INTERCROPPING STUDIES IN ORGANIC PEA PRODUCTION

BY

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ABSTRACT

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Semi-leafless field peas (*Pisum sativum* L.) do not compete well with weeds and synthetic herbicides are prohibited in certified organic crop production. Therefore, significant interest has been placed on the development of alternative strategies of weed management in organic field pea production. Pea intercropping has recently become popular in the Canadian Prairies as a means of suppressing weeds. However, little research has been completed on additive pea intercrops under organic management. The objectives of this research project were to evaluate different yellow pea (cv. CDC Amarillo) intercrop mixtures to examine their effect on weed suppression, grain yield and quality, plant growth, and profitability. In 2019 and 2020 three separate pea intercrop experiments were completed in Carman Manitoba, Canada, under organic management. The three experiments were separated by companion crop species. Peas were planted in both monoculture and additive intercropping designs with low, medium, or high seeding rates of barley (*Hordeum vulgare* L.), mustard (*Brassica juncea* L.), or oats (*Avena sativa* L.). When averaged across site-years weed biomass suppression varied between the three experiments. The medium and high seeding rates reduced ($P<0.05$) weed biomass by 17% to 44% and resulted in a significant ($P<0.05$) pea yield penalty from 8% to 26%. Pea-cereal intercropping appeared to provide a greater level of weed biomass suppression compared to pea-mustard intercropping. Furthermore, pea-mustard intercrops were unstable across the three site-years suggesting that pea-mustard intercropping in organic production may result in unpredictable outcomes. In most instances, across all three experiments, pea growth and grain quality were not affected by intercropping. Intercropping did not increase net returns across a wide range of market conditions. In conclusion, while all three intercrop mixtures exhibited the ability to suppress weed biomass, substantial reductions in pea yields were observed and the contribution of the non-pea companion crop grain yield did not benefit net returns significantly.

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Figure 16. Initial net returns of pea monoculture and three pea-oat intercrop treatments (pea + low oat, pea + med. oat, and pea + high oat) at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020. Error bars represent standard errors of the least-squares means. Treatments are clustered by site-year. Means with different letters are significantly different (Tukey's HSD, $p<0.05$).

Figure 17. Percent reduction in pea grain yield and weed biomass by three pea-barley, three pea-mustard, and three pea-oat intercrop treatments, compared to pea monoculture, averaged across site-years at the Ian N. Morrison Research Farm in 2019 and 2020.

1 INTRODUCTION

From 2015 to 2018 there has been a 40% increase in organic field pea acreage, reaching over 52,600 hectares (Canadian Organic Trade Association, 2018). Adding field peas to an organic rotation can increase crop diversity and disrupt the lifecycles of disease and weed communities (Anderson, 2005; Ma, 2016). Furthermore, in low-input agriculture, such as organic systems, the addition of a leguminous crop such as field peas can add nitrogen to the soil (Wallace & Canadian Organic Growers, 2001). Unfortunately, organic field pea production comes with a number of risks. For example, semi-leafless field peas do not compete well with weeds and it is recommended that field peas be planted a maximum of once every four years to reduce the risk of disease (Saskatchewan Pulse Growers, 2019a; Spies et al., 2010). Because synthetic herbicides, fungicides, and fertilizers are prohibited in certified organic agriculture, weed and disease control, as well as fertility management, is especially difficult for organic pea producers.

Intercropping peas with other crops, such as cereals and mustard, has emerged as a unique way to manage the risks associated with organic field pea production. Pea intercropping has been found to suppress weeds and disease, increase grain size, provide over-yielding, and reduce the incidence of lodging (Corre-Hellou et al., 2011; Langat, 1992; Pridham & Entz, 2008). Intercropping field peas with different crops such as wheat (*Triticum aestivum*), oats, barley, and mustard has been previously studied (Arlauskiene et al., 2014; Bedoussac & Justes, 2010a; Pridham & Entz, 2008). However, past studies have mainly used peas as a companion crop and not the dominant crop in the production system (Bedoussac & Justes, 2010b; Monti et al., 2016). In addition, many studies have focused their research on the nitrogen-providing capabilities of peas (Izaurralde et al., 1992; Patra et al., 1986) and not their yield and economic potential in an intercropping system. Furthermore, few studies focus on pea dominant intercrops in a certified organic context.

Many intercropping studies use replacement pea-intercrop designs whereby two crop species are planted in ratios of 50:50, 66:33, or 70:25, equating to a total plant density of 100% (Nelson et al., 2012). Weed suppression in replacement pea-intercrop designs has been well documented but varies between seeding rate and crop species (Arlauskiene et al., 2014; Corre-Hellou et al., 2011; Nelson et al., 2012). In addition, replacement pea-intercrop designs have been found to result in over yielding due to complimentary resource use between crop species. However, due to the lack of competitiveness of field peas and low seeding rates of the individual crop species, replacement designs such as a 50:50 ratio may not result in substantial pea yields and weed control may be low (Nelson et al., 2012; Pelzer et al., 2016; Pridham & Entz, 2008). Additive intercrop mixtures, whereby intercrops are formed by adding plants of one crop species to another crop species with a 100% total plant density, have been found to suppress weeds, however overyielding has not been well documented. It is hypothesized that additive intercrops may not result in a yield benefit because the high total plant density may lead to greater levels of inter and intra specific competition, thus reducing pea yields. Little research has been completed on the potential effects of additive intercrop designs on grain yield, and therefore demands further study.

The objectives of this study were to evaluate additive organic pea intercrop mixtures to further understand their impact on:

1) Weed suppression
2) Grain yield
3) Plant growth and grain quality
4) Profitability

The hypotheses that were generated from the objectives were:

i. Pea intercrops (barley, oat or mustard) will suppress weeds to a greater extent than pea monocultures due to increased crop density and resource use
ii. Pea intercrops (barley, oat or mustard) will have a negative effect on pea grain yields due to inter-specific competition
iii. Pea intercrops (barley, oat or mustard) will have a negative effect on pea growth and grain quality
iv. Pea intercrops (barley, oat or mustard) will be more profitable than pea monocultures due to the additional harvest of non-pea grain obtained from intercrops

2 LITERATURE REVIEW

2.1 Organic Crop Production in Canada

In 1962 Rachel Carson published *Silent Spring* which established the organic movement as an important component of the modern environmental movement (Kristiansen & Merfield, 2006). The modern organic agriculture movement was established by environmentally conscious farmers who wanted to distinguish their products from conventionally produced products. Organic farms will more often than not have a lower environmental impact than their conventional counterparts (Tuomisto et al., 2012). Hoeppner et al. (2006) compared on-farm energy use and efficiency (MJ ha^{-1} yr^{-1}) in the same organic and conventional crop rotations (wheat-pea-wheat-flax) and found that the conventional system had a 180% increase in on-farm energy use per unit area, because of the use of synthetic fertilizer and pesticides. There is strong evidence that organic farms have higher biodiversity than their non-organic counterparts (Bengtsson et al., 2005; Fuller et al., 2005; Hole et al., 2005; Maeder et al., 2002; Smukler et al., 2010). In a meta-analysis that compiled results on this topic it was found that organic farms on average had greater species richness and abundance, compared to their conventional counterparts (Bengtsson et al., 2005).

