank &Watkinson, 1985). For that reason, when plant densities are low, then competition between plants is low, and vice versa (Firbank &Watkinson, 1985).

Several studies have reported that different species mixtures showed improved competitive abilities against weeds (Gallandt et al., 2001; Jedel et al., 1998; Juskiw, et al., 2001; Rao & Prasad, 1985). The improved competitive ability of mixtures has been attributed to complementary competition (intraspecific competition) between mixture components (Early & Qualest, 1971). Kaut et al. (2008), who studied wheat and spring cereals mixtures, reported that wheat-barley mixtures showed potential weed suppression. Baumann et al. (2001) reported that leek-celery mixtures suppressed weeds and reduced weed seed production in Switzerland. Szumigalski and Van Acker (2005) also reported that wheat-canola mixtures reduced weed biomass at 1% of the sites with no in-crop herbicides application. In Ethiopia, maize-bean mixtures reduced weed biomass by 13% compared to maize monocultures and 30% compared to bean monocultures (Workayehu & Wortmann, 2011).

Improved competitive ability against weeds was also reported by some cultivar mixture studies. Binang et al. (2011) demonstrated that complementarity between a 3:2 rice (Faro 15- a semi-dwarf cultivar and Muduga- a tall cultivar) mixture reduced weed populations by 39.7%. Likewise, complementarity between three-way spring wheat mixture components increased grain yield and reduced genotype by environment interactions (Rao & Prasad, 1985). Gallandt et al. (2001) suggested that mixtures composed of components that had different morphological characteristics showed increased intraspecific competition and as a result, these mixtures suppressed weeds.

In contrast, not all mixtures offered improved competitive ability. A wheat-oriental mustard mixture did not reduce weed biomass in a three site-year field experiment that was carried out on organically managed land in Manitoba (Pridham & Entz, 2008). Organically managed spring wheat cultivar mixtures did not provide weed suppression (Pridham et al., 2007). Two-way winter wheat mixtures also showed no difference in weed suppression when compared to monocultures (Aknada & Mundt, 1997). Similarly, replacement series corn-soybean mixtures did not show greater weed suppression than their components in monoculture even where mixture densities were kept similar to monoculture densities (Gomez & Gurevitch, 1998).

Predicting a mixture's competitive ability based on the components performance in monocultures is not always possible (Akanda & Mundt, 1997; Finckh & Mundt, 1992). Juskiw et al. (2001), who studied competitive ability in different mixtures of small grain cereals, reported that competitive ability depends greatly on the complex interaction between cultivar and the environment, which cannot be always predicted. Moreover, the composition of mixtures changes with time if the same mixtures are grown repeatedly because the competitive ability of components changes with the environmental conditions (Blijenburg & Sneep, 1975).

2.5 Cultivar Mixtures (Intraspecific Mixtures)

2.5.1 Yield Effects of Cultivar Mixtures

Numerous studies have reported that mixtures increased grain yield in different crops. For example, six cultivars of winter wheat and their fifteen possible two-way mixtures yielded 1.5% more than mixture component cultivars that were grown in pure lines (Gallandt et al., 2001). Mahmood et al. (1991) also showed that the grain yield of 68% of two-way mixtures of winter wheat was higher or equal to the grain yield of their components that were grown in monocultures over several years and locations in Texas. Likewise, cultivar mixtures of spring and winter wheat in Germany had 5.1% and 5.7% grain yield advantages over their component cultivars in monocultures (Manthey & Fehrmann, 1993). In Iowa, two and three-way oat cultivar mixtures increased grain yield by 3% (Helland & Holland, 2001). Another study from Iowa reported that the grain yield of oat two-way mixtures was 11% greater than the highest yielding cultivar grown in monoculture (Shorter & Frey, 1979). Sarandon and Sarandon (1995) also reported that the grain yields of two-way mixtures of bread wheat were similar to the highest yielding cultivar components in monocultures, although mixtures exhibited an 8% increase in above-ground biomass.

Despite many studies that have reported the superior performance of cultivar mixtures to that of monocultures, there are several studies that reported mixtures had a little to no-effect on grain yield. For example, Juskiw et al. (2001)

conducted a study from 1992 to 1994 in several locations in Alberta and reported that three-way spring barley cultivar mixtures offered no yield advantages when compared with component cultivars that were grown in monocultures. The same study also reported that the yield of some of these mixtures declined as the ratio of the lower yielding cultivar increased in the mixture. Jedel et al. (1998) also reported that two-way and four-way cultivar mixture yields were intermediate to those of components grown in monocultures. A study from Manitoba also showed that wheat cultivar mixtures did not provide yield advantages over cultivar components grown in monocultures (Pridham et al., 2007). Two-way dry bean cultivar mixtures mixed in different proportions in Colorado showed that mixtures did not offer yield or yield component advantages over monocultures (Riley et al., 1993). The authors noted a lack of morphological and / or phenological differences in the mixture components. Likewise, ten two-way cultivar mixtures of spring wheat mixed in a 1:1 ratio in a greenhouse study in the U.K. showed that eight of the ten mixtures yielded less than their components in monocultures, one mixture was intermediate and only one mixture had 18% more grain yield than monocultures (Cheema et al., 1988).

The literature reviewed shows that the grain yield of cultivar mixtures can be overcompensatory (an indication of synergism between mixture components, which can offer advantages beyond the cultivars individual components abilities when grown in monocultures), neutral (mixture yields similar to components grown in monocultures) or undercompensatory (an indication of antagonism between mixture components, which can cause a yield reduction in the mixture’s overall productivity). Interestingly, the inconsistent performance of mixtures' grain yields was not only observed between mixtures composed of different components, but also between mixtures composed of the same components when grown in different environmental conditions (Jedel et al., 1998; Lee et al., 2006; Mahmood et al., 1991; Manthey & Fehrmann, 1993; Marshall et al., 2009; Sarandon & Sarandon, 1995). This may suggest that the performance of a specific mixture depends on how components interact with each other as well as on how these components interact with the environmental conditions. In general, the performance of cultivar mixtures for grain yield was generally found to range between the average yields of the components and the yield of the higher yielding component.

Interestingly, Sage (1971) concluded that the advantages of mixtures would only be observed when mixtures are grown under adverse environmental conditions. The results of many studies agreed with Sage's (1971) conclusion. For example, Sarandon and Sarandon (1995) reported that bread wheat grown in two-way mixtures with no fertilizer had improved resource complementarity and yielded more biomass than monocultures. A field study investigating two spring wheat cultivars (Neepawas and Pitic 62) in a two-way cultivar mixture (1:1 ratio) and seeded at five seeding rates 40, 115, 190, 265 and 340 seeds m^{-2} showed that under early drought conditions and low seeding rates (40 seeds m^{-2}), 71% of Neepawa plants in the two-way mixture survived compared to only 52% in pure lines (Baker, 1977). The author noted that Neepawa seeded at 40 seeds m^{-2} was able to survive the early drought when it was grown in a mixture with Pitic 62 better than when it was grown in monoculture due to the resource complementarity between components.

2.5.2 Cultivar Mixtures and Disease

Plant diseases can cause devastating reductions in crop yield and quality, especially when diseases infect susceptible cultivars grown in monocultures. In fact, the annual losses from plant diseases have been increasing despite the extensive use of fungicides (Bailey et al., 2003). The reliance on fungicides only to control plant diseases and reduce yield loss is a very risky and expensive choice (Bailey et al., 2003). Scientists suggested that adapting efficient disease management strategies that combine both chemical and cultural practices (Bailey et al., 2003; Finckh & Mundt, 1992; Mille et al., 2006; Wolfe, 1985) can cause substantial improvements in crop production and quality.

Many studies have documented cultivar mixtures as one of the sustainable tools to manage plant diseases in both conventional and organically managed systems (Lopez & Mundt, 2000; Mahmood et al., 1991; Manthey & Fehrmann, 1993). Wolfe (1985) suggested that mixtures composed of genetically diverse components and with different resistance genes can suppress diseases and prevent disease epidemics. In Germany, the effect of two- and three-way spring and winter wheat cultivar mixtures on powdery mildew (*Erysiphe graminis*) was evaluated (Manthey & Fehrmann, 1993). The results showed that disease infection was decreased by 50% in the three-way mixture, which included two resistant cultivars and one susceptible one. The authors also noted that the grain yield advantages over pure lines of the two- and three-way cultivar mixtures were 1%

and 5%, respectively, without fungicide treatments and 0.6% and 1.7% with fungicide treatments. Similarly, the effect of three-way mixtures of winter wheat on leaf rust disease (caused by *Puccinia recondita*) was investigated in Texas (Mahmood et al., 1991). The results showed that mixtures that included one resistant and two susceptible cultivars reduced disease severity by 50% compared to the susceptible cultivars in pure lines. Over four years at five locations of the experiment, 68% of the mixtures had grain yield greater or equal to the mean of the component cultivars in pure lines. In addition, 36% of mixtures had thousand kernel weights greater than the highest thousand kernel weight in pure lines.

Not all cultivar mixtures were successful in reducing disease severity. For example, in California, two fall hard red wheat cultivars that varied in their susceptibility to two diseases (Septoria blotch (*Septoria tritici*) and leaf rust (caused by *Puccinia triticina*)) were combined in two-way cultivar mixtures in order to investigate their effect on foliar disease severity (Jackson & Wennig, 1997). The results showed that mixtures offered limited protection against the two diseases. Similarly, the performance of three-way barley mixtures was evaluated in several locations in Alberta from 1992 to1994 (Juskiw et al., 2001). Disease levels of mixtures were intermediate to the cultivar components in pure stands. Likewise, barley cultivars mixed in two-, and three-way mixtures showed intermediate levels of disease compared to those cultivars grown in pure stands (Jedel et al., 1998). In another experiment in Manitoba, four wheat cultivars were grown in organically managed lands in two-, three-, and four-way cultivar mixtures over three-site-years (Pridham et al., 2007). The authors reported that mixtures did not cause a reduction in foliar diseases when compared with their cultivar components in pure stands.

2.5.3 Predicting and Composing Successful Mixtures

Predicting the performance of cultivar mixtures would definitely facilitate selecting the best components for mixture composition (Lopez & Mundt, 2000). However, making these predictions based on the performance of the components in monocultures is difficult. Many researchers suggested that the productivity of mixtures could be predicted from the yields of the components in monoculture in different environments (Cheema et al., 1988; Early & Qualset., 1971; Gallandt et al., 2001; Helland & Holland, 2001; Riley et al., 1993). However, many other researchers demonstrated that because components grown in mixture usually interact differently compared with when they are grown in monocultures, the performance of mixtures could not be predicted based only on the component's yield when grown in monocultures (Akanda & Mundt, 1997; Baker, 1977; Finckh & Mundt, 1992).

Gallandt et al. (2001) reported that some mixture components tend to promote higher yields than others. However, finding these components is not always possible because it requires detailed information about how these components perform in different environments. When selecting mixture components, many researchers recommend choosing components that have similar agronomic traits such as maturity and quality. It is also important to choose cultivars with a wide range of diversity in their competitive abilities, disease resistance and resource use efficiencies (Gallandt et al., 2001; Jedel et al., 1998; Wolfe, 1985). Root distribution of the mixture components in the soil profile can be a major factor that affects the crop's ability to acquire soil water and nutrients. Sarandon and Sarandon (1995) suggested that combining genotypes that differ in rooting structure and morphological characteristics improved the whole mixture's performance since they acquired soil nutrients from different levels of the soil. Similarly, Liu et al. (2011) demonstrated that mixtures which consist of components that have different rooting depths can capture resources more efficiently and thus, improve yield and productivity. On the other hand, it is also important to carefully examine rooting structure and morphological characteristics of the components to avoid any potential antagonism that would lead to reduced productivity of the whole mixture. Fukai and Trenbath (1993) reported that when a mixture component dominated utilization of the available resources excessively and inefficiently, the productivity of the whole mixture was affected negatively. Competitive ability is another characteristic to look for when selecting between mixture candidates. Willey and Rao (1980) noted that maximum yield advantages in mixtures were achieved when diverse components with different competitive abilities were grown together. Kaut et al. (2008) also suggested that high yield and competitive ability may be considered when selecting mixture components. Similarly, Jedel et al. (1998) noted that the variation in mixture components' competitive abilities, can improve the ability of mixtures to perform better than monocultures in a wide range of environments.

The literature reviewed in this chapter shows that genotypic mixtures have potential for increasing crop productivity, competitive ability and disease tolerance in cereal crops. However, there is no research that has been conducted to investigate the influence of genotypic mixtures on field pea yield or competitive ability. For that reason, this thesis will examine the effect of growing field pea in two-way genotypic mixtures on productivity, the crop's competitive ability against weeds, as well as the effect of genetic relatedness on genotype mixing ability.

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CHAPTER 3: EFFECTS OF GENOTYPIC MIXTURES ON FIELD PEA (*Pisum sativum* L.) YIELD AND COMPETITIVE ABILITY

3.1 Introduction

Canada is the world's major producer of field peas, which is one of the most important rotational crops in western Canada. In 2011, Saskatchewan, Alberta and Manitoba accounted for 63%, 36% and 1%, respectively, of the total Canadian field pea production of 2.1 million tonnes (Canadian Grain Commission, 2011).

Field peas are a desirable crop to grow because they add nitrogen to the soil and increase diversity in the cropping system. However, field pea's poor competitive ability with weeds can cause considerable reductions in the crop's yield and quality (Harker, 2001; Johnston et al., 2002; Lemerle et al., 2006; McDonald, 2003). Because of its improved standabiltiy, the most commonly grown type of field pea is the semi-leafless type. However, the semi-leafless type was noted in many studies to negatively affect crop competitive ability (Semere & Froud-Williams, 2001). The lack of complete ground cover due to the crop's open canopy, especially in the early stages of crop development, allows weeds to heavily infest field pea crops and thus, to compete with the crop aggressively. Martin et al. (1994) noted that the poor competitive ability of field pea could be due to the plant's shallow root system (within the top 70 cm of the soil), which makes the crop less competitive with weeds, especially under drought conditions. Numerous studies have estimated field pea yield losses due to weed competition and have found it to range between 27 and 85% (Harker, 2001; Johnson & Holm, 2010; Larsen & Andreasen, 2004; Lemerle et al., 2006; McDonald, 2003; Spies et al., 2011; Townley-Smith & Wright, 1994). As a result, field pea production depends heavily on herbicide applications to minimize weed competition and thereby produce a high yielding crop.

One of the solutions that may have potential for improving field pea competitive ability is genotypic mixtures. Genotypic mixtures have been proposed as a sustainable alternative to improve crop productivity (Jedel et al., 1998; Kaut et al., 2008; Sarandon & Sarandon, 1995; Shorter & Frey, 1979; Smithson & Lenne, 1996; Wolfe, 1985), because they tend to allow the crop to adjust to varied biotic and abiotic stresses during the growing season (Juskiw et al., 2001; Wolfe, 1985). Several studies have investigated the potential use of genotypic mixtures. Numerous studies have found a small increase in grain yield when mixtures were compared to monocultures. For example, Dubin and Wolfe (1994) reported a 2% increase in grain yield in three-way wheat cultivar mixtures compared with pure lines. Helland and Holland (2001) found that three-way oat cultivar mixtures increased grain yield by 3%. Manthey and Fehrmann (1993) noted that cultivar mixtures of spring and winter wheat had yield advantages ranging from 5.1% to 5.7% over their component cultivars. Likewise, Gallandt et al. (2001) reported that winter wheat two-way mixtures offered a 1.5% yield advantage compared to pure lines, whereas Sarandon and Sarandon (1995) reported that two-way bread wheat mixtures increased the above-ground biomass by 8% compared to pure lines.