The recent growth in demand for certified organic products is due to the consumer's desire for products that are produced using ecologically sustainable practices. In 2019, there were over 5,600 certified organic producers in Canada, equating to a total of over 1.3 million certified organic hectares (Canadian Organic Trade Association, 2019). In 2018, 389,700 hectares were planted to organic cereals, pulses, and oilseeds across the Canadian Prairies (Alberta, Saskatchewan, and Manitoba) (Canadian Organic Trade Association, 2018). Of the 389,700 hectares that were planted, 68% were cereals, 20% were pulses, and 8% were oilseeds (Canadian Organic Trade Association, 2018). In order of greatest to lowest acreage, the most common organic cereals grown throughout the Canadian Prairies are wheat (*Triticum aestivum* L.), oats (*Avena sativa* L.), barley (*Hordeum vulgare* L.), and rye (*Secale cereale* L.), respectively (Canadian Organic Trade Association, 2018). The most common pulses grown include peas (*Pisum sativum* L.), lentils (*Lens culinaris* Medik.), and beans (Fabaceae), and the most common oilseeds include flax (*Linum usitatissimum* L.) and mustard (*Sinapis alba* L. and

Brassica juncea L.), respectively (Canadian Organic Trade Association, 2018). While these statistics outline the most common organic crops grown across the Canadian Prairies, they fail to detail the specifics regarding on-farm crop rotations and farm management.

The Canadian Food Inspection Agency designates conformity verification bodies and certifying bodies to verify and enforce the Canadian Organic Standard (Government of Canada, 2002). The Canadian Organic Standard requires that "soil fertility and biological activity shall be maintained or increased through: crop rotations that are as varied as possible and include plough-down, legumes, catch crops and deep rooting plants." (Government of Canada, 2002). Organic farming is site-specific and crop rotations have been found to vary between farms (Knight et al., 2010). Knight et al. (2010) completed a survey of 39 organic farms across Saskatchewan Canada, representing 60 individual organic fields and their associated crop rotations. Of the 60 fields, 17% were perennial forages, 30% were mainly under summer fallow, 30% were considered a "diverse rotation", including broad-leaved crops, legumes, some cereals and some summer fallow, and 23% were considered a "cereal rotation", including mainly cereals and some summer fallow. Organic farms on the Canadian Prairies will often include the integration of livestock into the cropping system, as well as large areas of permanent pasture (Entz et al., 2001). Entz et al. (2001) found that organic farms throughout Saskatchewan, Manitoba, and North Dakota ranged from 28 to 367 ha in size, with a large portion of certified land being seeded to forage-type crops. In Wallace & Canadian Organic Growers (2001) a number of organic farmers presented their crop rotation plans and many of them illustrate the incorporation of perennial forages like alfalfa (*Medicago sativa* L.) as being the foundation of their crop rotation plan. For example, Moose Creek Organic Farm in Oxbow, Saskatchewan, incorporates alfalfa into seven growing seasons of their thirteen-year crop rotation. The use of perennial forages in organic crop rotations to enhance soil quality, increase levels of available nitrogen, and suppress weeds has been well documented in scientific literature (Arshad et al., 2011; Entz et al., 1995; Ominski et al., 1999).

While organic grain farms across the Prairies contain a range of different crop rotation plans, there is a consistent level of diversity in crops being grown that is generally not seen in many of the larger non-organic grain farms. However, the amount of summer fallow that Knight et al. (2010) observed should not go unnoticed. Summer fallow is conducted by farmers to retain winter precipitation, control weeds and mineralize nutrients (Campbell et al., 2008; Hunt et al., 2013; Wuest & Schillinger, 2011). Unfortunately, summer fallow will cause wind and water erosion (Mikha et al., 2013; Pi et al., 2018). In addition, having the soil bare for an entire growing season increases the downward movement of nitrates, increasing the risk of nitrate leaching (Campbell et al., 1984). In non-organic agriculture, to better manage soil erosion and nitrate leaching, summer fallow has been replaced by the incorporation of a pulse crop into many crop rotations across the Canadian Prairies (Carlyle, 2004). Increasing organic pulse acreages may lead to fewer acres being subjected to summer fallow.

2.2 Weeds in Organic Crop Production

In organic crop production, weeds play a major role in the reduction of yields and net returns (Caldwell et al., 2014). Because synthetic herbicides are prohibited in organic agriculture, to manage weeds, farmers must use a multi-tactical approach, using a combination of cultural and mechanical strategies and approved herbicides (Bàrberi, 2002; Wallace & Canadian Organic Growers, 2001).

There is often a disconnect between organic farmers and the scientific community (Zwickle et al., 2016). Thus, the diffusion of information regarding weed management tactics in organic agriculture will often occur through word-of-mouth between farmers, and personal experience (Zwickle et al., 2016). Historically, a reductionist approach – whereby studies deal with “specific research issues out of a system framework” – to weed management has been taken, making the long-term, holistic approach – whereby studies deal with weed management in a system context” – that is required in organic agriculture difficult for organic farmers (Bàrberi, 2002; Frick, 1993; Zwickle et al., 2014, 2016). Bàrberi, (2002) reviewed 101 papers on the topic of weed management, published between 1995 and 2000 and found that 64% were viewed through a “reductionist” lens, rather then a “holistic” lens (Bàrberi, 2002). Furthermore, the adherence to a long-term, holistic approach to weed management varies from farmer-to-farmer, thus the level of weeds vary (Thiessen Martens et al., 2019; Zwickle et al., 2016).

Frick, (1993) observed that organic fields have a greater diversity of weeds, compared to their non-organic counterparts. In two studies that surveyed weed communities in organic and non-organic fields across the Canadian Prairies it was found that wild mustard (*Sinapis arvensis* L.) and Canada thistle (*Cirsium arvense* L.) were more common on organic farms (Entz et al., 2001; Frick, 1993). Thiessen Martens et al. (2019) found that in 41 fields planted to organic green manures across Manitoba and Saskatchewan the average weed biomass was 675 kg ha^{-1} (0 to 3266 kg ha^{-1} range). In a 2-year experiment, organic monocultures of wheat, barley, canola (*Brassica napus*), and peas were grown at the University of Alberta, Edmonton and a certified organic farm near Camrose, Alberta (Nelson et al., 2012). Similar to Thiessen Martens et al. (2019) study, a wide range of weed biomass (25 to 868 kg ha^{-1} range) was measured between the four different crops (wheat: 140 kg ha^{-1}; barley: 52 kg ha^{-1}; canola: 556 kg ha^{-1}; pea: 430 kg ha^{-1}), across the two sites (Nelson et al., 2012). By comparison, Nelson et al. (2012) found that non-organic plots treated with chemical weed control contained weed biomass levels that were lower (wheat: 97 kg ha^{-1}; barley: 12 kg ha^{-1}; canola: 57 kg ha^{-1}; pea: 255 kg ha^{-1}). The level of weed biomass found in the four different crops, across both organic and non-organic sites, aligns well with Blackshaw et al. (2002) who found that wheat and barley have similarly greater weed competitive abilities than peas and canola, and Frick, (1993) who observed more weeds in organic fields.

2.3 Organic Field Pea Production

2.3.1 Role of Peas in Organic Rotation

In 2018, 97% of Canadian organic pulses, including field peas, were produced on the Canadian Prairies (Canadian Organic Trade Association, 2018). From 2015 to 2018, the acreage dedicated to organic pulses on the Canadian Prairies increased by 117% from 35,800 hectares to 77,950 hectares (Canadian Organic Trade Association, 2018). Much of the growth in organic pulse production can be attributed to the 40% increase in organic field pea acreage (Canadian Organic Trade Association, 2018).

The addition of field peas to a cereal dominant rotation will help break disease cycles and disrupt the lifecycle of weed communities (Anderson, 2005; Ma, 2016). Because the use of synthetic fertilizer is prohibited in certified organic agriculture, nitrogen is often a limiting factor to successful organic crop production (David et al., 2005; Government of Canada, 2002). Thus, having a pulse such as field pea in an organic rotation is fundamental to sustainable fertility management (Wallace & Canadian Organic Growers, 2001). Field peas are a leguminous crop that are capable of fixing atmospheric nitrogen through biological interactions with *Rhizobium* bacteria (Raza et al., 2020). In organic agriculture, field peas will generally follow a nitrogen depleting crop, such as a small cereal grain (Wallace & Canadian Organic Growers, 2001). While much of the biologically fixed nitrogen that could potentially be provided to the subsequent crop that follows a pea crop is lost when the pea seed is harvested, the residue produced can still add up to 15 kg ha^{-1} nitrogen to the soil for the subsequent crop (Beckie & Brandt, 1997). Non-legume crops that follow a legume crop will consistently have higher grain yields than if the same crop had followed a non-legume crop (Beckie & Brandt, 1997; Przednowek et al., 2004; Wright, 1990). For example, Przednowek et al. (2004) found that of four commonly grown leguminous grain crops (field pea, dry bean, chickpea, and soybean) field peas provided the greatest yield increase to the subsequent wheat crop over three of the four site-years in the study.

In addition to peas grown as cash crops many organic producers incorporate a leguminous based green manure or cover crop into their rotation to manage fertility and weeds, and to reduce the risk of plant diseases in the subsequent crop (Henriksen & Eltun, 2007; Larkin et al., 2011; Snyder et al., 2016). A survey of green manure productivity on organic farms in Saskatchewan and Manitoba found that green manures that included field peas contained a nitrogen concentration of 15 to 35 g per kg^{-1} of dry matter and a nitrogen fixation estimate of 7 to 89 kg ha^{-1} (Thiessen Martens et al., 2019). A leguminous green manure may result in more available nitrogen to the subsequent crop when compared to a leguminous grain crop, however, the use of a full-season green manure results in a lack of economic return during the growing season. For example, Zentner et al. (2006) compared net returns of a legume green manure-wheat rotation, and a continuous wheat rotation and found that the continuous wheat rotation offered the highest net returns ($41 ha^{-1}), $25 ha^{-1} more than the legume green manure-wheat rotation. The Province of Manitoba estimates that organic farmers in Manitoba should budget between $32.43 to $121.77 ha^{-1} yr^{-1} for inclusion of a green manure crop once every four years in rotation (Province of Manitoba, 2020c). The cost of seeding a cover crop, alongside the potential for poor establishment is a risk to organic farmers.

The addition of field peas to an organic crop rotation can provide significant benefits to the productivity and sustainability of the agroecosystem. However, organic semi-leafless pea production comes with a range of potential issues that must be addressed to ensure that the benefits of incorporating a legume such as field peas into a crop rotation are not over-shadowed by the common problems that come with organic field pea production.

2.3.2 Current Organic Field Pea Production Methods

Saskatchewan Pulse Growers recommend that conventional field pea producers establish a target plant density of 75 to 85 plants m^{-2} (Saskatchewan Pulse Growers, 2019b). However, Baird et al. (2009) found that the optimal target plant density for organic field pea producers is 120 plants m^{-2}. The 31% increase in target plant density is recommended to combat the poor ability of semi-leafless field pea cultivars to successfully suppress weeds in organic farming systems, where weeds are often more prevalent (Baird et al., 2009; Frick, 1993). Semi-leafless field pea cultivars are less competitive with weeds than the less commonly grown leafed pea cultivars because semi-leafless pea cultivars have tendrils instead of auxiliary leaf's, resulting in lower light interception (Spies et al., 2010). Due to the late canopy closure that is associated with semi-leafless field peas, early season perennial and annual weeds can cause significant field pea yield losses (Boerboom & Young, 1995).

Yield losses in pea production due to weeds is an annual concern for farmers, and a survey of Alberta pea, barley and canola fields found that 67% of the surveyed pea fields suffered significant yield losses due to weeds, with peas suffering the greatest losses of all three surveyed crops (Harker, 2001). Organic farms will typically have a greater level of weeds when compared to their non-organic counterparts, thus yields may be impacted to a greater extent (Frick, 1993). Entz et al. (2001) found that average on-farm organic pea yields, under various planting densities and weed conditions, were 1257 kg ha^{-1} (201 to 2690 kg ha^{-1} range). In a experimental setting, under weedy conditions, Baird et al. (2009) found that organically grown field peas in Saskatchewan displayed a yield of 1725 kg ha^{-1} with a plant density of 146 plants m^{-}

[2]. Baird et al. (2009) and Entz et al. (2001) results provide a realistic understanding of typical on-farm organic field pea yields.

The prohibition of synthetic herbicides in organic agriculture, alongside the poor competitive ability of semi-leafless pea cultivars, has resulted in a range of cultural and mechanical weed management methods that have been adopted by organic farmers and researched by agronomists. For example, a combination of pre and post emergent inter and intra row cultivation is a common practice to manage weeds in organic field pea production. However, pre and post emergent mechanical weeding in organic field peas requires an additional pass over the field after seeding resulting in additional operational costs (Alba, 2019). Furthermore, pre and post emergent mechanical weeding is time sensitive as it must be done at specific times in the growth stage of weeds and/or the crop (Alba, 2019; Stanley et al., 2018). Mixtures of leafed and semi-leafless pea cultivars, as well as increasing monoculture and mixture seeding rates has been found to reduce weed biomass (Syrovy & Shirtliffe, 2013). Similarly, pea and cereal or oilseed intercropping is commonly practiced by organic farmers – the increased density and associated interspecific competition will suppress weeds in the field and may reduce the need for mechanical weed management.

2.4 Intercropping in Canada

2.4.1 Introduction to Grain Intercropping

Intercropping, whereby two or more different crop species are grown in close proximity. The benefits of intercropping include weed and disease suppression, reduced lodging, efficient resource use, and soil erosion protection (Corre-Hellou et al., 2011; Podgórska-Lesiak & Sobkowicz, 2013; Pridham, 2006; Wall et al., 1991). In addition, research shows that the crop diversification associated with intercropping can lead to increased per hectare yields and gross returns, as well as reducing the risk of total crop failure (Anil et al., 1998; Martin-Guay et al., 2018).

While intercropping has recently gained popularity in modern agriculture across Canada, it is not a newly invented production system. A diversity of intercropping systems, many of which have been practiced by Indigenous peoples for centuries, has been well documented across North America (Vandermeer, 1992). For example, Wilson et al. (1917) documented traditional Hidatsa gardening in what is now considered North Dakota USA and found that beans were traditionally planted between rows of corn (*Zea mays* L.). Similarly, milpa- an agroforestry system that is traditionally practiced by the Maya people of the historical region of Mesoamerica- involved the intercropping of corn, beans, and squash (*Cucurbita* L.) (Nigh & Diemont, 2013).

Relay intercropping is when two or more different crop species are planted together but their growth and development is staggered to ensure that maturation does not take place at the same time. In Canada, relay intercropping has traditionally been practiced whereby two crops are grown with only one being harvested for grain. For example, a common relay intercropping system includes field crops under-seeded to alfalfa or red clover (*Trifolium pratense* L.) (Blackshaw et al., 2010; Wall et al., 1991). In the first year, the alfalfa or clover is grown with the cash crop to suppress weeds, and in the following years the alfalfa is used as a green manure plough down or forage crop.