The aforementioned studies clearly show that genotypic mixtures can offer improvements in crop competitive ability with weeds, but many other studies also have reported improvements in crop resistance to diseases and reduced disease severity. Manthey and Fehrmann (1993) found that powdery mildew (*Erysiphe graminis*) was reduced by 50% when winter wheat three-way cultivar mixtures included two disease resistant cultivars with one susceptible cultivar. Likewise, Mahmood et al. (1991) reported that a reduction in the leaf rust disease (*Puccinia recondita*) severity of winter wheat mixtures increased yield by 32% when mixtures included two cultivars with moderate resistance and one that was susceptible. Mundt et al. (1995) also reported that barley mixtures composed of resistant and susceptible cultivars reduced the scald (*Rhynchosporium secalis*) and net blotch (*Pyrenophora teres*) disease severities by 12% compared to pure lines.

To constitute a successful genotypic mixture, mixture components need to be compatible so that they can interact positively with each other. For example, complementarity between genotypes in a mixture may occur because of the reduced level of intraspecific (within species) competition, which can improve the components' ability to compete against weeds (Didon & Rodriguez, 2006). In contrast, the productivity of the whole mixture can be affected negatively if one component can dominate utilization of the available resources excessively and inefficiently (Fukai & Trenbath, 1993). Many studies have reported that cultivar mixtures were able to use available resources more efficiently than those cultivars that were grown in monoculture (Jedel et al., 1998; Sarandon & Sarandon, 1995). In contrast, other studies reported that mixtures did not provide any yield advantages over monocultures (Juskiw et al., 2001; Pridham et al., 2007; Revilla-Molina et al., 2009). No information exists on how field pea genotypic mixtures affect yield, productivity or competitive ability. However, there could be substantial benefits to mixtures both in the presence or absence of weed competition. Therefore, the objectives of the present study were to determine the effect of field pea genotypic mixtures, differing in genetic relatedness, on crop competitive ability and weed suppression.

3.2 Materials and Methods

Field studies were conducted at two locations in Alberta (St. Albert and Lethbridge) in 2010 and 2011. Soil at the St. Albert site had a pH of 7.4, organic matter content ranged between 10.8 and 13.3 % and soil electric conductivity (EC) was between 0.51 to 0.56 dS m^{-1} (0-15 cm depth). The Lethbridge site had a pH of 7.8, organic matter content between 3.8 and 4.2 % and soil electric conductivity (EC) between 0.5 to 0.6 dS m^{-1} (0-15 cm depth) (Table 3.1).

Four semi-leafless field pea genotypes were selected for this study on the basis of pedigree: two sister lines (CDC1897-3 and CDC1897-14), one common parent (Eclipse) (one quarter of the pedigree CDC1897-3 and CDC1897-14 is Eclipse) (T. Warkentin, personal communication, 2013) and one distantly-related genotype (SW Midas). Genotypic mixtures consisted of the six possible 50:50 mixture combinations of the four genotypes, as well as the four genotypes growing in monoculture (Table 3.2). The substitutive equal proportions design in which mixtures and monocultures have the same density (n) and each mixture component has a density of ($n / 2$) was used as a mixing technique (Harper, 1977). Seeding rates were calculated based on germination tests to achieve a target plant population of 75 plants m^{-2}, which is the recommended field pea target plant population in Alberta (Alberta Agriculture and Rural Development, 2011).

The experimental design was a strip-plot arrangement of a randomized complete block design, with four replications (5 x 2 m) per treatment. Each block was divided into two strips, with one strip (half of each block) being weedy and the other strip (half of block) kept weed-free. Sub-plots consisted of field pea genotypic mixtures and monocultures. To ensure uniform weed competition, the weedy portion of each block was cross-seeded with 'CDC Cowboy' barley (*Hordeum vulgare* L.) immediately prior to field pea seeding at a target plant population of 30 plants m^{-2}. Barley was used as a pseudo weed because volunteer barley is a common weed in field pea crops in Alberta (Strydhorst et al., 2008). The presence and absence of the pseudo weed (called weedy and weed-free stands hereafter) were used to compare the competitive abilities of field pea mixtures and monocultures to weeds.

Metalaxyl-M 1.10% and fludioxonil 0.73% fungicides were used as a seed treatment and applied prior to seeding at a rate of (325 mL / 100 kg seed). Field pea was seeded into oat stubble with a plot seeder equipped with hoe openers spaced at 20 cm at St. Albert in 2010 and 2011. At Lethbridge, field pea was seeded into wheat stubble in 2010 and barley stubble in 2011. The plots were 6 m by 2 m with 2 m alleys. Granular field pea inoculant (*Rhizobium leguminosarum* biovar *viceae*) was applied at seeding at the manufacturer's recommended rate of 5.3 kg ha^{-1}. All plots received seed-placed phosphate (30 kg ha^{-1}) at St. Albert and side-banded phosphate (25 kg ha^{-1}) in Lethbridge. Fertilizer applications at both sites were based on the soil test recommendations.

Prior to seeding, glyphosate was applied at 900 g a.e. ha^{-1} to control emerged weeds. After field pea emergence and at the 1- 4 true-leaf stage, weed-free stands received an application of sethoxydim (450g/L) at a rate of 211g a.i. ha^{-1} in combination with (imazamox 35% + imazethapyr 35%) at a rate of 22.6 g a.i. ha^{-1} plus Merge adjuvant at 0.1% v/v. Weedy stands received an application of imazethapyr (240 g/L) at a rate of 48 g a.i. ha^{-1} + adjuvant (Merge®) at rate of 0.25 % of total spray volume in an attempt to remove all weeds except barley (pseudo weed) (Table 3.3). To control foliar diseases at all site-years of this experiment, pyraclostrobin was applied twice to field pea at flowering and two weeks after flowering at a rate of 99 g a.i ha^{-1}. Plots were desiccated at field pea physiological maturity with glyphosate at 900 g a.e. ha^{-1} plus carfentrazone-ethyl at 18 g a.i ha^{-1} and harvested with a plot combine.

Stand establishment counts for both field pea and barley were performed 14 days after emergence. The number of field pea plants in 2, 1- m rows was assessed at two random locations in each plot. Barley plants were counted at two random locations using two 0.25 m^2 quadrats. Field pea and barley above ground biomass were collected from each plot at early pod filling of field pea by cutting plants in 2, 1- m rows at the soil level in both weedy and weed-free stands. Samples collected from weedy plots were separated by species, placed in paper bags, dried at 60ºC for 72 hours, and weighed. Due to a lack of barley stand establishment, above-ground biomass and barley grain yields could not be assessed at St. Albert in 2011.

Prior to fungicide applications, foliar leaf diseases of field pea were assessed by randomly selecting five leaves on each of five plants when 10% or more of the plants exhibited greater than 20% visual leaf disease. This occurred only the St. Albert site in 2010 and 2011 as very little disease pressure existed at the Lethbridge site. The leaves of each plant were placed in separate envelops and transported back to the laboratory where they were scanned by a computer image scanner. The images were saved with a unique code that describes the site name and plot number. All images were assessed by Assess 2.0 software (Lamari, 2008), which identifies lesions based on their color degree differences in the image and calculates the total disease lesion area relative to the total leaf area.

Vine length was measured at the late podding stage of field pea by measuring the extended vine lengths of five individual plants of field pea, as well as the height of five individual plants of barley. Stand ability of mixtures and pure lines was also assessed by visually rating field pea plants in weed-free stands only, using a 1-9 scale (1= erect, 9 = flat) (Alberta Pulse Growers, 2001). All plots (5 x 2) were harvested with a Wintersteiger plot combine. Seed samples were dried to below 16% moisture for uniformity, cleaned and weighed. Sieves were used to separate barley from field pea seeds. Thousand seed weight (TSW) of field pea and barley was determined by counting 250 seeds and multiplying by a factor of four.

To determine whether mixtures would affect dehulling procedures, field pea seeds of all genotypic compositions grown in weed-free stands were dehulled using a mechanical dehuller. Five hundred gram subsamples were taken from each of the four reps at both sites in 2010 and mixed together to form one composite sample. From this composite sample a single 500 g subsample was taken and cleaned of chaff and cracked seeds. Samples were then weighed before being processed with a Strong-Scott 17810 dehuller, and were then weighed again after processing.

3.3 Statistical Analysis

Data were initially tested to ensure that they conformed to the assumptions of analysis of variance (ANOVA). Normality of residuals was assessed with the Shapiro-Wilk test in PROC UNIVARIATE (SAS Inst., 2009), with homoscedasticity evaluated in PROC GLM (SAS Inst., 2009) using Levene’s test. All data conformed to the assumptions of ANOVA and no transformations were required.

Genotypic composition, competition (the presence or absence of pseudo-weed competition) and their interaction were considered fixed effects. Site-year, replication and their interactions with treatment and competition within a strip plot analysis of variance were considered random. Because the ANOVA analysis indicated that site-year and site-year x genotypic composition effects were significant ($P \leq 0.05$) for several variables (Table 3.4), data were analyzed within site-years. Data were subjected to a strip-plot ANOVA using PROC MIXED (Littell et al., 2006). Mean were separated using Fisher’s protected LSD with treatment effects declared significant at $P \leq 0.05$. Single degree of freedom contrasts were used to make specific comparisons between different mixture treatments as well as between mixtures and their mid-component average (the average of mixture components grown as monocultures).

3.4 Results

3.4.1 Field pea Above-Ground Biomass

The effects of genotypic composition, weed competition, and their interaction varied among different site-years of this study. ANOVA analysis at Lethbridge in 2010 showed that the effect of weed competition was significant, while the effect of genotypic composition was not (Table 3.5). Because the interaction of genotypic composition x weed competition was significant at this site-year (Table 3.5), the biomass averages of the genotypic compositions were analyzed within competition treatments (weed-free and weedy) (Table 3.6). Differences at this site-year were only detected in weedy stands where the Eclipse monoculture treatment yielded 47% (2432 kg ha^{-1}) more biomass than the distantly-related mixture of Eclipse x Midas (Table 3.6). The sister lines (CDC1897-3 x CDC1897-14) mixture was the highest yielding biomass mixture at this site-year (Table 3.6).

Contrasts showed that the distantly-related mixture (Eclipse x Midas) yielded less than the mid-components average (the average of the respective components when grown in monocultures) by 28% (1993 kg ha^{-1}) (Table 3.6). Moreover, the CDC1897-3 x CDC1897-14 (sister lines) mixture produced significantly more 43% biomass than the Eclipse x Midas mixture (Table 3.6). No other statistically significant differences were found at this site-year.

At Lethbridge in 2011, the effect of weed competition on field pea biomass was also significant (Table 3.5). Weed (barley) competition reduced the total field pea biomass by 48% (4916 kg ha^{-1}) at this site-year (Figure 3.1-A). However, the effects of genotypic composition and the genotypic composition x weed competition interaction were not significant (Table 3.5). The biomass of mixtures at this site-year was within the range of their respective components regardless of weed competition. Similarly, no significant differences were found at St. Albert in 2010 (Table 3.5).

3.4.2 Field Pea Seed Yield

At Lethbridge in 2010, the main effects (genotypic composition and weed competition) and the interaction between genotypic composition x weed competition on seed yield were significant (Table 3.5). Hence, the seed yield data was analyzed within weedy and weed-free stands (Table 3.6). In weedy stands, the seed yield data showed that CDC1897-3 yielded 17% (479 kg ha^{-1}) more seed than the distantly related mixture (Eclipse x Midas), whereas the seed yield of Eclipse was intermediate to all other monocultures and mixtures at this site-year (Table 3.6). The sister lines mixture (CDC1897-3 x CDC1897-14) was the highest yielding mixture at this site-year (3559 kg ha^{-1}) (Table 3.6). In addition, contrasts showed that the sister lines mixture (CDC1897-3 x CDC1897-14) yielded 30% (816 kg ha^{-1}) more seed than the distantly-related mixture (Eclipse x Midas) in weedy stands (Table 3.6).

At Lethbridge in 2011, the effects of genotypic composition and weed competition were significant for field pea seed yield, but the interaction of these two factors was not (Table 3.5). Not surprisingly, competition from the pseudo-weed (barley) caused a 58% (1969kg ha^{-1}) reduction in field pea seed yield compared to yields under weed-free conditions (Figure 3.1-B). Similar to the results in 2010, CDC1897-3 once again had the highest seed yield (3543 kg ha^{-1}), while Eclipse yielded the least (1744 kg ha^{-1}) (Table 3.7). Yield of mixtures at this site-year were intermediate to their respective components grown in monocultures (Table 3.7). Interestingly, mixtures including CDC1897-3 (CDC1897-3x CDC1897-14, CDC1897-3 x Eclipse, and CDC1897-3x Midas) tended to yield more than mixtures that did not include CDC1897-3 (Table 3.7), which may indicate that the seed yield of mixtures at this site-year was mainly driven by the inclusion of the highest yielding genotype, CDC1897-3. Contrasts showed that the sister lines mixture (CDC1897-3 x CDC1897-14) yielded 51% (987 kg ha^{-1}) more seed than the distantly-related genotypic mixture (Eclipse x Midas), 30% (665 kg ha^{-1}) more seed than the average yields of both the CDC189-3 x Eclipse and CDC1897-14 x Eclipse mixtures, and 27% (626 kg ha^{-1}) more than the average yields of the CDC1897-3 x Midas and CDC1897-14 x Midas mixtures (Table 3.7).

At St. Albert in 2010, the main effects of genotypic composition, weed competition and their interaction were not significant for field pea seed yield (Table 3.5).

3.4.3 Field Pea Vine Length

In this study, significant differences in vine lengths were only detected at Lethbridge in 2011 (Table 3.5). Genotypic composition had a significant effect on field pea vine length, whereas weed competition and the interaction of genotypic composition x weed competition were not significant (Table 3.5). Of the monocultures, the sister line genotypes CDC1897-3 and CDC1897-14 were significantly taller than Eclipse and Midas (Table 3.7). For mixtures, however, CDC1897-3 x CDC1897-14 and CDC1897-3 x Midas had the longest vine length in this site-year (Table 3.7). Contrasts showed that the vine lengths of the sister lines (CDC1897-3 x CDC1897-14) mixture exceeded by 9 cm the average of all other mixtures grown at this site-year combined (Table 3.7). In addition, the average vine length of CDC1897-3 x CDC1897-14 was 16 cm longer than Eclipse x Midas vines, 8 cm taller than the average of CDC1897-3 x Eclipse and CDC1897-14 x Eclipse vines, and 8 cm taller than the average of CDC1897-3 x Midas and CDC1897-14 x Midas vines (Table 3.7).