As the scale of organic farms has grown, there has been more focus on the intensification of organic grain systems. Thus, mixed intercropping to produce two grain cash crops is becoming increasingly popular among organic grain farmers across the Canadian Prairies. Mixed intercropping refers to two or more crop species grown together with little temporal and spatial segregation (Brooker et al., 2015). In mixed intercropping, crops are seeded together, grow in the same rows, and are generally harvested at the same time. Across the Canadian Prairies, mixed intercropping is commonly practiced as a method of producing two different grain crops on the same field. In a mixed intercrop the two different crop species are often paired together because they provide a certain level of resource complementarity, and facilitation through modifications to the environment. Data from the Saskatchewan Crop Insurance Corporation and the Manitoba Agricultural Services Corporation found that in 2020 the most common intercrops insured by non-organic and organic producers were pea and oat or canola intercrops. Additional mixed intercrops that are practiced in Canada include pea-barley, flax-wheat, chickpea (*Cicer arietinum*)-flax, and chickpea-mustard (Wallace & Canadian Organic Growers, 2001).

2.4.2 Management Considerations in Organic Grain Intercropping

Growing two different crop species together in an intercrop can lead to plant-plant interactions. For example, interspecific competition may occur between two crops when one crop species modifies the environment of the other crop species (Vandermeer, 1992). In contrast, complementarity may occur between crops when the two crop species are not in competition for the same resources, thereby leading to an increase in total productivity (Vandermeer, 1992). Finally, facilitation may occur when one crop species modifies the environment in a way that benefits at least one of the crop species in the intercrop (Vandermeer, 1992).

Organic farmers will often plant replacement intercrop mixtures that are formed by replacing a given number of plants of one monoculture species density by the same number of another crop species. Thus, in replacement designs the densities of both crops will often end up being lower than their recommended monoculture densities. By reducing the densities of the two crops to form a replacement design, the risk of competition between the two crop species is reduced (Vandermeer, 1992). However, in a replacement design that uses for example, equal ratios of 50:50, the individual per hectare grain yields of the two crops may end up being low because of the low planting densities of the individual crop species (Nelson et al., 2012).

Grain intercrops may also be planted as additive mixtures whereby mixtures are formed by adding plants of one crop species to another crop species with a monoculture density. Additive designs favour one crop over the other. The most common additive design is one in which a recommended monoculture density of one crop species includes a density of another recommended monoculture density that has been reduced.

In community ecology, the competitive exclusion principle dictates that if the environmental niche requirements of two species are similar, they cannot occupy the same niche (Vandermeer, 1992). Interspecific competition is a form of competition whereby different plant species are in competition for the same resources. In grain intercropping, as one crop species density is increased over another with similar environmental niche requirements, the level of interspecific competition will increase, resulting in reduced biomass and crop yields of the crop species that is being outcompeted (Pelzer et al., 2016; Vandermeer, 1992). The level of interspecific competition within an intercrop can be manipulated by the intercrop design and the ratios of plant densities within the intercrop design. In an additive design the increased crop density increases both inter and intra-specific competition for resources which may significantly impact per plant grain yields. Whereas a replacement design, if planted at the right densities, should increase per plant yields due to inter species complementarity in resource use (Vandermeer, 1992). While individual crop yields may not be as high in proportional replacement designs, due to lower crop densities, they have been found to have greater yield stability than additive designs (Raseduzzaman & Jensen, 2017). Furthermore, both replacement and additive designs have been found to facilitate reductions in weed biomass (Corre-Hellou et al., 2011). However, if the goal is to favour the productivity of one crop species and take advantage of the weed suppressing capabilities of the other, an additive design may be more beneficial than a replacement design due to its potential ability to maintain high grain yields of the dominant crop species.

In addition to manipulating crop densities to promote competition and/or facilitation, farmers can control the relative ratios of intercrops to encourage resource complementarity. For example, in a pea and cereal or oilseed intercrop, at certain points in the crop-cycle, there exists an interspecific plant-plant relationship between the two species. Because of the nitrogen fixing capabilities of peas, the two different plant species are not competing for the same chemical forms of nitrogen. However, during the beginning of plant growth (before nitrogen fixing nodule communities have fully formed on the root mass of the peas) both peas and the other crop will compete for the same chemical form of nitrogen (Bedoussac et al., 2015). Bedoussac & Justes (2010) found that if a winter pea-winter wheat intercrop is planted in nitrogen rich soil, the wheat will outcompete the peas early in the crop-cycle, reducing the final biomass of the pea crop. Similar effects were observed in a pea-mustard intercrop study (Waterer et al., 1994). According to Bedoussac & Justes (2010) and Hauggaard-Nielsen et al. (2009), peas thrive in low nitrogen soil conditions, and nitrogen use efficiency is higher in pea intercrop treatments than their monoculture counterparts. Therefore, pea intercrops are best used in low-input farming systems, like organic agriculture, where nitrogen is often a limiting nutrient, or in a phase of the crop rotation where nitrogen supply is low.

Due to the complexity of individual agroecosystems, it is difficult to identify standards for the design and management of intercrops. However, Bedoussac et al. (2015) identified two general rules when using intercrops: “i) improve use of light energy and ii) improve use of nitrogen sources”. These two rules help summarize the important inter species interactions to consider within a grain intercrop, however, they are in reference to the more commonly practiced cereal-dominant intercrops that are used to maximize cereal productivity or cereal grain quality and not pea productivity or pea grain quality.

2.5 Organic Pea Intercropping

2.5.1 Pea Intercrop Companion Crops

Organic farmers across the Canadian Prairies plant a number of different pea intercrop mixtures, however, pea-oat, pea-barley and pea-mustard are consistently favoured. Barley, oats, and mustard are compatible with peas in an intercropping system because they carry traits that can reduce the risk of crop damage and monetary loss from many of the common agronomic issues that are associated with organic field pea production. For example, legumes such as field peas are known to experience unstable yields and lack the ability to tolerate variable environmental conditions such as high soil moisture and high temperatures at flowering (Jiang et al., 2019; Rahman et al., 2020; Watson et al., 2017). In a pea intercropping system, barley, oats, and mustard are considered tolerant to variable soil and environmental conditions, which may allow them to generate yields in circumstances where pea productivity is depressed, thus, reducing the risk of total crop failure (Altieri et al., 2015).

For weed suppression, barley and oats are often included in pea intercrops because they have a greater competitive ability against early season weeds than field peas, due to rapid canopy development and allelopathic compounds found in their plant residue (Beres et al., 2010; Bouhaouel et al., 2015; Satorre & Snaydon, 1992; Wallace & Canadian Organic Growers, 2001). Barley and oats are cool-season annual cereals belonging to the Poaceae family (Sustainable Agriculture Research and Education, 2021a, 2021b). Mustard is a cool-season annual oilseed that belongs to the Brassicaceae family (*Brassicas and Mustards*, 2021). Although *brassicas* have been found to have a weaker competitive ability against weeds when compared to barley and oats, their rapid growth and high level of biomass production can result in weed suppression (Blackshaw et al., 2002; *Brassicas and Mustards*, 2021).

The differences in root architecture between different crop species in an intercropping system can facilitate the extraction of soil nutrients and water from different zones in the soil profile, leading to a more efficient use of resources and yield advantage (Zhang et al., 2014). Field peas have a shallow root system with the majority of the root biomass within approximately 0.6 m of the soil surface (North Dakota State University Extension, 2016). Mustard has a tap-root structure (0.3 to 1 m length) which centralizes the majority of the root biomass in one area (Province of Ontario, 2016c). In comparison, oats and barley have deep fibrous root structures that can reach depths of 0.84 to 1.95 m and 1.8 to 2.1 m, respectively (Province of Ontario, 2016a, 2016b).

Understanding common organic seeding rates of potential pea intercrop candidates and their potential yields can help researchers understand the impact on productivity when incorporated in an intercrop. High seeding densities of spring cereals will increase crop competitiveness with weeds, thus it’s recommended that monoculture organic seeding rates be greater than non-organic monoculture rates (Baird et al., 2009; Mason et al., 2007; O’Donovan et al., 1999). Beres et al. (2010) found that barley plant densities of 210-400 plants m^{-2} were productive in weedy conditions, yielding an average of 5352 kg ha^{-1} of grain and 10,024 kg ha^{-1} total biomass. Although treatments received a range of herbicide applications, wild oat (*Avena fatua* L.) and canola were broadcast throughout plots as surrogates to generate uniform weedy conditions. It has been recommended that oats be seeded to reach a target plant density of 200-270 plants m^{-2} in organic production (Wallace & Canadian Organic Growers, 2001). Arlauskiene et al. (2014) found that under organic management oat monocultures planted at densities of 259-499 plants m^{-2} resulted in average grain yields of 3135 kg ha^{-1} (2308-4314 kg ha^{-1} range).

A common mustard in organic rotations is a canola-quality mustard cultivar, such as oriental mustard. Beckie et al. (2008) found that in weedy conditions, with an indigenous weed seed bank resulting in an average of 280 weeds m^{-2}, oriental mustard cultivars were more competitive with weeds than canola and yellow mustard cultivars. While *brassicas* are known to suppress weeds to a greater extent when compared to a crop such as field peas (Blackshaw et al., 2002), in an intercropping system weed suppression has been found to be lower than cereal intercrops, and flea beetle damage to mustard has been found to reduce the competitive ability of mustard (Nelson et al., 2012; Pridham & Entz, 2008). Little research has been completed on seeding rates for organic oriental mustard. Non-organic seeding rates are typically 4-6 lb acre to achieve a target plant density of 70-110 plants m^{-2} (Manitoba Agriculture and Resource Development, 2020b). In Beckie et al. (2008), oriental mustard was established with an average plant density of 98 plants m^{-2} in weedy conditions, resulting in an approximate average of 5000 kg ha^{-1} aboveground shoot biomass at maturity and 1400 kg ha^{-2} grain yield.

2.5.2 Weed Management in Organic Pea Intercropping

Intercropping can reduce weed populations in the field by outcompeting the weeds for light, water and nutrients (Carr et al., 1995; Corre-Hellou et al., 2011), and preventing weed seed germination (Anil et al., 1998).

The reduction in weed biomass that is associated with pea intercrops is achieved through competition, complementarity, and facilitation between the two crop species, resulting in increased resource use (light, water, nutrients), thereby reducing available resources for weeds (Bedoussac et al., 2015). For example, when compared to peas, crops such as barley, mustard and oats are known to emerge and establish rapidly, which can lead to early competition with weeds (Beres et al., 2010; *Brassicas and Mustards*, 2021; Satorre & Snaydon, 1992). In low-nitrogen soils, intercropping will increase the rate of N^2 fixation by peas (Hauggaard-Nielsen et al., 2009). Corre-Hellou et al. (2011) found that pea-barley intercrops that were established in an additive design reduced ($P<0.05$) weed biomass from 985 kg ha^{-1} to 279 kg ha^{-1}, when compared to a pea monoculture. Corre-Hellou et al. (2011) found that the total accumulation of soil nitrogen by weeds was greater ($P<0.05$) in pea monocultures, compared to pea-barley intercrops and barley monocultures. In contrast, the total accumulation of soil nitrogen by crops was greater ($P<0.05$) in the pea-barley intercrops and barley monocultures, compared to pea monocultures. These findings indicate that a greater depletion of soil nitrogen in the intercrops led to the reduction in weed biomass.

In pea-cereal intercrops, peas have been found to transfer nitrogen to cereals during the growing season. The mechanisms for nutrient transfer in pea-cereal intercrops are direct root-to-root contact, diffusion of root exudates, and arbuscular mycorrhizal fungi (Hupe et al., 2021). Nutrient transfer through arbuscular mycorrhizal fungi can lead to increased total crop productivity, and may result in weed suppression (Qiao et al., 2016), however, peas have been found to transfer nitrogen to a variety of weed species, which may increase the competitive ability of weed populations (Moyer-Henry et al., 2006). Legume root exudates lead to the liberation of phosphate, thereby increasing phosphorous uptake in the non-pea component crop (L. Li et al., 2007). In addition, cereal root exudates liberate iron and zinc, thereby increasing micronutrient uptake in legume crops when intercropped (Y. Xue et al., 2016).

Corre-Hellou et al. (2011) found that pea-barley intercrops that were established in an additive design to an approximate density of 150 plants m^{-2} barley and 90 plants m^{-2} peas reduced ($P<0.05$) weed biomass from 985 kg ha^{-1} to 279 kg ha^{-1}, when compared to a pea monoculture. In a similar pea-cereal intercrop study, Arlauskiene et al. (2014) used pea-barley and pea-oat intercrops in a 50:50 replacement design. Across 3 years and 2 sites the pea-barley and pea-oat intercrops reduced ($P<0.05$) weed biomass by 79 and 82%, respectively. In the pea-barley intercrop treatment of Arlauskiene et al. (2014) study the average pea plant density of pea was 38 plants m^{-2}, while the average plant density of barley was 254 plants m^{-2}. The 38 plants m^{-2} of pea is far lower than Baird et al. (2009)'s recommended 120 plants m^{-2} for monoculture organic field peas, while the barley establishment is similar to a recommended monoculture rate (Beres et al., 2010).

In a barley-pea intercropping experiment Poggio (2005) did not find that intercrops favoured annual weeds and/or perennial weeds, or vice versa. However, Poggio (2005) did observe lower winter-emerging weed populations when compared to spring-emerging weed populations, likely due to the early resource competitiveness of the intercropping mixtures. In a pea-cereal intercrop trial, Šarūnaitė et al. (2013) found that the abundance of weed functional groups changed over time within the intercropping systems. Annual weeds were more dominant during the beginning of the crop-cycle, but as the crop matured closer to the end of the growing season, perennial weeds were more dominant. Similar results would likely be observed in the Canadian Prairies, due to the ability of perennial weeds to exist during the drought conditions that are often associated with the timing of crop maturity.

2.5.3 Insect and Disease Management in Organic Pea Intercropping

In organic field pea production, it is recommended that peas be planted once every four years to mitigate plant disease (Saskatchewan Pulse Growers, 2019a). Intercropping peas with a cereal can potentially mitigate plant disease populations from establishing (Schoeny et al., 2010). According to Schoeny et al. (2010) the non-pea crop acts as a physical barrier between sources of ascochyta blight (*Mycosphaerella pinodes*) and the pea crop. In their research, Schoeny et al. (2010) didn't observe any reduction in blight on the stipules of pea plants but did see a reduction in disease on the pods and stems of the pea plants, in cases when blight populations were abundant. Similar results were found in Kinane & Lyngkjær (2002) research, however they hypothesized that the intercrop canopy may have resulted in a microclimate that was less favourable for ascochyta blight due to changes in temperature and humidity. In the Canadian Prairies, Pridham & Entz (2008) found that wheat-pea intercrops reduced the incidence of wheat flag disease, but no measurements were taken for pea disease. Pridham & Entz (2008) seeding rate was a 50:50 ratio of wheat:pea and resulted in yield instability and high levels of weed biomass. Similarly, Schoeny et al. (2010) used a 50:50 replacement design: The target plant density of peas in the intercrop was 80-90 plants m^{-2} and the target plant density for cereals was 150 plants m^{-2}. This 50:50 replacement design is used as the general method to develop seeding rates for intercropping systems. In order to further assess the capabilities of intercropping systems, it is important to research more varied seeding rates, such as additive designs.