The main effects of genotypic composition, weed competition and their interaction on field pea vine lengths were not significant at either of St. Albert in or Lethbridge in 2010 (Table 3.5).

3.4.4 Field Pea Thousand Seed Weight (TSW)

At St. Albert in 2010, genotypic composition, weed competition, and their interaction (genotypic composition x weed competition) were found to significantly affect TSW (Table 3.5). However, the differences in the TSW were only detected in the absence of weed competition (weed-free stands) (Table 3.8). In weed-free stands at this site-year, the TSW of the Eclipse monoculture (239 g) was significantly greater than CDC1897-3 (200 g), CDC1897-14 (192 g), and Midas (202 g) (Table 3.8). Mixtures including Eclipse generally had a higher

TSW than all other mixtures not containing it (Table 3.8). Contrasts showed that the TSW of CDC1897-3 x CDC1897-14 was significantly lower (7%) than that of Eclipse x Midas (Table 3.8).

Similar to St. Albert 2010, the effects of genotypic composition, weed competition, and their interaction (genotypic composition x weed competition) were found to significantly affect the TSW of field pea at Lethbridge in 2010 (Table 3.5). ANOVA analysis showed that in weed-free stands, Eclipse had the highest TSW of the monocultures (262 g), and it was significantly higher than CDC1897-3 (242 g), CDC1897-14 (234g), and Midas (228) (Table 3.6). In addition, CDC1897-3 x Eclipse had the highest TSW of 257 g (Table 3.6). In weedy stands, however, the Eclipse monoculture had the lowest TSW (227 g) of all monocultures (Table 3.6). Under these conditions, the CDC1897-3 x Eclipse mixture also had the highest TSW (251 g) of the mixtures (Table 3.6).

Comparisons of the mixtures at Lethbridge in 2010 showed that in weed-free stands, the TSW of the distantly related mixture (Eclipse x Midas) was significantly (3%) lower than the average TSW of the components grown in monocultures. Also, the TSW of CDC1897-3 x CDC1897-14 (the sister lines mixture) was significantly (4%) lower than the average of both of the CDC1897-3 x Eclipse and CDC1897-14 x Eclipse mixtures combined. However, in weedy stands, CDC1897-3 x Eclipse was the only mixture to have a higher TSW than its mid-components average in monocultures (Table 3.6). In fact, most mixtures grown in weedy stands at this site-year had lower TSW than when grown in weed-free stands (Table 3.6), indicating that weed competition influenced TSW.

At Lethbridge in 2011, the main effects of genotypic composition and weed competition on field pea TSW were significant, whereas the interaction between them was not (Table 3.5). Weed competition was found to significantly reduce the total TSW of all genotypic compositions by 4% (9 g) at this site-year (Figure 3.1-C). The Eclipse monoculture once again had the highest TSW of monocultures (246 g) and it was significantly greater than CDC1897-3 (213 g), CDC1897-14 (204 g) and Midas (209g) (Table 3.7). Contrasts showed that there were significant reductions in the TSW of mixtures when compared to their mid-components average in monocultures at Lethbridge in 2011. Reductions in the TSW of mixtures compared to their mid-components average were 5% (11 g) for CDC1897-3 x Eclipse, 6% (13 g) for CDC1897-14 x Eclipse, and 4% (9 g) for Eclipse x Midas (Table 3.7). In addition, the TSW of CDC1897-3 x CDC1897-14 was reduced by 6% (12 g) when compared to the Eclipse x Midas mixture, and by 4% (9 g) when compared to both the CDC1897-3 x Eclipse and CDC1897-14 x Eclipse mixtures average combined (Table 3.7).

3.4.5 Field Pea Foliar Disease Rating, Standability and Dehulling

For foliar disease rating, the data was negligible for this study due to insufficient disease severity. Field pea standabiltiy data showed that there were no significant differences between mixture compositions in the absence of weed competition and all field pea entries’ average standabilties fell around 4 on a 1-9 scale. Dehulling numerical data showed differences between genotypic compositions, which implies that the seed coat of field pea did not differ when mixtures were compared to monocultures (Appendix I).

3.4.6 Pseudo-Weed Variables

Pseudo-weed (barley) above-ground biomass

Field pea genotypic composition significantly affected barley biomass at Lethbridge 2010 (Table 3.9). Eclipse had the lowest competitive ability compared to the other monocultures as barley biomass produced in Eclipse stands was significantly higher (3917 kg ha^{-1}) than that produced in CDC1897-14 (1949kg ha^{-1}), with CDC1897-3 (2744 kg ha^{-1}) and Midas (2754 kg ha^{-1}) exhibiting intermediate above-ground biomass weights (Table 3.10). Contrasts showed that there was 36% (1014 kg ha^{-1}) less barley biomass produced when barley competed with mixtures compared to monocultures (Table 3.10). In addition, when the barley biomass in CDC1897-3 x Eclipse, CDC1897-14 x Eclipse, and Eclipse x Midas mixtures were compared to the respective mid-components average in monocultures, the biomass produced in the mixtures was 41%, 54%, and 50% lower, respectively (Table 3.10). However, barley biomass in the CDC1897-3 x CDC1897-14 (sister lines), CDC1897-3 x Midas, and CDC1897-14 x Midas mixtures was not significantly different than the respective mid-components average in monocultures (Table 3.10).

At St. Albert in 2010, the main effect of genotypic composition did not significantly affect barley biomass (Table 3.9). Only one significant contrast was detected at St. Albert in 2010, and it was the CDC1897-3 x Eclipse mixture, which suppressed barley biomass by 61% (831 kg ha^{-1}) when compared to the components in monocultures (Table 3.10). Field pea genotypic composition also did not significantly affect barley biomass at Lethbridge in 2011 (Table 3.9).

Pseudo-weed (barley) seed production

The effect of genotypic composition on barley seed production was significant at Lethbridge in both years (2010 and 2011) (Table 3.9). Similar to the barley biomass data, Eclipse was the worst competitor of the monocultures at Lethbridge in 2010 (Table 3.10). Barley seed production in Eclipse (1309 kg ha^{-1}) and Midas (1032 kg ha^{-1}) monoculture stands was significantly higher than the barley seed produced in CDC1897-3 (564 kg ha^{-1}) and in CDC1897-14 (448 kg ha^{-1}) monoculture stands (Table 3.10). Interestingly, contrasts showed that mixtures significantly reduced barley seed production by 41% (344 kg ha^{-1}) compared to that of monocultures (Table 3.10). Of the mixtures, CDC1897-3 x Eclipse suppressed seed production by 47% (344 kg ha^{-1}), CDC1897-14 x Eclipse by 56% (490 kg ha^{-1}), CDC1897-14 x Midas by 44% (326 kg ha^{-1}) and Eclipse x Midas by 44% (518 kg ha^{-1}) compared to their respective components in monocultures (Table 3.10). CDC1897-3 x CDC1897-14 and CDC1897-3 x Midas were the only mixtures that showed no differences in barley seed production when compared to their respective mid-components average in monocultures at this site-year (Table 3.10).

At Lethbridge in 2011 the only significant effect on pseudo-weed (barley) seed production was that of CDC1897-3 x Eclipse. The amount of barley seed produced in this mixture was the lowest at this site-year, significantly lower than other genotypic mixtures. No differences were detected in barley seed production between monocultures (Table 3.10). Nevertheless, contrasts at Lethbridge in 2011 showed that CDC1897-3 x Eclipse suppressed barley seed production by 61%

(391 kg ha^{-1}) compared to the mid-components average in monocultures (Table 3.10).

Genotypic composition did not significantly affect barley seed production (Table 3.9) at St. Albert in 2010.

3.5 Discussion

The majority of the variables measured in this study were found to vary between site-years in this experiment. It is possible that differences occurred due to wide variations in soil properties and environmental conditions between the two sites and years (Tables 3.1 and 3.11). For example, organic matter content of the soil at St. Albert (10.8-13.3%) was approximately three-fold greater than it was at Lethbridge (3.8-4.2%). Precipitation events also differed during the growing seasons at different sites and even at the same site in different years (Figure 3.2 and 3.3).

The ability of mixtures to improve field pea competitive ability over monocultures was only observed in one (Lethbridge 2010) of the three site-years in which this study was conducted. In this site-year, there was 36% (1014 kg ha^{-1}) less weed biomass and 41% (344 kg ha^{-1}) less weed seed produced when barley (pseudo-weed) competed with mixtures as compared with monocultures (Table 3.10). These results agree with Jedel et al. (1998), who reported that two- and three- way mixtures showed improvements in a barley crop's ability to compete with weeds. Interestingly, at Lethbridge in 2010, field pea experienced more adverse growing conditions compared to those in the other site-years of this study. This site-year received the highest rainfall (246 mm) between May and June

(Figure 3.2) which resulted in a very wet site. In addition, the data showed that barley (pseudo-weed) biomass produced in the four field pea monocultures at this site-year was the highest (11,364 kg ha^{-1}) indicating that barley grew vigorously under these wet conditions (Table 3.10). Adverse conditions (Figure 3.2) may have contributed to the mixtures showing improved competitive ability at Lethbridge in 2010, but not at any of the other sites. Similar observations were also reported by Peltonen-Sainio and Karjalainen (1991), who found that two- and three-way oat cultivar mixtures yielded more grain than monocultures when they were grown under adverse conditions, whereas the same mixtures were intermediate to their components in monocultures when grown under optimal conditions. Likewise, Bechere et al. (2008) demonstrated that two-way cotton mixtures showed better adaptability to stressful conditions compared with their components grown in monocultures.

Of all the mixtures included in this study, CDC1897-3 x Eclipse was the only mixture to consistently suppress the pseudo-weed in different site-years. Compared to the components grown in monoculture, CDC1897-3 x Eclipse was able to suppress pseudo-weed biomass by 61% (831 kg ha^{-1}) at St. Albert in 2010, and by 41% (1372kg ha^{-1}) at Lethbridge in 2010 (Table 3.10). In addition, this mixture suppressed pseudo-weed seed production by 41% (442 kg ha^{-1}) at Lethbridge (2010), and by 61% (391 kg ha^{-1}) at Lethbridge (2011). Although CDC1897-3 x Eclipse exhibited better competitive ability than the monocultures, it did not result in significant increases in field pea seed or biomass yields (Tables 3.6 and 3.7). This suggests that even though a mixture is highly competitive with weeds, it does not always translate into significant increases in seed or biomass yields. This is in agreement with Juskiw et al. (2000) who reported that improved competitive ability did not always lead to high yield potential. The authors noted that although the triticale cultivars Seebe and Wapiti both had similar biomass production, Seebe was found to be more competitive than Wapiti. In the current study, seed yields of mixtures generally fell between the highest-yielding monoculture (CDC1897-3) and the lowest-yielding monoculture (Eclipse), regardless of weed competition (Table 3.7). These results are congruent with the findings of Juskiw et al. (2001), who reported that the yields of three-way barley mixtures were not significantly different than the mid-components average in monoculture, and fell between the highest yielding monoculture Tukwa and the lowest yielding monoculture Abee.

Results from the current study also showed that genetic relatedness of the mixture components did not appear to affect the yield or competitive ability of mixtures (Tables 3.6, 3.8, and 3.10). None of the mixtures (either the closely-related or distantly-related components) produced more seed or biomass yield than the mid-components average (Tables 3.6 and 3.8). For mixtures to offer yield advantages, Sarandon and Sarandon (1995) suggested that the genotypes combined in mixtures must differ in rooting structure and morphology so that they complement each other and thus improve the whole mixture's performance. The four field pea genotypes chosen for this study generally had few differences in their morphological characteristics (vine length, height, and standabiltiy) (Tables 3.6 and 3.8). This may be one of the reasons that genotype complementarity did not occur, as evidenced by the fact that the yield of mixtures was intermediate to those of components grown in monocultures. We did not, however, investigate root morphology in this study and it is likely that because several highly related genotypes were chosen, few differences would have existed in their rooting morphology. In addition, we only studied two-way mixtures, but many studies have previously reported that using mixtures composed of more than two components demonstrated improved performance and offered greater advantages. For example, Mundt and Browning (1985) suggested that growing complex mixtures (composed of more than two components) offers more advantages compared to simple mixtures (two-way mixtures). More recently, Mahmoud et al. (1991) reported that three-way winter wheat mixtures yielded better than two-way mixtures. Newton et al. (2012) found that complex mixtures of winter barley complex mixtures (composed of three and four components) had 32% less disease than simple mixtures (two-way).

The Eclipse monoculture consistently produced the highest TSW of the genotypes studied (Tables 3.6, 3.7, and 3.8). In addition, the mixture of CDC1897-3 x Eclipse had the highest TSW at Lethbridge in 2010 regardless of weed competition (Table 3.7). A strong correlation has been established between high TSW and high grain yield in a number different crops including reed canarygrass (*Phalaris arundinacea* L.) (Sahramma & Jauhiainen, 2003), safflower (*Carthamus tinctorius* L.) (Bidgoli et al., 2006), and faba bean (*Vicia faba* L.) (Tadesse et al., 2011). Our results contrast with these studies as we observed that the monoculture with the highest TSW (Eclipse) did not always have higher seed yields. Furthermore, even mixtures that consistently had a lower TSW than their mid- components average (Tables 3.6, 3.7 and 3.8) did not show a significant relationship between the TSW and seed yield. These results agree with the findings of Morrison et al. (2000), who reported that there was no relationship between seed weight and yield of short-season soybean *(Glycine max* L.*)*. Likewise, Khan et al. (1992) reported that there was no relationship between (*Brassica juncea* L.) TSW and grain yield.

3.6 Conclusions

This study revealed that genotypic mixtures improved field pea competitive ability only in one site-year (Lethbridge in 2010). Mixtures at Lethbridge in 2010 had 36% (1014 kg ha^{-1}) less weed biomass and 41% (344 kg ha^{-1}) less weed seed production than monocultures. CDC1897-3 x Eclipse (the common parent) was the most consistent mixture to suppress the pseudo-weed (barley), causing a reduction in barley biomass and seed production compared to their respective components monocultures at Lethbridge 2010 and Lethbridge 2011, respectively. Field pea seed yield and biomass of mixtures were intermediate to monocultures either in the presence or the absence of weed competition in nearly all site-years studied. Although mixtures demonstrated the potential to improve field pea competitive ability, they had no significant effect on competitive ability in three of the three site-years over which the study was conducted. Nevertheless, some mixtures did improve yield and competitive ability over poorly competitive genotypes in monoculture. In this case, if field pea farmers grow a poorly competitive genotype, growing a genotypic mixture may be used to improve competitive ability. However, more studies are required to develop selection criteria for mixture components to help growers compose successful mixtures that suit their needs.

Table 3.1 Soil test results at St. Albert and Lethbridge, Alberta, in 2010 and 2011.