Across the Canadian prairies, insect damage in field peas is not as prevalent of a concern as disease damage. One of the few insect pests in field pea is the pea aphid (*Acyrthosiphon pisum*). Intercropping has been found to suppress a wide range of insects across a number of different crops, including pea aphids on field peas (Corre-Hellou & Crozat, 2005; Lopes et al., 2016; RäMerti & Ekbom, 1996). However, few intercropping studies have centered on insect suppression in Canada, and many studies have found that insect suppression from intercrops is not highly effective (Lopes et al., 2016). In Europe, Ndzana et al. (2014) found that durum wheat-winter pea intercropping reduced the presence of pea aphid, compared to pea monocultures. Early in the growing season aphid infestation was similar, but as the growing season progressed the intercrops contained fewer numbers of aphids. Of interest to note is that Ndzana et al. (2014) found a negative effect on aphid populations across a wide range of intercrop designs, including mixed intercrops and row intercrops. Furthermore, Ndzana et al. (2014) found that pea monocultures which contained lower levels of biomass, contained lower populations of aphids, suggesting that pea density may increase insect infestation.

The species diversity in intercropping is regarded as the major mechanism behind insect suppression (Russell, 1989). One explanation for this is that insect pests in simpler agroecosystems such as monocultures are able to establish to a greater extent because resources are more accessible than in a more diverse cropping system such as intercropping (Russell, 1989). A second explanation is that a more diverse cropping system such as intercropping results in a diversity of predatory insects, and thus lower levels of individual insect species abundance (Russell, 1989).

2.5.4 Grain Yields in Organic Pea Intercropping

The intercrop design will influence the degree of interspecific competition, facilitation, and complementarity between the different crop species, which will ultimately influence final grain yields. Under organic conditions, Nelson et al. (2012) studied two, three, and four crop pea intercrop mixtures using a replacement design. Peas were seeded to plant densities that were proportional to a pure stand density of 75 viable seeds m^{-2} (two crop: 38 seeds m^{-2}; three crop: 25 seeds m^{-2}; four crop: 19 seeds m^{-2}). When averaged across two years and two sites, pea yields were found to be low (two crop: 54 kg ha^{-1}; three crop: 25 kg ha^{-1}; four crop: 22 kg ha^{-1}) and decreased as the number of crop species within the intercrop mixture increased (Nelson et al., 2012). Although the combined yield of the different crops from Nelson et al. (2012) study may have resulted in positive net returns, the pea yields represent poor yields relative to average organic monoculture yields and may not be advantageous to a farmer that may have certain yield expectations when producing organic peas.

Research completed in Redvers, Saskatchewan suggests that doubling the pea seeding rate in an additive pea-mustard intercrop (totalling 250% total plant density) was beneficial for pea yields, resulting in a 19% increase in pea grain yields when compared to the pea monoculture grain yields (Shaw, 2018). However, these results are based on one year of testing and therefore requires more exploration. Over two years, Bitew et al. (2020) studied, in an additive design, finger millet (*Eleusine coracana*) intercropped with haricot bean (*Phaseolus vulgaris*) (100:25; 100:50; 100:75). They found that monoculture finger millet yields were greater than the 100:50 and 100:75 intercrop treatments by 2 and 5%, respectively. However, in only one of two years were there significant differences in finger millet yields among 100:50 and 100:75 treatments, where it was found that as the density of haricot bean increased was increased by 25%, the finger millet yields were reduced by 8%. Organic farmers already seed at a higher seeding rate than non-organic for many crops (Mason et al., 2007), therefore increased plant densities in intercropping systems may lead to high adoption if the research can support it, especially if additive designs with 100:50 and 100:75 plant density ratios only reduce the dominant crop yields by 2 to 5% below monoculture yields, as seen in Bitew et al. (2020) research.

2.5.5 Grain Quality in Organic Pea Intercropping

As demand for plant-based protein products increases, Canadian pulse growers may focus on achieving high protein concentrations in their crops, instead of focusing on achieving the highest yield possible (Government of Alberta, 2020). Genotype, growing environment and availability of nitrogen can influence the seed protein concentration of a pea crop (Hood-Niefer et al., 2012; Igbasan et al., 1996). Wang & Daun (2004) observed a wide range of protein concentrations, ranging from 201.6 to 266.6 g per kg^{-1} dry matter, across four different pea varieties. While genotype plays a major role in protein concentration, generally, as nitrogen uptake by plants increases, the protein concentration of grain will increase (Holl & Vose, 1980; Igbasan et al., 1996). However, nitrogen uptake is highly dependant on environmental conditions. For example, Frimpong et al. (2009) found that in a Mediterranean semi-arid climate, during years that had low rainfall and high temperatures, the protein concentration of their pea crops increased due to smaller seed size. Stoddard et al. (1993) observed similar trends in Southern Australia. Both Stoddard et al. (1993) and Frimpong et al. (2009) observed that as yield increased due to a more favourable growing site-year, protein concentration decreased.

Multiple studies have observed increases in protein concentrations in cereals when intercropped with peas (Hauggaard-Nielsen et al., 2001; Lauk & Lauk, 2008). For example, Lauk & Lauk (2008) observed that cereal protein concentration increased by 2.6% as the seeding rate of intercropped peas increased from 0-120 seeds m^{-2}. In the Lauk & Lauk (2008) study, as the seeding rate of peas increased within the pea-cereal intercrop, the cereal protein concentration gradually increased, while the thousand kernel weight decreased. These findings were likely due to the fact that as the individual cereal seed size is reduced due to interspecific competition within the intercrop, the protein concentration will naturally increase. Beckie et al. (2008) studied canola and mustard cultivars under weedy and weed free conditions and found no significant change in seed oil and protein contents between treatments.

While multiple studies have identified protein dynamics of cereals when intercropped with peas, few studies have measured the potential change in protein concentrations of peas when intercropped with cereals or mustard. Langat (1992) studied pea and canola or mustard intercrops and found that the thousand kernel weight of peas was higher in intercrop treatments, when compared to monoculture treatments. Langat (1992) hypothesized that the change in thousand kernel weight was due to the interspecific competition within the intercrop, causing poor pod development, resulting in fewer seeds within each pod, but higher individual pea seed weight.

Organic farmers prioritize using larger seed over smaller seed of the same varieties when possible because it may lead to greater yields (Demirlicakmak et al., 1963; Wallace & Canadian Organic Growers, 2001). Furthermore, as outlined by the Canadian Grain Commission, pea size is a factor in the grading of yellow field peas and larger seed size may result in greater economic returns (Government of Canada, Canadian Grain Commission, 2019).

2.6 Markets for Organic Peas

As concerns with the environmental impact of our food system have risen, the demand for certified organic food has increased (Irandoust, 2016). In 2019, the value of the organic retail market in Canada was $6.9 billion (Canada Organic Trade Association, 2019). From 2018 to 2019 there was a 20% increase in the export of certified organic products, worth approximately $460.9 million (Canada Organic Trade Association, 2019). A market analysis completed by the Agro-Food Innovation Council of Canada found that "in Canada, sales of plant-based protein products rose 7% to more than $1.5 billion in the 2016/2017 fiscal year" (Canada National Research Council, 2019).