	St. Albert		Lethbridge	
Soil properties	2010	2011	2010	2011
	0-15 cm	0-15 cm	0-15 cm	0-15 cm
pH	7.4	7.4	7.8	7.8
Nitrate (mg kg^{-1})	18.0	16.0	3.0	3.5
Phosphorous (mg kg^{-1})	51.0	50.0	54.5	144.4
Potassium (mg kg^{-1})	200.0	324.0	534.7	866.6
Sulfur (mg kg^{-1})	11.0	8.0	7.1	5.1
Organic matter (%)	10.8	13.3	3.8	4.2
E.C (dS m^{-1})	0.51	0.56	0.50	0.60

Table 3.2 Treatment list of field experiments at St. Albert and Lethbridge, Alberta, in 2010 and 2011.

Genotypic composition			Mixture ratio [a]	Competition treatment
CDC1897-3			Monoculture	Weedy
CDC1897-14			Monoculture	Weedy
Eclipse			Monoculture	Weedy
Midas			Monoculture	Weedy
CDC1897-3	X	CDC1897-14	50:50	Weedy
CDC1897-3	X	Eclipse	50:50	Weedy
CDC1897-3	X	Midas	50:50	Weedy
CDC1897-14	X	Eclipse	50:50	Weedy
CDC1897-14	X	Midas	50:50	Weedy
Eclipse	X	Midas	50:50	Weedy
CDC1897-3			Monoculture	Weedfree
CDC1897-14			Monoculture	Weedfree
Eclipse			Monoculture	Weedfree
Midas			Monoculture	Weedfree
CDC1897-3	X	CDC1897-14	50:50	Weedfree
CDC1897-3	X	Eclipse	50:50	Weedfree
CDC1897-3	X	Midas	50:50	Weedfree
CDC1897-14	X	Eclipse	50:50	Weedfree
CDC1897-14	X	Midas	50:50	Weedfree
Eclipse	X	Midas	50:50	Weedfree

[a] Mixtures were composed on a seed number basis to achieve a standard seeding rate of 75 seeds m^{-2}.

Table 3.3 Date of herbicide applications at St. Albert and Lethbridge, Alberta, in 2010 and 2011.

Stands	Chemical	St. Albert		Lethbridge	
		2010	2011	2010	2011
All stands	Pre-burn application : Glyphosate at a rate of 900 g a.e. ha^{-1}	May-19	May-10	May-03	May-06
Weedy stands	Imazethapyr(240 g/L) at 48.0 g a.i. ha^{-1}	Jun-19	NA	Jun-15	Jun-20
Weed-free stands	Sethoxydim(450 g/L) at 211g a.i. ha^{-1}+ (Imazamox 35%+ Imazethapyr 35%) at 22.6 a.i. ha^{-1}	Jun-19	NA	Jul-06	Jun-20

NA: Not applicable (weedy stands were not present at St. Albert in 2011 site-year).

Table 3.4 *P*-values derived from analysis of variance for field pea seed yield, above-ground biomass, vine length (VL), thousand seed weight (TSW), and standabiltiy at St. Albert and Lethbridge, Alberta, in 2010 and 2011.

Source	Yield	Biomass	VL	TSW	Standability
	P-values				
Site-year (SY)	< 0.0001***	< 0.0001***	0.0009***	< 0.0001***	0.3343
Genotypic composition (G)	0.0096**	0.1209	0.0003***	0.0005***	0.4541
Competition (C)	< 0.0001***	0.0073**	0.0183*	0.0955	0.0942
G X C	0.0068**	0.9859	0.2359	0.0492*	0.6731
SY X G	0.0006***	0.0213*	0.0179*	0.0005***	0.0598
SY X C	< 0.0001***	0.0003***	0.0002***	< 0.0001***	0.0910
SY X C X G	0.1312	0.0875	0.0931	0.0003***	0.2025

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

Table 3.5 *P*-values derived from analysis of variance of field pea seed yield, above-ground biomass, vine length (VL) and thousand seed weight (TSW) based on site-years (St. Albert 2010, Lethbridge 2010 and Lethbridge 2011).

Site-year	Yield	Biomass	VL	TSW
	P-values			
St. Albert 2010				
Genotypic composition (G)	0.0711	0.1664	0.7006	0.0002***
Competition (C)	0.4435	0.8776	0.4857	0.0026**
G x C	0.9065	0.3449	0.6409	0.0044**
Lethbridge 2010				
Genotypic composition (G)	0.0283*	0.3385	0.1569	0.0001***
Competition (C)	0.0078**	0.0013**	0.2190	0.0048**
G x C	0.0230*	0.0217*	0.0597	0.0001***
Lethbridge 2011				
Genotypic composition (G)	0.0001***	0.3657	0.0007**	0.0001***
Competition (C)	0.0001***	0.0006***	0.1148	0.0264*
G x C	0.0566	0.0700	0.7538	0.8619

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

Table 3.6 Least square means of seed yield, above-ground biomass, and thousand seed weight (TSW) of field pea monocultures and mixtures grown with and without pseudo-weed (barley) competition at Lethbridge, Alberta, in 2010.

	Weed-free			Weedy		
Genotypic composition	Yield	Biomass	TSW	Yield	Biomass	TSW
	Kg ha^{-1}	Kg ha^{-1}		Kg ha^{-1}	Kg ha^{-1}	
CDC1897-3	6548	14967	242 b[†]	3222 a	6437 ab	225 cd
CDC1897-14	5569	9536	234 cd	3146 ab	5919 ab	241 ab
Eclipse	4065	8914	262 a	3199 ab	7652 a	227 c
Midas	5040	10460	228 cd	3128 ab	6774 ab	230 bc
CDC1897-3 x CDC1897-14	5447	10418	241 b	3559 a	7481 a	220 cd
CDC1897-3 x Eclipse	5284	10527	257 a	2882 ab	6320 ab	251 a
CDC1897-3 x Midas	5129	10902	238 bc	2834 ab	5927 ab	217 d
CDC1897-14 x Eclipse	5181	9849	242 b	3508 ab	7089 ab	216 d
CDC1897-14 x Midas	5499	9479	232 cd	2987 ab	7013 ab	233 bc
Eclipse x Midas	5260	11256	238 bc	2743 b	5220 b	230 bc
LSD 0.05	NS	NS	7	805	1980	11
	Estimates [a]					
Monocultures vs. mixtures	56	564	0	88	187	3
CDC1897-3 x CDC1897-14 vs. components	-612	-1834	3	375	1303	-13*
CDC1897-3 x Eclipse vs. components	-23	-1414	5	-329	-725	25***
CDC1897-3 x Midas vs. components	-665	-1812	3	-341	-679	-11*
CDC1897-14 x Eclipse vs. components	364	624	-6	336	304	-18**
CDC1897-14 x Midas vs. components	195	-519	1	-150	667	-3
Eclipse x Midas vs. components	708	1569	-7*	-421	-1993*	2
CDC1897-3 x CDC 1897-14 vs. Eclipse x Midas	187	-838	3	816*	2261*	-10
CDC1897-3 x CDC 1897-14 vs. CDC1897-3 x Eclipse + CDC1897-14 x Eclipse	215	230	-9**	364	777	-14*
CDC1897-3 x CDC 1897-14 vs. CDC1897-3 x Midas + CDC1897-14 x Midas	133	228	6	649	1011	-5
CDC1897-3 x CDC 1897-14 vs. all other mixtures	176	15	0	568	1167	-9

[†] Means within a column followed by the same lower case letter are not significantly different based on $LSD_{0.05}$.

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

[a] Estimate of difference between means.

Table 3.7 Least square means of seed yield, above-ground biomass, vine length (VL), and thousand seed weight (TSW) of field pea monocultures and mixtures at Lethbridge, Alberta , in 2011.

Genotypic composition	Yield	Biomass	VL	TSW
	Kg ha^{-1}	Kg ha^{-1}	cm	
CDC1897-3	3543 a[†]	9022	76 a	213 bc
CDC1897-14	2643 bc	7461	75 a	204 d
Eclipse	1744 e	7606	64 bc	246 a
Midas	2159 cde	7494	61 c	209 cd
CDC1897-3 x CDC1897-14	2911 b	7737	78 a	207 cd
CDC1897-3 x Eclipse	2405 bcd	8767	66 bc	219 bc
CDC1897-3 x Midas	2504 bcd	7590	75 a	212 bcd
CDC1897-14 x Eclipse	2088 cde	7399	74 ab	212 bc
CDC1897-14 x Midas	2066 cde	7536	66 bc	206 cd
Eclipse x Midas	1924 de	7406	62 c	219 bc
LSD 0.05	622	NS	8	9
	Estimates [a]			
Monocultures vs. mixtures	206	157	-1	6
CDC1897-3 x CDC 1897-14 vs. components	-182	-505	3	-2
CDC1897-3 x Eclipse vs. components	-239	453	-4	-11**
CDC1897-3 x Midas vs. components	-347	-668	7	1
CDC1897-14 x Eclipse vs. components	-106	-135	5	-13**
CDC1897-14 x Midas vs. components	-335	59	-2	-1
Eclipse x Midas vs. components	-28	-144	-1	-9*
CDC1897-3 x CDC 1897-14 vs. Eclipse x Midas	987**	331	16**	-12**
CDC1897-3 x CDC 1897-14 vs. CDC1897-3 x Eclipse + CDC1897-14 x Eclipse	665*	-346	8*	-9*
CDC1897-3 x CDC 1897-14 vs. CDC1897-3 x Midas + CDC1897-14 x Midas	626*	174	8*	-2
CDC1897-3 x CDC 1897-14 vs. all other mixtures	714*	-3	9*	-7

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

[†] Means within a column followed by the same lower case letter are not significantly different based on $LSD_{0.05}$.

[a] Estimate of difference between means.

Table 3.8 Least square means of thousand seed weight (TSW) of field pea monocultures and mixtures grown with or without pseudo-weed (barley) competition at St. Albert, Alberta, in 2010.

Genotypic composition	Weed-free	Weedy
CDC1897-3	200 d[†]	187
CDC1897-14	192 d	177
Eclipse	239 a	198
Midas	202 cd	176
CDC1897-3 x CDC1897-14	200 d	183
CDC1897-3 x Eclipse	217 b	191
CDC1897-3 x Midas	196 d	173
CDC1897-14 x Eclipse	216 b	178
CDC1897-14 x Midas	202 cd	171
Eclipse x Midas	214 bc	197
$LSD_{0.05}$	13	NS
	Estimates [a]	
Monocultures vs. mixtures	1	2
CDC1897-3 x CDC 1897-14 vs. components	4	1
CDC1897-3 x Eclipse vs. components	-3	-2
CDC1897-3 x Midas vs. components	-5	-9
CDC1897-14 x Eclipse vs. components	1	-10
CDC1897-14 x Midas vs. components	5	-6
Eclipse x Midas vs. components	-7	10
CDC1897-3 x CDC 1897-14 vs. Eclipse x Midas	-14*	-14
CDC1897-3 x CDC 1897-14 vs. CDC1897-3 x Eclipse + CDC1897-14 x Eclipse	-17**	-2
CDC1897-3 x CDC 1897-14 vs. CDC1897-3 x Midas + CDC1897-14 x Midas	1	11
CDC1897-3 x CDC 1897-14 vs. all other mixtures	-9	1

*,** significant at the 0.05, and 0.01 probability level, respectively.

[†] Means within a column followed by the same lower case letter are not significantly different based on $LSD_{0.05}$.

[a] Estimate of difference between means.

Table 3.9 The effect of field pea genotypic composition on pseudo-weed (barley) seed production and biomass at St. Albert (2010) and Lethbridge (2011), Alberta.

Site-year	Barley seed production	Barley above-ground biomass
	P-values	
St. Albert 2010		
Genotypic composition	0.6223	0.3712
Lethbridge 2010		
Genotypic composition	0.0007***	0.0459*
Lethbridge 2011		
Genotypic composition	0.0127*	0.2922

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

Table 3.10 Least square means for pseudo-weed (barley) seed and biomass production in the stands of field pea monocultures and mixtures across three site-years (St. Albert 2010, Lethbridge 2010, and Lethbridge 2011) in Alberta.

	St. Albert 2010		Lethbridge 2010		Lethbridge 2011	
Genotypic composition	Seed	Biomass	Seed	Biomass	Seed	Biomass
	Kg ha^{-1}	Kg ha^{-1}	Kg ha^{-1}	Kg ha^{-1}	Kg ha^{-1}	Kg ha^{-1}
CDC1897-3	127	1484	564 b[†]	2744 abc	635 b	1889
CDC1897-14	142	764	448 b	1949 bc	523 b	1801
Eclipse	163	1259	1309 a	3917 a	655 bc	2448
Midas	109	792	1032 a	2754 ab	632 b	1795
CDC1897-3 x CDC1897-14	161	885	533 b	1916 bc	524 b	1752
CDC1897-3 x Eclipse	126	541	495 b	1959 bc	254 a	1618
CDC1897-3 x Midas	162	1216	480 b	1986 bc	804 c	2186
CDC1897-14 x Eclipse	170	768	389 b	1352 c	777 c	2378
CDC1897-14 x Midas	126	1269	414 b	2072 bc	665 bc	1829
Eclipse x Midas	153	1028	653 b	1676 bc	664 bc	2074
LSD 0.05	NS	NS	320	968	259	NS
	Estimates [a]					
Monocultures vs. mixtures	-14	124	344*	1014*	-3	10
CDC1897-3 x CDC 1897-14 Vs. Components	27	-239	27	-431	-55	-93
CDC1897-3 x Eclipse vs. components	-19	-831*	-442*	-1372**	-391**	-551
CDC1897-3 x Midas vs. components	44	78	-318	-763	171	344
CDC1897-14 x Eclipse vs. components	18	-244	-490**	-1581**	188	254
CDC1897-14 x Midas vs. components	1	491	-326*	-280	88	31
Eclipse x Midas vs. components	17	3	-518**	-1660**	21	-48
CDC1897-3 x CDC 1897-14 vs. Eclipse x Midas	8	-143	-120	240	-140	-322
CDC1897-3 x CDC 1897-14 vs. CDC1897-3 x Eclipse + CDC1897-14 x Eclipse	13	231	91	261	9	-246
CDC1897-3 x CDC 1897-14 vs. CDC1897-3 x Midas + CDC1897-14 x Midas	17	-358	86	-113	-211	-256
CDC1897-3 x CDC 1897-14 vs. all other mixtures	14	-79	47	107	-109	-265

*,** significant at the 0.05, and 0.01 probability level, respectively.

[†] Means within a column followed by the same lower case letter are not significantly different based on $LSD_{0.05}$.

[a] Estimate of difference between means.

Table 3.11 Temperature data for field trials conducted at St. Albert and Lethbridge, Alberta, in 2010 and 2011.

	Temperature (°C) [a]				
Site	May	Jun	Jul	Aug	Sep
St. Albert 2010	8.1	13.9	15.6	14.4	8.2
Lethbridge 2010	7.6	14.0	17.0	15.7	10.7
St. Albert 2011	11.2	15.1	15.3	14.6	14.5
Lethbridge 2011	9.1	13.5	16.9	17.5	15.1
Long term average					
St. Albert	11.7	15.5	17.5	16.6	11.3
Lethbridge	11.4	15.6	18.2	17.7	12.3

[a] Environment Canada, 2012.

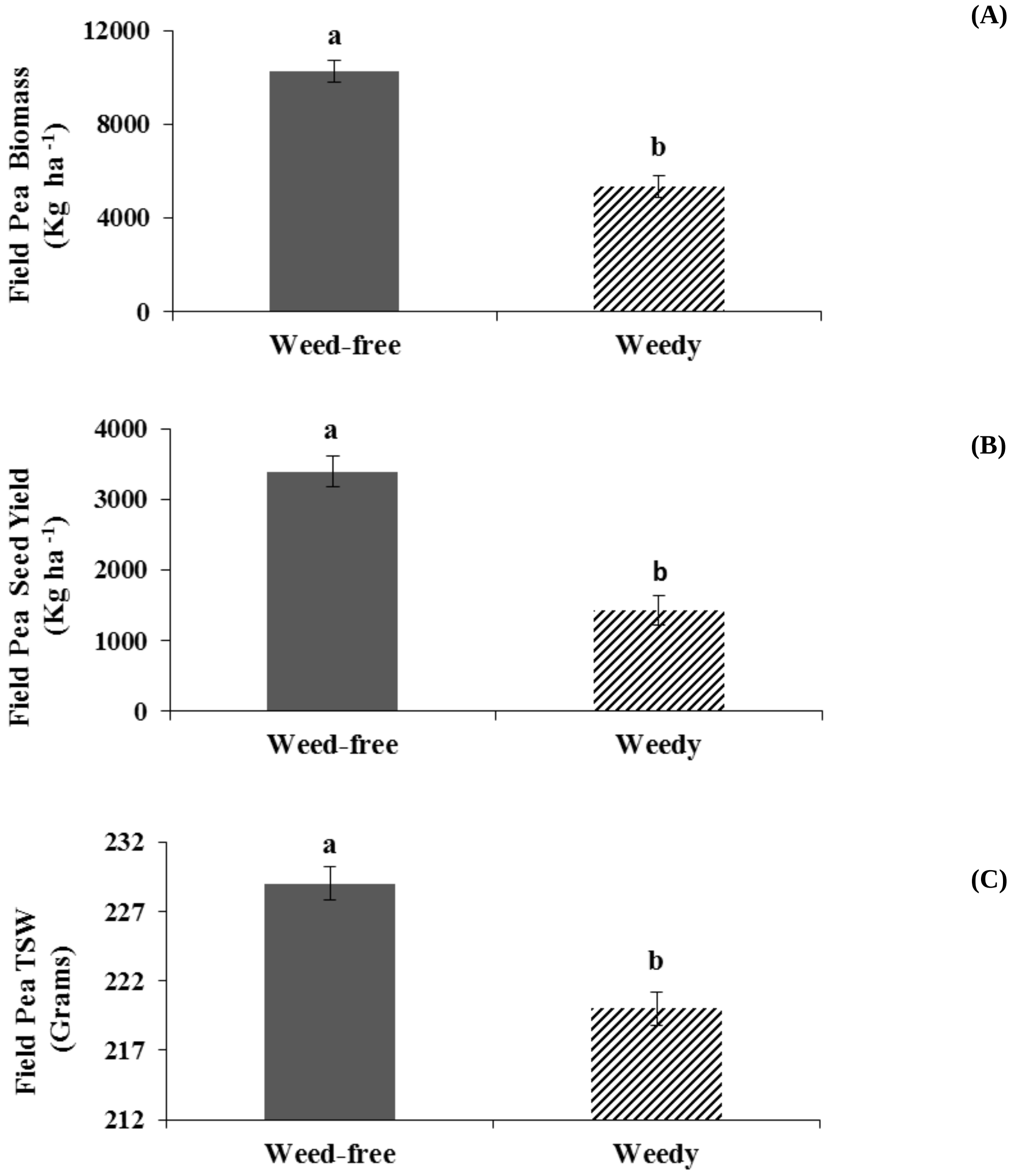

Figure 3.1 The effect of pseudo-weed (barley) competition at Lethbridge (2011) on (A) the above-ground biomass, (B) the seed yield, and (C) the thousand seed weight (TSW) of field pea genotypic compositions. Different letters indicate a significant difference at $P \leq 0.05$, and bars represent $\pm$ 1 SEM (standard error of the mean).

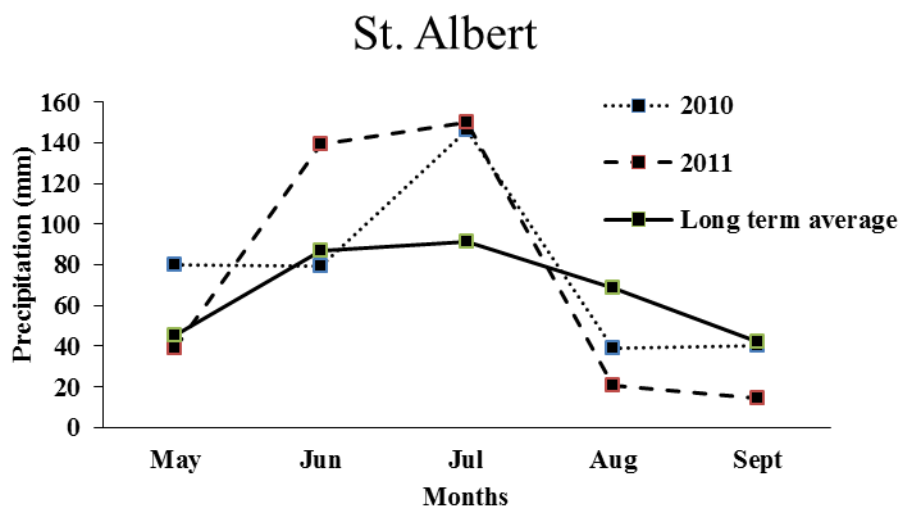

Figure 3.2 Precipitation data for field trials conducted at St. Albert, Alberta, in 2010 and 2011 (Environment Canada, 2011).

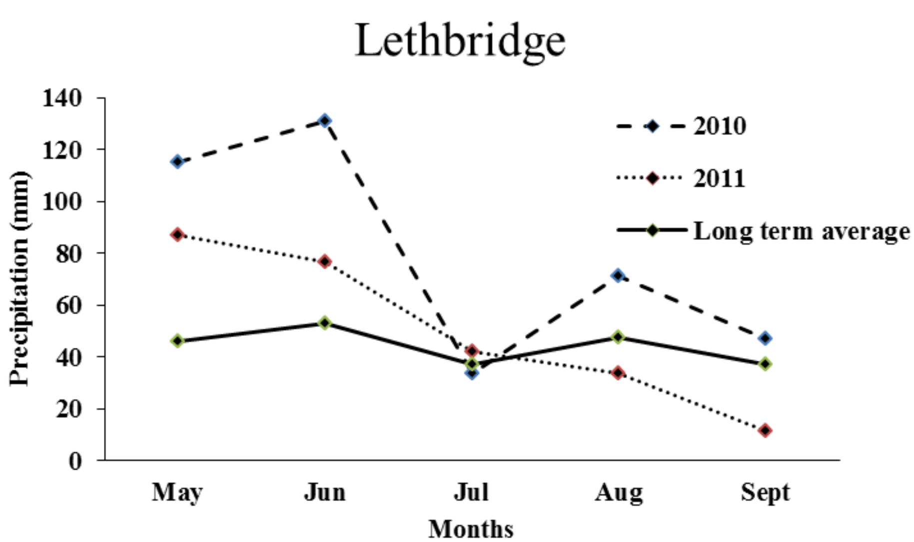

Figure 3.3 Precipitation data for field trials conducted at Lethbridge, Alberta, in 2010 and 2011 (Environment Canada, 2011).

3.7 Literature Cited

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CHAPTER 4: THE COMPETITIVE ABILITY OF FOUR FIELD PEA (*Pisum sativum* L.) GENOTYPES IN A REPLACEMENT SERIES

4.1 Introduction

In nature, plants experience two kinds of competition that can influence crop productivity; interspecific competition, or competition between different species of plants, and intraspecific competition, or competition between plants of the same species (Firbank & Watkinson, 1985; McDonald & Gill, 2009). The replacement series diagram, first introduced by De Wit in 1960, can be a valuable tool to study plant competition because it is possible to detect competition from the change in shoot or root biomass accumulation across a range of densities compared to where no competition occurred (Maddonni et al., 2001; Pagano & Maddonni, 2007). For that reason, this method has been extensively used in many studies to assess competition between plants of the same or different species (De Wit, 1960; Harper, 1977; Jedel et al., 1998; Li et al., 1999; Radosevich, 1987).

The replacement series design has been criticized for focusing on the effects of plant density in mixtures, which could lead to misinterpretation of the results (Connolly, 1986; Jolliffe et al., 1984; Snaydon, 1994). Nevertheless, the validity of this design has been advocated by many researchers. Harper (1977) reported that the replacement series method is a valid approach to describing the relationship between plants grown together in pairs. Radosevich (1987) described the replacement series as the most valuable method for assessing competitive effects at a single, total density. Furthermore, Li et al. (1999) found the replacement series approach to be excellent for evaluating the influence of resource availability on competition between genotypes of a same species.

The most important metrics derived from the replacement series method are relative yield (RY) and relative yield total (RYT). Relative yield (RY) is the yield of a genotype when grown in a mixture relative to the yield of the same genotype grown in monoculture (Aminpanah & Javadi, 2011; Hoad et al., 2008; Pridham & Entz, 2008). Relative yield (RY) has been used extensively to measure the ability of plants to capture resources (Aminpanah & Javadi, 2011; Asghar et al., 2011; Cheema et al., 1988; Firebank & Watkinson, 1985; Jedel et al., 1998). The relative yield total (RYT) is the sum of relative yields of the mixture components and is a useful tool to measure the ability of a mixture (as a whole) to capture resources relative to its components when grown alone (De Wit, 1960). A mixture is considered neutral or complementary when the value of the relative yield total (RYT) is equal to or greater than 1. This indicates that the two components, when grown together, were making similar demands on or complement each other with regard to resource acquisition (Asghar et al., 2011; Cheema et al., 1988; Firebank & Watkinson, 1985). However, a RYT value that is less than 1 indicates the presence of competition and antagonism between the components. This antagonism can cause reductions in mixture yield compared to the average expected yield which is calculated from the yield of the components when grown alone (Cheema et al., 1988; Firebank & Watkinson, 1985).

Because competition between plants' roots and shoots has significant effects on plant growth (Wilson, 1988), researchers traditionally have used the physical separation of shoot and root systems to study competition (Aminpanah & Javadi, 2011; Barrett & Campbell, 1973; Haugland & Froud-Williams, 1999).

This technique was first used by Donald (1958), who studied the physical separation of shoot and root systems on *Lolium preenee* L. and *Phalaris tuberosa* L. Shoot interactions are often an indication of competition for light and space, which has been found to be more intense if soil moisture and nutrients are abundant (Cahill, 1999). However, root interactions can result in competition between plants for soil moisture and nutrients. The strength of root competition is known to be negatively correlated with the availability of resources (Cahill et al., 2003). In other words, the more resources available to plants, the less root that competition occurs.

Root:shoot ratio is one of the most commonly used approaches to explore the relationship between root and shoot biomass (Gower et al.,1992; Li et al., 2003; Schenk & Jackson, 2002; Titlyanova et al., 1999). Root:shoot ratios have been used to describe the differential investment of photosynthate between above- and below-ground organs (Li et al., 2003; Titlyanova et al., 1999). Mokany et al. (2006) reported that many factors have the potential to influence root:shoot ratio, including species characteristics and environmental conditions (soil moisture, nutrient availability and competition for light). However, Bloom et al. (1985) was more specific and suggested that plants allocate additional biomass to the organs that capture the most limiting resources. Similar results have been obtained in other studies, which have determined that root:shoot ratio of several herbaceous species decreases as the mean annual precipitation increased (Gower et al.,1992, Schenk & Jackson, 2002), and it increased significantly when grown under low levels of soil nutrients (Shipley & Meziane, 2002).

Cultivar mixtures are comprised of different cultivars of the same species that may vary in attributes such as disease resistance, competitive ability, and other morphological characteristics, but have sufficient similarity to be grown together simultaneously (Wolfe, 1985). Growing cultivar mixtures is considered a sustainable method of growing crops, and it is an ideal method for conventional, low-input, and organic systems (Helland & Holland, 2001; Jedel et al., 1998; Kaut et al., 2008; Kwabiah, 2004). Cultivar mixtures have been extensively studied in cereal crops (Gallandt et al., 2001; Helland & Holland, 2001; Kaut et al., 2008; Marshall et al., 2009; Mengistu et al., 2010; Sarandon & Sarandon, 1995; Smithson & Lenne, 1996) and have been shown to provide yield and quality advantages when compared to monocultures (Dubin & Wolfe, 1994; Helland & Holland, 2001; Kaut et al., 2008; Manthey & Fehrmann, 1993; Sarandon & Sarandon, 1995). In fact, mixtures are gaining support as an alternative approach to monocultures (Jedel et al., 1998; Kaut et al., 2008; Kiaer et al., 2009). Moreover, mixtures are considered to be a practical and relatively easy to implement approach to increasing biological diversity in the agroecosystem and to improving the ability of crops to succeed under a range of environmental conditions (Buhler, 2005; Helland & Holland, 2001; Jedel et al., 1998; Kaut et al., 2008; Kiaer et al., 2009; Kwabiah, 2004).

The advantages of mixtures have been attributed both to cultivar complementarity and to their effective use of environmental resources compared with monocultures (Jedel et al., 1998; Sarandon & Sarandon, 1995; Smithson & Lenne, 1996). Differences in competitive ability among genotypes of the same species have been identified by many studies and attributed to different morphological and physiological characteristics within the species (Early & Qualest, 1971; Juskiw et al., 2000; Zerner et al., 2008).

Competitive components (cultivars) of mixtures can drive a mixture's ability to compete better with weeds. For example, wheat cultivar mixtures demonstrated an improved competitive ability against weeds compared to monocultures (Binang et al., 2011; Gallandt et al., 2001; Rao & Prasad, 1985). For that reason, growing field pea mixtures that are composed of components with different competitive abilities may also have the potential to improve the crop's poor competitive ability against weeds, which is considered one of the major constraints to field pea production (Chapter 3). However, no study has examined how field pea genotypes interact in mixtures and thus, the objective of this study was to examine the shoot and root competitive ability and performance of the four genotypes chosen for the aforementioned field experiment (Chapter 3).

4.2 Materials and Methods

A greenhouse experiment was conducted at the University of Alberta in Edmonton, Alberta, from March to May, and from October to December, in 2011. The day and night temperatures were maintained at 23 ºC ($\pm$ 3 ºC), with relative humidity between 60 to 70%. Natural irradiance was supplemented for 15 h d^{-1}, with artificial lighting provided by lamps with a radiation level of 128 µmol m^{-2} s^{-1}. Treatments consisted of four semi-leafless field pea genotypes that differed in their genetic relatedness: two sister lines (CDC1897-3, CDC1897-14), one common parent (Eclipse) and one distantly-related genotype (SW Midas). The four genotypes were grown in a replacement series (100:0, 75:25, 50:50, and 25:75, 0:100) (Table 4.1), with four replications per treatment. The experiment was a randomized complete block design, and the experiment was repeated twice.