Consumers of certified organic products and plant-based protein products hold similar values regarding environmental sustainability, and use their buying power as consumers to express those values (Canada National Research Council, 2019; Irandoust, 2016). Canada is the world's largest producer and exporter of dry peas and lentils (Canada National Research Council, 2019), and is a net exporter of agricultural products with approximately half of Canada's raw agricultural commodities being processed domestically into value-added products (Senate of Canada, 2019). Many government officials, private sector individuals, and consumers view this as an indicator that Canada's food system should increase their domestic capacity to produce value-added food products in an effort to develop a domestic food system that relies less on imported value-added food products (Senate of Canada, 2019). In 2019, Manitoba released the *Manitoba Protein Advantage*, a provincial strategy designed to increase the capacity of Manitoba to process protein rich crops into plant-based protein products, with the goal of attracting $1 billion in new plant protein processing infrastructure. The strategy will also further develop the livestock industry and is expected to increase the demand for high protein livestock feeds, such as pea and cereal mixtures (Canada Agriculture and Agri-Food, 2020).

The increased interest in certified organic and plant-based protein products is beneficial to organic pea producers because it represents an increase in demand for their products. However, like any farmer, organic farmers must sell their products at a price that goes above and beyond their annual operating and fixed costs to ensure that their business is profitable. While yields are often lower in organic production systems compared to non-organic systems (Halde et al., 2015; Maeder et al., 2002), the economic performance of organic production systems is still comparable due to the organic premiums that organic producers receive for their products (Offermann & Nieberg, 2000). In December 2021, the market price for organic yellow peas was trading at $0.49 to 0.59 per kilogram (OrganicBiz, 2020). The Province of Manitoba estimates that when using a pea market price of $0.53 per kilogram a farmer must achieve pea yields over 2183 kg ha^{-1} in order to cover normal operating and fixed costs (Province of Manitoba, 2020c). Entz et al. (2001) surveyed 14 organic farms across Saskatchewan, Manitoba and North Dakota. They found that average organic pea yields were 1257 kg ha^{-1} (201 to 2690 kg ha^{-1} range). Thus, the current market price of organic peas may not allow many farmers to cover their typical production costs.

2.7 Literature Review Summary

The Canadian organic industry is one of the fastest growing agri-food sectors in Canada. Specifically, there has been an increased demand for organic field peas (Canadian Organic Trade Association, 2018). The addition of field peas to a cereal dominant crop rotation will help break disease cycles and disrupt the lifecycle of weed communities, as well as add nitrogen to the soil for the subsequent crop (Anderson, 2005; Beckie & Brandt, 1997; Ma, 2016). While significant expansion in organic pea acreage is occurring throughout the Canadian Prairies, there is still room for improvement in crop rotation management to reduce the use of summer fallow and further diversify crop rotations away from cereal dominant rotations (Canadian Organic Trade Association, 2018; Knight et al., 2010). Semi-leafless field pea production can play an important role in the diversification of organic acreages across the Canadian Prairies, however, organic semi-leafless pea production comes with a range of potential issues like weed and disease problems, lodging, and low profitability.

Pea intercropping with cereals or oilseeds is becoming increasingly common among organic pea producers because it can help manage some of the agronomic issues that are associated with organic semi-leafless pea production systems. In addition, pea intercrops have been found to increase pea grain size, increase cereal protein concentration, and may reduce the risk of total crop failure (Anil et al., 1998; Langat, 1992; Lauk & Lauk, 2008). However, the potential agronomic benefits of organic pea intercropping depend on the intercrop design and resulting plant densities of the two crop species. There is limited research that has focused on the overall effect of organic pea-dominant additive intercrop designs on pea grain yield and quality, weed suppression, and profitability, and should therefore be studied further.

3 MATERIALS AND METHODS

3.1 Site Description

In 2019 and 2020 three separate semi-leafless yellow pea intercrop experiments (yellow pea-barley, yellow pea-oat, and yellow pea-oriental mustard) were completed at the Ian N. Morrison Research Farm in Carman, Manitoba Canada. In 2020, the same three experiments were repeated, twice, with early and late seeding dates to provide a degree of temporal variation. Thus, the research project resulted in three separate pea intercrop experiments across three different site-years. The Carman 2019, Carman 2020 early seeding date, and Carman 2020 late seeding date site-years are hereinafter referred to as Carman 2019, Carman 2020-1, and Carman 2020-2, respectively.

The experiments took place in the Prairies Ecozone region and can be described by sub-humid conditions, typified by seasonal air temperatures that are highly variable, characterized by cold winters (average low of -17.1°C in January) and hot summers (average high of 18.9°C June-August) (Smith et al., 1998). Similarly, precipitation is varied, with an annual average of 515 mm, which predominantly takes place in the spring and fall, with the potential for drought conditions in the summer (Smith et al., 1998). The soil in Carman is orthic black chernozem of the Hochfeld series with a very fine sandy loam texture and an average pH of 6.6-7.3 (neutral) (Mills & Haluschuk, 1993; Manitoba Agriculture and Resource Development, 2020a).

3.2 Site Management

In 2019, all three intercrop experiments (Carman 2019) were seeded into an area that had been oats in 2018. In 2020, the early-seeded intercrop experiments (Carman 2020-1) were seeded into an area that had previously been fall rye, and the late-seeded intercrop experiments (Carman 2020-2) were seeded into an area that had previously been wheat. All of the experiments took place on land that has been managed organically since 2004. The fields were tilled 1-2 times (8-12 cm deep) the day of seeding, depending on the amount of residue and soil moisture. Peas and their associated companion crops were seeded together at a depth of 2-5 cm, depending on soil moisture and companion crop species. Trials were seeded using a cone seeder with double disc openers, with 15 cm row spacing (Fabro Enterprises Ltd., Swift Current, SK). The only weed management that took place throughout the trials was rogue weeding of volunteer fall rye in the 2020 field trials. Entire plots were harvested using a Wintersteiger plot combine (Wintersteiger Ag., Ried im Innkreis, Austria).

3.3 Experimental Design

Peas were planted in both monoculture and additive intercrop plant stands. Peas (cv. CDC Amarillo) were sown to achieve a target plant density of 120 plants m^{-2}. The non-pea companion crop species were seeded to low, medium, or high densities of their recommended monoculture target plant densities: low barley, 40 plants m^{-2}, medium barley, 75 plants m^{-2}, high barley, 150 plant m^{-2}, low mustard, 43 plants m^{-2}, medium mustard, 87 plants m^{-2}, high mustard, 131 plants m^{-2}, low oat, 48 plants m^{-2}, medium oat, 80 plants m^{-2}, and high oat, 160 plants m^{-2}. In 2019, due to a mechanical error, barley and oats were over-seeded, resulting in plant population numbers that were approximately double the planned target plant densities. Approximately 1-2 hours before seeding, peas were inoculated with a liquid-based rhizobium (*Rhizobium leguminosarum*) inoculant, that is approved for organic use, at the recommended rate of 35 ml per 11 kg of seed.

Each experiment was a randomized complete block design replicated four times. The targeted plot length was 10 metres and the targeted plot width was 1.83 metres, with two-metre alleyways between replicates. In 2019 the experiments were seeded on May 10 (Carman 2019). In 2020, the same experiments were repeated, twice, with staggered seeding dates (Carman 2020-1, May 7, 2020, Carman 2020-2, May 21, 2020). In each site-year the three separate pea intercrop experiments (pea-barley, pea-oat, and pea-mustard) were planted side-by-side in field sections that were separated by a 2 metre border.

3.4 Data Collection

Table 1. Timeline of management and data collection for three pea intercrop experiments (pea-barley, pea-mustard, and pea-oat) at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020, located in Carman Manitoba, Canada.