Field pea seeds of each genotype were planted in 25.4-cm diameter x 19.1-cm deep plastic pots (6.62 L). SunGro® potting mix was used as the growth media and contained 55 to 65 % sphagnum field peat moss, a pH of 5.8 and an EC (electric conductivity) of 1.84 dSm^{-1}. Four field pea plants were planted in each pot to approximate the recommended field pea target plant population of 75 plants m^{-2} (Alberta Agriculture and Rural Development, 2011). A planting apparatus was constructed to place seeds of appropriate genotypes at a constant depth of 2.5 cm and in a square arrangement, such that they were equidistant and equiangular to each other so as not to bias the outcome of competition (Figure 4.1). Two seeds were planted in each of the four positions, covered with dry soil and slightly compacted to simulate field conditions. Granular field pea inoculant (*Rhizobium leguminosarum* biovar *viceae*) was applied during seeding at the manufacturer's recommended rate of 5.3 kg ha^{-1}. Seedlings were thinned to four plants per pot three days after emergence. Each pot received 1.5 g of 14-14-14 slow-release fertilizer one week after emergence. All plants were watered to capacity every two days until the biomass harvest was complete. Pots were rotated to new positions every two weeks to minimize the environmental variability and border effects within the experiment. Wire cages were used in each pot to support plant shoot biomass and to facilitate separating the biomass material at sampling time (Figure

4.2). The cages contained very thin, galvanized wire (2.0 mm diameter) that would not be expected to interfere with light interception (Walker & King, 2009).

Destructive sampling of all plants in each pot was conducted at early pod filling (63 days after emergence and 69 days after emergence in the first and second run, respectively) to determine shoot and root biomass. Plants were gently removed from the pots, and roots were very carefully and thoroughly washed to remove soil particles. Plants were sectioned into roots and shoots, with each plant placed separately in a paper bag. Samples were dried at 60ºC for five days to dissipate moisture and were then weighed.

Competition within mixture component plants was assessed based on the relative yield (RY) of the dry weight of above- and below-ground biomass. RY was calculated as (De Wit & Bergh, 1965):

$$RY_{\text{of genotype}} = \frac{\text{Yield per pot of genotype in a mixture}}{\text{Yield per pot of genotype in a monoculture}}$$

Relative Yield Total (RYT) was calculated by adding the RY of the mixture components:

$$RYT_{ab} = RY_a + RY_b$$

where RYT_{ab} is the relative yield total of the mixture genotypes (a) and (b), RY_a is the relative yield of genotype (a) in the mixture, and RY_b is the relative yield of genotype (b) in the mixture. When the relative yield total value is greater than 1, the mixture is over-compensatory, because the total mixture yield is greater than the expected average of the components. However, a RYT value less than 1 suggests that the mixture is under- compensatory due to antagonism between the components.

4.3 Statistical Analysis

In this greenhouse study, plants were only exposed to intraspecific competition, the competition induced from plants of the same species (field pea) but different genotypes. Relative yields of the replacement series mixtures were analyzed graphically as described by De Wit (1960) and Harper (1977). Actual RY of each genotype was plotted against the appropriate planting proportion. Expected RY of each genotype (the straight dashed line in figures 4.3, 4.4) was calculated on the basis of its proportion in the mixture, assuming that both genotypes have equal competitive ability. Statistical significance of the deviations of actual RY from expected RY and thus, deviations of RYT from 1 were determined by a Student’s t-test (Akey et al., 1991) using SAS software (SAS Inst., 2009).

All residuals initially were tested to ensure that data conformed to the assumptions of ANOVA. Normality was assessed with the Shapiro-Wilk test of PROC UNIVARIATE (SAS Inst., 2009), while homoscedasticity was assessed using Levene’s test in PROC GLM (SAS Inst., 2009). All data conformed to the assumptions of ANOVA and thus, no transformations were required. The data of the two-runs of this experiment did not differ significantly, nor did the effect of run and it’s interaction with fixed effects (mixture components) (data not shown). Thus, the data were pooled over the two runs for the analysis. A one-way ANOVA was performed to compare root:shoot data of mixtures. Means were separated using Fisher's Protected LSD, with treatment effects declared significant at $P \leq 0.05$. Because the objective of this study was to determine the effect of competition within the two-way mixture components, the data from monocultures were not included in any statistical analysis except for the determination of RYT (Akey et al., 1991).

4.4 Results

4.4.1 Root Biomass

The root biomass of CDC1897-3, CDC1897-14, and Eclipse (the closely-related genotypes) monocultures was significantly different ($P \leq 0.05$) than Midas (the distantly-related genotypes) (Table 4.2). Averaged across replications, root biomass of the closely-related monocultures (CDC1897-3, CDC1897-14, and Eclipse) was 82% greater than that of Midas (Table 4.2). There were no significant differences between the sister lines (CDC1897-3 and CDC1897-14) or their common parent (Eclipse) with respect to root biomass production.

The relative yield of the genotypes was analyzed graphically (Figure 4.3). The actual RYs for each genotype in a mixture were compared to their expected RYs in monoculture using a Student's t-test. Figure 4.3 shows that the CDC1897-3 x CDC1897-14, CDC1897-3 x Eclipse, and CDC1897-14 x Eclipse mixtures were over-yielding compared with each of the components in monoculture . When sister lines were combined with a distantly-related genotype (Midas), however, the resulting mixture did not exhibit RYT values that were significantly different from 1 (Figure 4.3; Table 4.3). When the common parent to the sister lines (Eclipse) was combined in a mixture with a distantly-related genotype (Midas), the resulting RYT indicated that under-yielding or antagonism was occurring between these genotypes. Indeed, the RYT of this mixture averaged across all mixture proportions was significantly lower than 1 (Table 4.3).

Figure 4.3 also shows that the RY lines of CDC1897-3 and CDC1897-14, when combined in a mixture, intersect at the point of equivalency of the expected yield (50:50 mixture proportions), which indicates that CDC1897-3 and CDC1897-14 genotypes are equally competitive (Figure 4.3). However, for most other mixtures, RY lines intersect to the left or the right of the point of equivalency of the expected yield (Figure 4.3), indicating that CDC1897-3 was more competitive than Eclipse and CDC1897-14 was more competitive than both Eclipse and Midas (Figure 4.3). Midas had a competitive ability that was equal to both CDC 1897-3 and Eclipse. Although the overall competitive ability of these four genotypes is similar, these results suggest the following general ranking for cultivar below-ground competitive ability: CDC 1897-14 > CDC 1897-3 > Midas > Eclipse.

4.4.2 Shoot Biomass

The differences between RYT for the shoot biomass were much less pronounced than for root biomass of mixtures in this study (Figure 4.4, Table 4.3). The sister lines mixture (CDC1897-3 x CDC1897-14) and the mixtures of sister lines and their common parent (CDC1897-3 x Eclipse, and CDC1897-14 x Eclipse) all exhibited convex above-ground biomass RYT curves, with actual RYT values greater than that expected (>1) if each genotype had been grown alone in monoculture. However, only the mixture of CDC1897-3 x Eclipse exhibited a RYT total that was significantly ($P \leq 0.05$) greater than 1 when averaged across all mixture proportions (Table 4.3). Although, not statistically significant, all other mixtures of sister lines and their common parent had RYT totals greater than 1 (1.12 and 1.17). This indicates that similar to root biomass, mixtures of sister lines and mixtures including their common parent are over-yielding or synergistic in nature.

When sister lines were combined with a distantly-related genotype (Midas), however, the resulting mixture did not exhibit RYT values that were significantly different from 1 (Figure 4.4; Table 4.3). When the common parent to the sister lines (Eclipse) was combined in a mixture with a distantly-related genotype (Midas), the resulting RYT was severely concave, indicating that substantial under-yielding or antagonism was occurring between these genotypes. Indeed, the RYT of this mixture averaged across all mixture proportions was significantly lower than 1 (Table 4.3).

Despite significant differences between genotypes for total root biomass production (averaged across proportions), no significant differences were found between genotypes for shoot biomass production (Table 4.3). Nevertheless, examination of the RY curves for shoot biomass revealed significant differences in above-ground competitive ability between field pea genotypes (Figure. 4.4). The RY lines of CDC1897-3 x CDC1897-14, CDC1897-3 x Midas, and CDC1897-14 x Eclipse components intersect at the point of equivalency of the expected yield, which indicates that these genotypes are of equal above-ground competitive ability (Figure 4.4). However, the RY lines of the genotype components of CDC1897-3 x Eclipse, CDC1897-14 x Midas, and Midas x Eclipse mixtures intersect to the left or the right of the point of equivalency of the expected yield (Figure 4.4). These results show that CDC1897-3 and Midas were both more competitive than Eclipse, while CDC1897-14 was more competitive than Midas (Figure 4.4).

4.4.3 Root:Shoot Ratio

In the current study, root:shoot ratio was calculated at the pot level. The data showed that all of the closely-related monocultures (CDC1897-3, CDC1897-14, and Eclipse) had a root:shoot value of 0.21 (Table 4.4). In contrast, the root:shoot ratio of the distantly-related genotype (Midas) had a value of 0.12 (Table 4.4). Bloom et al. (1985) demonstrated that plants allocate additional biomass to the organ that captures the resource that most limits growth. Data from the current study (Table 4.4) showed that the components of the distantly-related mixtures were allocating more biomass to the roots. Based on Bloom et al.'s (1985) observation, this indicates the presence of root competition between these components for limited below-ground resources. However, for the closely-related mixtures (CDC1897-3x CDC1897-14, and CDC1897-14 x Eclipse), the root:shoot ratio generally was not affected by the proportion of the component genotypes in mixtures (Tables 4.5 and 4.6). This suggests that these closely-related genotypes did not allocate more resources to root production and consequently, did not interfere with each other even when mixed in different ratios (Tables 4.5 and 4.6). One exception to this was CDC1897-3, which did allocate significantly more resources to root production when grown in a mixture with Eclipse (Table 4.7).

Not surprisingly, CDC 1897-3 also exhibited a significantly greater below-ground competitive ability than Eclipse (Figure 4.3).

Neither of the sister lines included in this study exhibited a significant increase in root:shoot ratios when grown in mixture with Midas, a more distantly related genotype (Tables 4.8 and 4.9). Midas, on the other hand, exhibited a significant increase (40% to 57%) in root:shoot ratio when grown in a mixture with either of the sister lines (Tables 4.8 and 4.9). Nevertheless, increased allocation to roots did not result in an increase in below-ground competitive ability in Midas because these plants had significantly lower root biomass production than all of the other genotypes (Table 4.4).

Likewise, root:shoot ratios in Midas also increased significantly when grown in mixture with the genotype Eclipse as compared to when Midas was grown in monoculture (Table 4.10). In fact, as the proportion of Eclipse in the mixture increased, so too did the root:shoot ratio of Midas plants (Table 4.10). Similar observations were made for Eclipse, in which plants of that genotype also exhibited a significant increase in root:shoot ratios (compared with monoculture) as the proportion of Midas plants increased in the mixture (Table 4.10). The result of both species increasing allocation to roots was an increase in below-ground competition, as evidenced by the concave RYT for this mixture (Figure 4.3).

4.5 Discussion

The replacement series diagrams generated in this study suggest the following general ranking for cultivar shoot competitive ability: CDC 1897-14 > CDC 1897-3 ≈ Midas > Eclipse. (Figures 4.3 and 4.4). Of all the mixtures in this study, CDC1897-3 x Eclipse was the only mixture to produce significantly ($P \leq 0.05$) more shoot biomass than its components when grown in monocultures (Table 4.3). The RYT of the shoot biomass of this CDC1897-3 x Eclipse mixture was significantly ($P \leq 0.05$) greater than 1. This increase in biomass was explained by Bebawi and Naylor (1981) as a synergetic relationship between components, which may exhibit functional niche differentiation. However, in the distantly-related mixture (Midas x Eclipse), Midas was the stronger above-ground competitor compared to Eclipse (Figure 4.4). Shoot biomass yields of both Midas and Eclipse were significantly ($P \leq 0.05$) lower than those of the expected yields (the average yield of the components grown alone) (Figures 4.4). Antagonism between Midas and Eclipse genotypes was also detected when RYT values of the Midas x Eclipse mixture were found to be significantly less than 1 for both root biomass ($P \leq 0.05$), and shoot biomass ($P \leq 0.001$) (Table 4.3).

Four of the six mixtures in this study exhibited an increase in root:shoot ratio values compared to when the component genotypes were grown in monoculture (Tables 4.6, 4.7, 4.9, and 4.10), which indicates that plants allocated more biomass to roots in these mixtures. This suggests that competition for below-ground resources may be driving competitive ability between the field pea genotypes grown in mixtures. Many studies have reported that the presence of neighbouring plants and the intensity of competition can influence biomass allocation, allowing plants to acquire more of the limited resources (Agren & Franklin, 2003; Austin et al., 1988; Bloom, et al., 1985, Mokany et al., 2006; Wilson, 1988). In fact, Moora and Zobel (1996) reported that in some cases, plant response to competition is only observed by an increase in root biomass allocation.

Bloom et al. (1985) observed that plants allocate additional biomass to the organs that capture the most limiting resources. Interestingly, the genotypes that had shifted allocation to roots in the current study were the components of the distantly-related mixtures (Midas when allocated more biomass to the roots when grown with CDC1897-3, CDC1897-14 and Eclipse) (Tables 4.7, 4.9, and 4.10). In the distantly-related mixtures (CDC1897-3 x Midas, CDC1897-14 x Midas and Eclipse x Midas), one of the mixture components (Midas) always responded to the presence of neighbouring plants by allocating more biomass to roots. In fact, for the most distantly-related mixture (Eclipse x Midas), both of the component genotypes shifted allocation of biomass to roots when combined in a mixture (Table 4.10). The increased allocation of biomass to roots in Eclipse and Midas suggests that both genotypes competed more intensely for below-ground resources and consequently, were antagonistic to each other. Similar shifts in biomass have been reported in other legume crops, including lupin (*Lupinus angustifolius* L.) and common vetch (*Vicia sativa* L.), when intense competition for below-ground resources (nitrogen) occurred (Mariotti et al., 2009).

A very interesting observation from the current study was that the closely-related mixtures exhibited no change in root:shoot ratios, regardless of the presence or identity of neighbouring plants (CDC1897-3 x CDC1897-14 and CDC1897-14 x Eclipse). This may be due to a lack of intense competition for resources between these component genotypes (Tables 4.5 and 4.8). Although the objective of this experiment was not to study plant recognition responses, the results showed some recognition of neighbour identity may exist in field pea. For example, the root:shoot ratios of the closely-related mixtures were not different than those of the components in monocultures, but Midas and Eclipse consistently allocated more resources to below-ground than to above-ground biomass (Tables 4.5, 4.6, and 4.8). The magnitude of the differences in allocation appeared to be a function of the identity of the neighbouring plant, as evidenced by the differences in root: shoot ratios observed in the study (Tables 4.4 to 4.10). This may suggest the presence of some recognition mechanism between the genotypes (CDC1897-3 x CDC1897-14, CDC1897-3 x Eclipse and CDC1897-14 x Eclipse), which led to closely-related genotypes avoiding each other. It also suggests that the two sister lines may have an inherent ability to tolerate the presence of neighbors better than the other genotypes included in this study, regardless of the identity of neighbors. In nearly all mixture combinations, both sister lines (CDC1897-14 and CDC 1897-3) did not exhibit significant changes in the root:shoot ratio in presence of neighbouring plants (Tables 4.5, 4.7, and 4.9), The ability of plants to withstand competition can be evaluated by the yield loss caused by neighbouring plant competition (Watson et al., 2006). Swanton (2005) suggested that the shifting of biomass allocation to roots may cause pre-conditioned yield loss. If these genotypes do indeed tolerate better the presence of neighbors (and thus, competitors), it may explain why they were also more competitive than the other two genotypes included in this study (Midas and Eclipse).

4.6 Conclusions

The greenhouse study revealed that there is a synergetic relationship between CDC1897-3 and Eclipse genotypes when grown in a mixture. It was the only mixture to significantly produce more above-ground biomass than its components in the greenhouse experiment (Table 4.3). This study also detected antagonism between Midas and Eclipse genotypes when grown in a mixture and caused significant reductions to the biomass of both components compared to monocultures. The results also showed that field pea plants might have responded differently to the identity of neighbors and the components of the distantly-related genotype (Midas) by allocating more biomass to the roots when grown with CDC1897-3, CDC1897-14 and Eclipse (Tables 4.7, 4.9, and 4.10).

It is important to note that the results of this experiment are valid when the environmental conditions are optimal because it was carried out in a greenhouse. Although the results of this experiment will help us to form a better understanding of how field pea genotypes interact when they are grown in mixtures, it can also help us to compare and contrast these results with the results obtained the field experiment (Chapter 3). However, these results cannot be completely extrapolated, because field conditions are different than those in the greenhouse.

Table 4.1 Treatment list for the greenhouse experiment.

Genotypic composition			Seed ratio [a]
CDC1897-3	X	CDC1897-14	100:0
CDC1897-3	X	CDC1897-14	75:25
CDC1897-3	X	CDC1897-14	50:50
CDC1897-3	X	CDC1897-14	25:75
CDC1897-3	X	CDC1897-14	0:100
CDC1897-3	X	Eclipse	100:0
CDC1897-3	X	Eclipse	75:25
CDC1897-3	X	Eclipse	50:50
CDC1897-3	X	Eclipse	25:75
CDC1897-3	X	Eclipse	0:100
CDC1897-3	X	Midas	100:0
CDC1897-3	X	Midas	75:25
CDC1897-3	X	Midas	50:50
CDC1897-3	X	Midas	25:75
CDC1897-3	X	Midas	0:100
CDC1897-14	X	Eclipse	100:0
CDC1897-14	X	Eclipse	75:25
CDC1897-14	X	Eclipse	50:50
CDC1897-14	X	Eclipse	25:75
CDC1897-14	X	Eclipse	0:100
CDC1897-14	X	Midas	100:0
CDC1897-14	X	Midas	75:25
CDC1897-14	X	Midas	50:50
CDC1897-14	X	Midas	25:75
CDC1897-14	X	Midas	0:100
Eclipse	X	Midas	100:0
Eclipse	X	Midas	75:25
Eclipse	X	Midas	50:50
Eclipse	X	Midas	25:75
Eclipse	X	Midas	0:100

[a] Mixtures were composed on a seed number basis to achieve standard seeding rate of 75 seeds m^{-2}.

Table 4.2 Least square means of the root and shoot biomass of the four field pea genotypes grown in monocultures averaged across all replications.

Monocultures	Root biomass	Shoot biomass
	g pot^{-1}	g pot^{-1}
CDC1897-3	13.6 a[†]	64.2
CDC1897-14	12.4 a	59.2
Eclipse	11.2 a	53.6
Midas	6.8 b	55.2
$LSD_{0.05}$	2.8	NS
	Estimates [a]	
CDC1897-3+CDC1897-14+ Eclipse vs. Midas	5.6**	3.8

[†] Means within a column followed by the same lower case letter are not significantly different based on $LSD_{0.05}$.

** significant at the 0.01 probability level.

[a] Estimate of difference between means.

Table 4.3 Relative yield total (RYT) calculated from below- and above-ground dry matter for each of the six, two-way field pea genotypic mixtures averaged across all proportions.

Genotypic Composition	Root biomass [a]	Shoot biomass [a]
CDC1897-3 x CDC1897-14	1.30**	1.12
CDC1897-3 x Eclipse	1.20**	1.23*
CDC1897-3 x Midas	1.01	1.00
CDC1897-14 x Eclipse	1.23***	1.17
CDC1897-14 x Midas	1.06	1.10
Eclipse x Midas	0.93*	0.68***

[a] The data was calculated at the pot level. Statistical significance of deviations of (RYT) from 1.0 was determined with a Student's t-test.
*,**, ***, significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

Table 4.4 Root: shoot ratios of the six, two-way field pea genotypic mixtures and their various mixture proportions.

	Mixing ratios [a]				
Genotypic Composition	100:0	75:25	50:50	25:75	0:100
CDC1897-3 X CDC1897-14	0.21	0.21	0.22	0.21	0.21
CDC1897-3 X Eclipse	0.21	0.25	0.25	0.25	0.21
CDC1897-3 X Midas	0.21b[†]	0.25b	0.20b	0.24b	0.12a
CDC1897-14 X Eclipse	0.21	0.22	0.24	0.20	0.21
CDC1897-14 X Midas	0.21b	0.21b	0.21b	0.19b	0.12a
Midas x Eclipse	0.12b	0.41c	0.43c	0.40c	0.21a

[a] Root: shoot ratios data were calculated at the pot level. Letters represent the statistical comparison using contrasts of the means.

[†] Means within a row followed by the same lower case letter are not significantly different based on $LSD_{0.05}$.

Table 4.5 Root:shoot ratios of CDC1897-3, CDC1897-14 and their various mixture proportions.

Genotypic Composition	CDC1897-3	CDC1897-14	Mixture
	root:shoot [a]	root:shoot [a]	root:shoot [a]
CDC1897-14	-	0.21	0.21
(25:75) CDC1897-3 x CDC1897-	0.20	0.22	0.21
(50:50) CDC1897-3 x CDC1897-	0.22	0.22	0.22
(75:25) CDC1897-3 x CDC1897-	0.22	0.20	0.21
CDC1897-3	0.21	-	0.21
$LSD_{0.05}$	NS	NS	NS

[a] Root: shoot ratios data were calculated at the pot level.

Table 4.6 Root:shoot ratios of CDC1897-14, Eclipse and their various mixture proportions.

Genotypic Composition	CDC1897-14	Eclipse	Mixture
	root:shoot [a]	root:shoot [a]	root:shoot [a]
Eclipse	-	0.21	0.21
(25:75) CDC1897-14 x Eclipse	0.22	0.22	0.22
(50:50) CDC1897-14 x Eclipse	0.22	0.26	0.24
(75:25) CDC1897-14 x Eclipse	0.24	0.26	0.20
CDC1897-14	0.21	-	0.21
$LSD_{0.05}$	NS	NS	NS

[a] Root: shoot ratios data were calculated at the pot level.

Table 4.7 Root:shoot ratios of CDC1897-3, Eclipse and their various mixture proportions.

Genotypic Composition	CDC1897-3	Eclipse	Mixture
	root:shoot [a]	root:shoot [a]	root:shoot [a]
Eclipse	-	0.21	0.21
(25:75) CDC1897-3 x Eclipse	0.28 b[†]	0.22	0.25
(50:50) CDC1897-3 x Eclipse	0.30 b	0.20	0.25
(75:25) CDC1897-3 x Eclipse	0.30 b	0.20	0.25
CDC1897-3	0.21 a	-	0.21
$LSD_{0.05}$	0.05	NS	NS

[a] Root: shoot ratios data were calculated at the pot level.

[†] Means within a column followed by the same lower case letter are not significantly different based on $LSD_{0.05}$.

Table 4.8 Root:shoot ratios of CDC1897-3, Midas and their various mixture proportions.

Genotypic Composition	CDC1897-3	Midas	Mixture
	root:shoot [a]	root:shoot [a]	root:shoot [a]
Midas	-	0.12 a[†]	0.12 a
(25:75) CDC1897-3 x Midas	0.22	0.28 b	0.25 b
(50:50) CDC1897-3 x Midas	0.24	0.26 b	0.20 b
(75:25) CDC1897-3 x Midas	0.22	0.26 b	0.24 b
CDC1897-3	0.21	-	0.21 b
$LSD_{0.05}$	NS	0.06	0.07

[a] Root: shoot ratios data were calculated at the pot level.
[†] Means within a column followed by the same lower case letter are not significantly different based on $LSD_{0.05}$.

Table 4.9 Root:shoot ratios of CDC1897-14, Midas and their various mixture proportions.

Genotypic Composition	CDC1897-14	Midas	Mixture
	root:shoot [a]	root:shoot [a]	root:shoot [a]
Midas	-	0.12 a[†]	0.12 a
(25:75) CDC1897-14 x Midas	0.19	0.22 b	0.21 b
(50:50) CDC1897-14 x Midas	0.21	0.21 b	0.21 b
(75:25) CDC1897-14 x Midas	0.18	0.20 b	0.19 b
CDC1897-14	0.21	-	0.21 b
$LSD_{0.05}$	NS	0.05	0.05

[a] Root: shoot ratios data were calculated at the pot level.
[†] Means within a column followed by the same lower case letter are not significantly different based on $LSD_{0.05}$.

Table 4.10 Root:shoot ratios of Midas, Eclipse and their various mixture proportions.

Genotypic Composition	Midas	Eclipse	Mixture
	root:shoot [a]	root:shoot [a]	root:shoot [a]
Eclipse	-	0.21 a	0.21 b
(25:75) Midas x Eclipse	0.47 c[†]	0.35 b	0.41 c
(50:50) Midas x Eclipse	0.44 bc	0.42 c	0.43 c
(75:25) Midas x Eclipse	0.38 b	0.41 c	0.40 c
Midas	0.12 a	-	0.12 a
$LSD_{0.05}$	0.07	0.04	0.04

[a] Root: shoot ratios data were calculated at the pot level.

[†] Means within a column followed by the same lower case letter are not significantly different based on $LSD_{0.05}$.

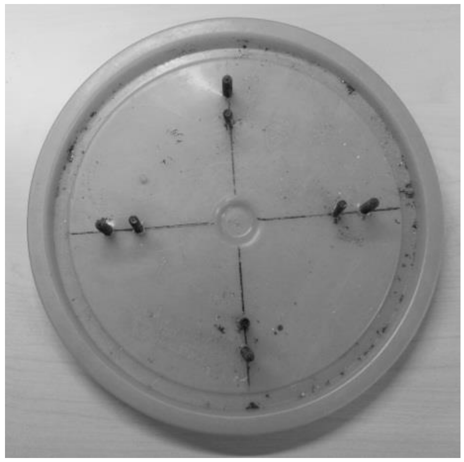

Figure 4.1 Planting apparatus for a 25.4 cm diameter growing pot, which was used to sow seeds at the same depth and ensure that they were equally spaced in a square arrangement.

Figure 4.2 Two-way mixtures in a replacement series (25:75, 50:50, and 75:25) and their four component monocultures were grown in four replications in a fully randomized complete block design. Eight field pea seeds were planted in each pot and seedlings were thinned to four plants three days after emergence. Wire cages were used to facilitate separating shoot biomass materials.

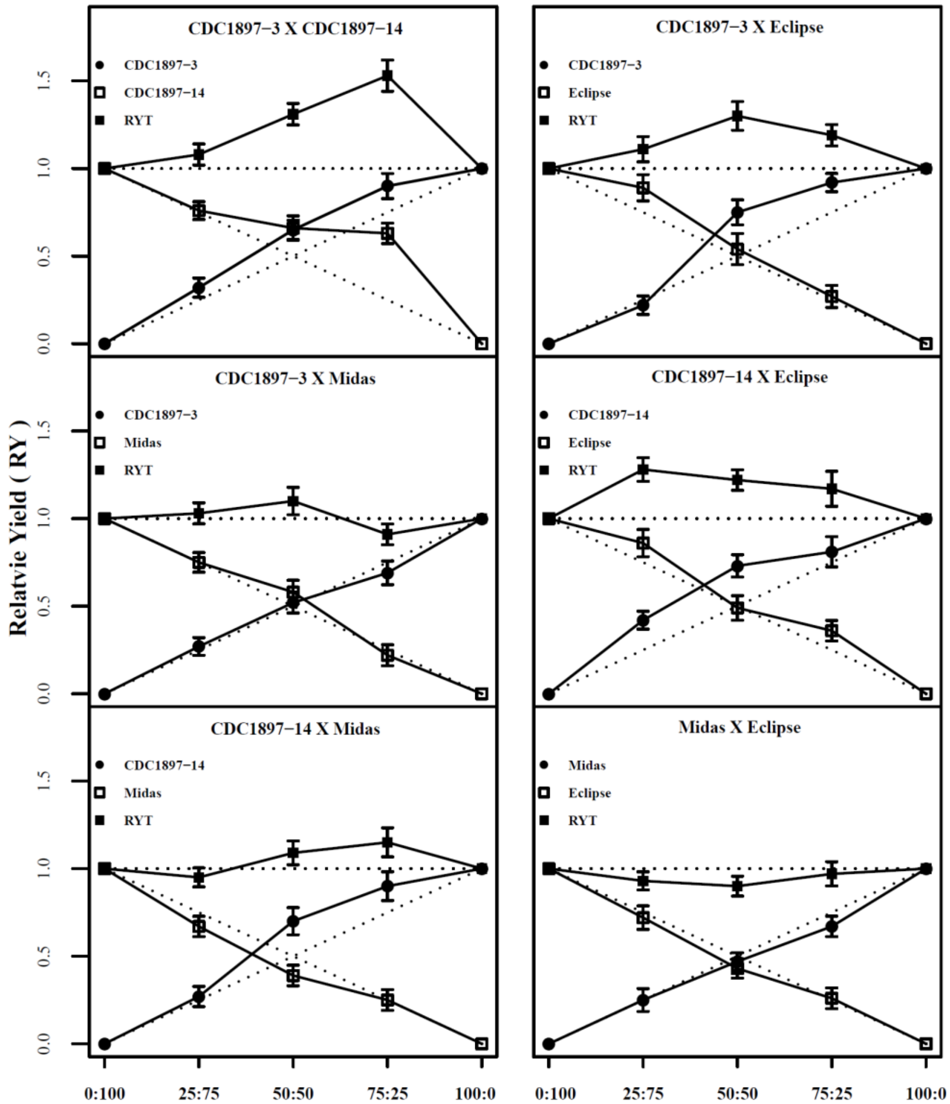

Figure 4.3. Relative yield (RY) and relative yield total (RYT) diagrams of root biomass (dry weight) of the six, two-way replacement series mixtures. RY and RYT values are the averages of two runs of a greehouse expriement. The straight dashed lines in each frame indicate the theoretically expected responses for two genotypes that have equal competitive ability, which intersect at the point of equivalency (Harper, 1977).

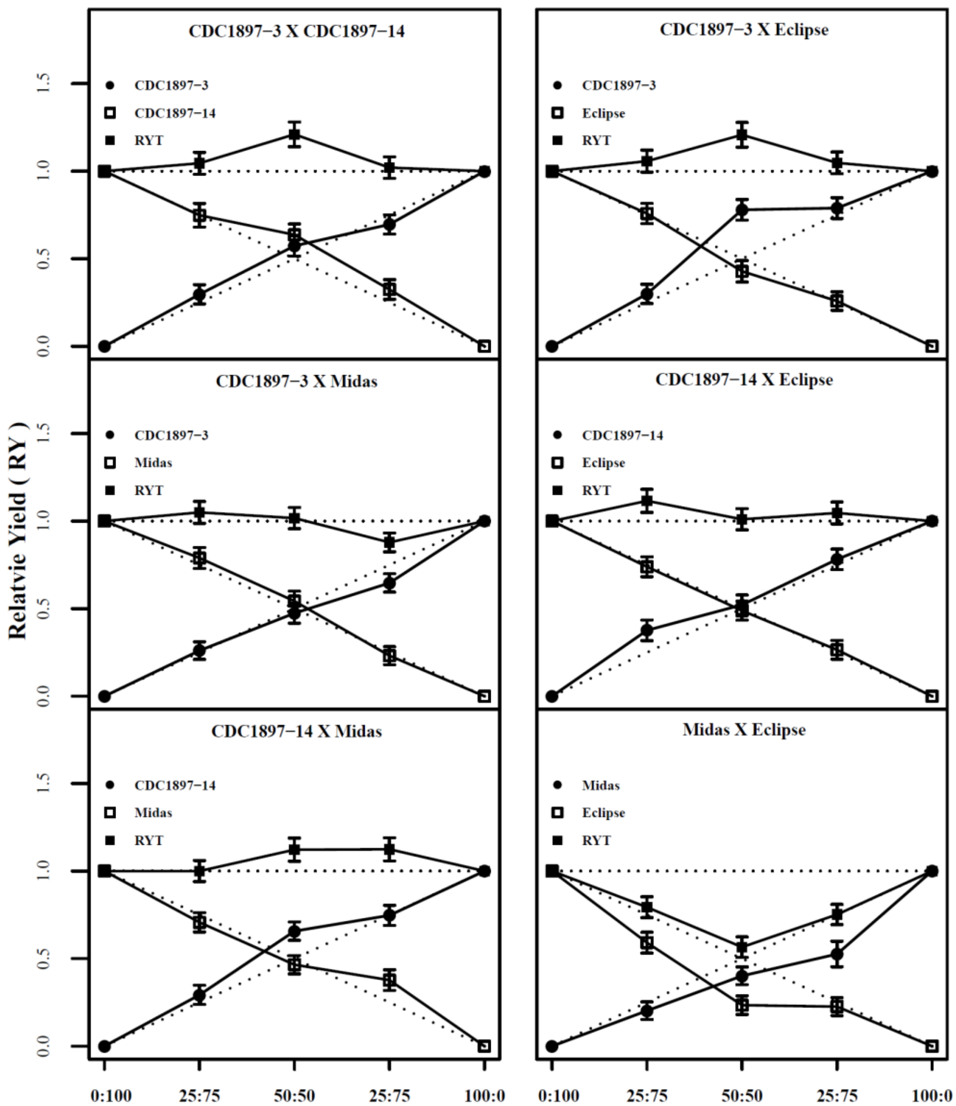

Figure 4.4 Relative yield (RY) and relative yield total (RYT) diagrams of shoot biomass (dry weight) of the six, two-way replacement series mixtures. RY and RYT values are the averages of two runs of a greehouse expriement. The straight dashed lines in each frame indicate the theoretically expected responses for two genotypes that have equal competitive ability, which intersect at the point of equivalency (Harper, 1977).

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CHAPTER 5: GENERAL DISCUSSION

5.1 Field Pea Genotypic Mixtures

In the current study, an improved competitive ability of mixtures under field conditions was only detected at one site-year, Lethbridge in 2010 (Table 3.10). At this site-year, genotypic mixtures reduced pseudo-weed (barley) biomass and seed production compared to monocultures (Chapter 3). However, no significant yield or biomass differences were detected between mixtures and monocultures. Overall, only the CDC1897-3 x Eclipse mixture was found to be consistent at significantly suppressing the pseudo-weed in this study. This suppression was observed in three out of three site-years of the field experiment (Table 3.11). In addition, the CDC1897-3 x Eclipse mixture was the only mixture to significantly produce more above-ground biomass than its components in the greenhouse experiment (Table 4.3). The performance of this mixture in the field and greenhouse experiments implies that CDC1897-3 and Eclipse are complimentary and improved their mixture's overall competitive ability. Several studies have also reported improvements in the competitive abilities of mixtures. Binang et al. (2011) showed the complementary competition between a 3:2 rice (Faro 15- a semi-dwarf cultivar and Muduga- a tall cultivar) mixture, which was able to reduce the weed population by 40%. Likewise, synergism between three-way spring wheat mixture components increased grain yield and reduced genotype by environment interactions (Rao & Prasad, 1985). The authors attributed this to improvements in the mixtures' competitive ability and resource utilization.

However, the reason for not detecting more profound advantages of mixtures in this study might be due to the near optimal growing conditions at two of the three site-years over which the study was conducted, where soil moisture and nutrients were adequate (Figures 3.1, 3.2 and Table 3.1) and overall disease pressure was relatively low. Sage (1971) suggested that the advantages of mixtures would only be observed when mixtures are grown in unfavorable environmental or resource-poor conditions. The author suggested that under adverse growing conditions, mixtures tend to allow the crop to adjust to varied biotic and abiotic stresses (Juskiw et al., 2001; Wolfe, 1985). For that reason, numerous studies in the literature have reported advantages to mixtures when grown under limited moisture conditions, poor fertility conditions, or moderate to severe disease levels. For example, Baker (1977) examined two-way spring wheat cultivars under early drought conditions. The author found that when cv. Neepawa was grown with Pitic 62 in a two-way mixture, 71% of Neepawa plants survived compared to only 53% in the pure lines. He attributed the increased survival rate to the resource complementarity between mixture components. Sarandon and Sarandon (1995) examined bread wheat in two-way mixtures without any fertilizer applied. Their results showed that mixtures had an average increase of 8% in above-ground biomass compared to monocultures. The authors suggested that this increase in above-ground biomass was due to a better use of available resources. Manthey and Fehrmann (1993) examined the effects of two- and three-way spring and winter wheat cultivar mixtures on powdery mildew (*Erysiphe graminis*) infection levels and showed that disease infection was decreased by 50% in the three-way mixture that included two resistant and one susceptible cultivars. The authors attributed the disease reduction to the dilution of pathogen inoculum and modification of the microclimate and thus, less infection in susceptible cultivars.

It is also important to note that in the current study, only simple mixtures (composed of two components) were used, which may be another reason for the lack of significant increases in biomass and seed yields observed in this study. Several studies have reported that complex mixtures offered more advantages than simple mixtures, especially when the components differed in root depth, competitive ability, and disease tolerance. For example, Helland and Holland (2001) reported that three-way oat cultivar mixtures increased grain yield more than two-way cultivar mixtures. Mundt et al. (1995) also noted that a four-way winter wheat cultivar mixture showed better yellow rust (*Puccinia striiformis*) control and more yield stability than the two-way mixtures. Likewise, Dubin and Wolfe (1994) demonstrated that three-way wheat cultivar mixtures grown in nine different environments (low-land, mid-hill, irrigated and rainfed) for three years had a slight but significant (2%) increase in grain yield over monocultures. The authors of the aforementioned studies attributed mixture advantages to an increase in biological diversity of the complex mixtures compared to monocultures. However, it is important to note that studying complex mixtures was not the intent of the current study; hence using simple mixtures was found to be more appropriate for comparing the effect of genetic relatedness of the components on the yield and competitive ability of mixtures.

Another important aspect of this thesis was to understand how field pea genotypes interact with each other when grown in mixtures. For that reason, the greenhouse study was designed to provide the conditions necessary to investigate the nature of plant competition and to provide a better understanding of how mixture components interact with neighboring plants. The greenhouse results showed that despite the fact that three out of the four genotypes included in this study were closely related, significant differences in competitive ability did exist between these genotypes (Chapter 4). CDC1897-14 was the most competitive cultivar below-ground, while Eclipse was the least competitive; CDC1897-3 and Midas (the distantly-related genotype) were intermediate (Figure 4.3). However, there were no significant differences detected among genotypes for above-ground competitive ability (Chapter 4). This suggests that the competitive ability of field pea plants may be driven by root competition more than shoot competition (Semere & Froud-Williams, 2001).

Bloom et al. (1985) demonstrated that plants which keep their normal biomass allocation even when neighbor plants are present have a better ability to withstand competition from neighboring plants than those that respond vigorously by allocating more biomass to the roots or shoots. Interestingly, the sister lines (CDC1897-3 and CDC1897-14) did not alter their biomass allocation in the presence of any of the neighboring plants in this study (Tables 4.5, 4.7, 4.9), which suggests that CDC1897-14 and CDC1897-3 have the ability to withstand competition from neighboring plants and may be better able to tolerate competition in the field. In contrast, Midas exhibited a significant increase in root biomass allocation when combined with other genotypes, which indicates that Midas had a lower ability to withstand the presence of neighboring plants compared to the sister lines (Tables 4.4, 4.8, 4.9). This agrees with the findings of Cahill et al. (2003), Mokany et al. (2006), and Swanton (2005) who demonstrated that under unfavorable soil conditions, plants put more energy into root production rather than shoot growth, which can result in significant yield reductions.

Results presented in this thesis show that the components of a mixture affect the overall mixture productivity in field pea, and thus, choosing mixture components can be an important consideration in finding successful mixtures. For example, CDC1897-3 and Eclipse genotypes exhibited complementarity, which was observed as improved competitive ability when grown in a mixture. However, Eclipse and Midas were antagonistic to each other when grown in a mixture and caused substantial yield reductions compared to monocultures. For that reason predicting the performance of mixtures is critical, but very complicated. Several researchers suggested that the productivity of mixtures could be predicted from the performance of the components in monocultures in different environments (Cheema et al., 1988; Early & Qualset, 1971; Gallandt et al., 2001). However, many other researchers demonstrated that because components grown in mixtures usually interact differently compared to when they are grown in monoculture, the performance of mixtures cannot be predicted solely based on their performance in monoculture (Akanda & Mundt, 1997; Baker, 1977; Finckh & Mundt, 1992). These results emphasize the importance of developing a method that can help predict the performance of mixtures, which would make growing mixtures more common and feasible for field pea growers.

5.2 Management Implications

The results of this thesis showed that although the four genotypes (CDC1897-3, CDC1897-14, Eclipse and SW Midas) have relatively similar vine heights, stand abilities, maturity dates and grain size and weights, their competitive abilities differ (Chapter 4). Thus, growers have options to compose mixtures with different competitive abilities without compromising the uniformity of yield.

Interestingly, combining closely-related genotypes that have different competitive abilities might improve a mixture's overall competitive ability (such as CDC1897-3 x Eclipse). This could be attributed to the mixtures' ability to take up moisture and nutrients from the soil in various conditions and environments (Stutzel & Aufhammer, 1990) and to complementarity between mixture components (Early & Qualest, 1971). This shows that mixtures have potential to improve the field pea competitive ability against weeds. However, finding suitable mixture components is still a great challenge with regard to feasibility and practicality.

Although field pea is an important crop in organic farming because of its nitrogen benefits, the crop's poor competitive ability makes managing weeds a major challenge. For that reason, the potential of genotypic mixtures to improve field pea competitive ability against weeds makes growing mixtures under organic management systems more acceptable.

Finally, the current thesis did not detect strong evidence for the benefits of using field pea mixtures. Most mixtures used in this study performed similar to their respective components in monocultures. However, field pea mixtures should be considered if field pea growers are planting a poorly competitive genotype as results from this thesis showed that combining poorly competitive genotypes with strong genotypes did improve competitive ability.

5.3 Future Research

The results of this study were based on only four genotypes that have similar phenotypic characteristics. Therefore, including more genotypes to identify which traits confer competitive ability of field pea is needed. In addition, growing mixtures composed of different components under a wide range of environments is essential to investigate the yield stability of mixtures, and to determine the characteristics needed to compose mixtures with high and stable yields. These studies would help plant breeders to focus on the traits that produce genotypes with improved competitive ability.

It is also important to note that mixtures in this study were only composed of two components. However, many cultivar mixtures of different crops showed that complex mixtures (composed of three or more components) performed better than those composed of two components (Dubin & Wolfe, 1994; Helland & Holland, 2001; Mundt et al., 1995).

Moreover, increasing diversity within field pea mixtures by including three or more components could improve the crop's productivity. For example, forage field pea genotypes have better competitive abilities (Semere & Froud-

Williams, 2001) and semi-leafless genotypes have better protein content (Cupina et al., 2010); growing mixtures of forage and semi-leafless field pea genotypes could help forage growers to increase their forage quality and productivity. Studying the feasibility of this approach may provide unique results that would allow for more diverse mixtures than used in the current study.

In this study, a greenhouse experiment was conducted under optimal growing conditions; however, Sage (1971) suggested that the advantages of mixtures would only be observed when mixtures were grown under adverse environmental conditions. Thus, introducing drought or nutrient stress into mixtures is suggested to investigate the level of complementarity between mixture components.

The current study also noted that field pea plants might have responded differently to the identity of neighbors and thus, studying whether field peas possess self-discrimination mechanisms or can identify other genotypes could provide valuable information for plant ecologists. In addition, studying below-ground and above-ground signaling and mechanisms of competition is extremely important, as this will aid our understanding of the implications of above- and below-ground mechanisms for crop-crop and crop-weed interactions.

Results presented in this thesis also show that choosing which genotypes are included in mixtures can be an important consideration in finding successful field pea mixtures. Therefore, developing criteria to decide which genotypes are more suitable to include in a mixture is crucial. In addition, identifying the major characteristics of genotypes that can complement other components and determining how to predict their performances when combined in mixtures would prove useful in constructing high-yielding, robust field pea mixtures.

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Appendix I. Weights and percentages of weight difference (Wt. diff.) after dehulling has been performed on 100 gram samples of the four field pea monocultures plus six resulting 50:50 ratio mixtures grown in weed-free stands at St. Albert, and Lethbridge in 2010.

	St. Albert		Lethbridge	
Genotypic composition	Wt. after dehulling	Wt. diff.	Wt. after dehulling	Wt. diff.
	grams	%	grams	%
CDC1897-3	68	32	76	24
CDC1897-14	70	30	74	26
Eclipse	51	49	68	32
Midas	72	28	72	28
CDC1897-3 x CDC1897-14	76	24	72	28
CDC1897-3 x Eclipse	62	38	78	22
CDC1897-3 x Midas	74	26	66	34
CDC1897-14 x Eclipse	76	24	74	26
CDC1897-14 x Midas	72	28	74	26
Eclipse x Midas	70	30	70	30