Site-year	Soil Sampling	Seeding	Seed Depth Assessment	Crop Density	Mid-Season Biomass	Biomass at Maturity	Pea Plant Height	Pea DTM֍	Harvest
Carman 2019	May 13	May 10	-	May 27	-	July 11	July 31	July 31	August 6 and 16
Carman 2020-1	May 4	May 7	May 22	May 27	June 18	July 21	July 30	July 31	August 6
Carman 2020-2	May 4	May 21	June 2	June 2	June 25	July 23	July 30	July 31	August 11

֍Days to maturity of pea crop

Climatic data was obtained from the Manitoba Ag-Weather Program and Environment Canada, Manitoba Station. Soil samples were taken at random in the spring before the growing season using a Dutch auger at a depth of 0-60 cm in 2019 and 0-30 cm in 2020. Soil was tested for soil nutrient status and pH by Agvise Laboratories (Northwood, ND, USA. A random sample of fifteen pea and fifteen companion crop seeds from each experiment were harvested approximately two weeks after seeding and seeding depth was determined by measuring the distance from the seed to the chlorophyllic portion of the seedling. Crop density was measured by counting two randomly placed one-metre sections in each plot, after full crop emergence which occurred approximately 2-3 weeks after seeding. Mid-season biomass samples were only taken in 2020. One randomly placed 0.25 m^{-2} quadrat from each plot was sampled and separated by pea, companion crop and weed biomass. Separated samples were dried in an oven at 65 °C for 48 hours and weights were taken. At the time of early biomass sampling, the pea crop was at flower bud and beginning bloom (59 to 62 BBCH development stage), oriental mustard was at early flowering (60-62 growth stage), and cereals were at stem elongation (Zadok stage 30-32) (Government of Western Australia, 2018; Manitoba Pulse & Soybean Growers, 2018; Saskatchewan Mustard Development Commission, 2020). Biomass at maturity samples were taken in 2019 and 2020. Two randomly placed 0.25 m^{-2} quadrats were sampled from each plot and separated into pea, companion crop and weed biomass. Separated samples were dried in an oven at 65 °C for 48 hours and weighted. At the time of biomass at physiological maturity sampling, peas had reached full pod (BBCH 79 development stage), oriental mustard had reached the ripening phase (84-88 growth stage) and cereals had begun to ripen (Zadok stage 90) (Government of Western Australia, 2018; Manitoba Pulse & Soybean Growers, 2018; Saskatchewan Mustard Development Commission, 2020). Plant height measurements were taken approximately 2-3 weeks before harvest. Two height measurements (front and back) of each plot were taken. Days to maturity (DTM) evaluations began taking place at the end of July. Maturity scores were taken three times a week until all plots had reached maturity (growth stage > R7), as described by 90% of the plants having brown pods at the bottom, yellow in the centre and green on top (Manitoba Pulse & Soybean Growers, 2018). Thousand kernel weights (TKW) were measured using a seed counter and scale. Pea protein percentage on a dry matter basis was measured using a Perten Inframatic 9500 near-infrared grain analyzer (PerkinElmer, Massachusetts, USA), at the Westman Agricultural Diversification Organization, Melita, MB. Pea intercrop grain yields were separated using a dockage sorter (Carterday International, Minnesota, USA) and spiral gravity separator (Can-Seed Equipment Ltd., Manitoba, Canada).

3.5 Pea Intercropping Survey

A pea intercropping survey was approved by the University of Manitoba Ethics Office (Appendix 8.7). The objective of the survey was to collect on-farm information regarding the true cost of organic pea intercropping. This on-farm information was then used to compliment the values used to complete the economic analysis of the different treatments that were studied in the field trials. A short summary of key survey findings can be found in the Appendix at 8.5.

Survey Participant Requirements:

- Operating a certified organic farm
- Farm located in Manitoba, Saskatchewan, or Alberta
- Field size of 40 acres or more
- Experience growing pea intercrops

There were two ways that farmers accessed the survey: the first was potential participants were contacted through the farmer network of the Natural Systems Agriculture Lab at the

University of Manitoba. The network of the Natural Systems Agriculture Lab is an email list of organic farmers that are known to be willing to participate in on-farm research. An email (Appendix 8.6) that outlined pertinent information about the survey was distributed throughout the Natural Systems Agriculture email list. If a farmer self-identified as meeting the survey criteria and wished to participate, they contacted the principal investigator (Will Bailey-Elkin) via email and requested the survey. The participant then completed the survey and sent it directly back to the principal investigator. The second way that a farmer accessed the survey was through advertisement: multiple media outlets expressed interest in discussing the research project and survey. The media outlets published pertinent information about the survey (Appendix 8.6) and if a farmer read the article and self-identified as meeting the survey criteria and wished to participate, they contacted the principal investigator via email and requested the survey. The participant then completed the survey and sent it directly back to the principal investigator.

A total of nine farmers completed the pea intercropping survey. However, due to technical difficulties, two of the nine surveys were completed as a phone interview. The information collected from the surveys was not coded or transcribed, nor statistically analyzed. The survey responses provided preliminary information that helped inform the economic analysis and provided a farmer point of view to the overall thesis.

3.6 Economic Analysis

An economic analysis was completed on each treatment, within each experiment, to determine the profitability of the different intercrop mixtures. Net returns were calculated for each treatment, within each experiment, by using organic production costs that were determined by reviewing the results of the pea intercropping survey, and by referencing Government of Saskatchewan, (2020); Manitoba Agricultural Services Corporation, (2020); Province of Manitoba, (2020); and Saskatchewan Crop Insurance Corporation, (2020). In the economic analysis, the only additional cost of pea intercropping compared to the pea monoculture was the cost of non-pea seed, the grain separation cost, and crop insurance. For crop insurance, Manitoba farmers who practice intercropping are eligible for specialty crop insurance that is approximately $18.06 per hectare lower than traditional crop insurance. A similar crop insurance program exists in Saskatchewan. A breakdown of the costs can be seen below (Table 2), and a breakdown of additional operating costs can be found in in Appendix 8.8. Net returns were defined as the gross revenue minus total costs (fixed costs + operating costs + labour). Following the initial economic analysis using the current market price of peas ($0.53 kg), two sensitivity analyses were then completed for each experiment using a 50% increase in the current market price of peas ($0.80 kg) and a 50% increase in the current market price of the companion crop (barley, $0.54 kg, oat, $0.74 kg, and mustard, $2.67 kg). An ANOVA was performed on the net returns as per the description outlined in Section 3.7.

Table 2. Grain prices and production costs used for economic analysis of three pea intercrop experiments (pea-barley, pea-mustard, and pea-oat) at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020, located in Carman Manitoba, Canada.

Seed Costs	
Pea + inoculant[a]	$0.61 kg
Barley[a]	$0.51 kg
Oat[a]	$0.59 kg
Mustard[b]	$9.64 kg
Other costs	
Seed separation cost[c]	$0.02 kg
Operating costs minus seed cost, separation cost, and crop insurance[d]	$511.89 ha
Fixed costs[d]	$337.48 ha
Labour[d]	$177.84 ha
Grain Market Prices	
Peas[e]	$0.53 kg
Barley[e]	$0.36 kg
Oat[e]	$0.49 kg
Mustard[e]	$1.78 kg

[a]Estimated seed cost adapted from (Province of Manitoba, 2020c)

[b]Estimated seed cost adapted from (Government of Saskatchewan, 2020)

[c]Average separation cost obtained from pea intercropping survey

[d]Production costs adapted from (Province of Manitoba, 2020c)

[e]Organic grain market prices adapted from (OrganicBiz, 2020)

3.7 Statistical Analysis

Using PROC Mixed procedure in SAS 9.4 (SAS Institute, Inc. 2020), the Analysis of Variance Method (ANOVA) was used to compare treatment differences within each experiment on the following measurements: plant population density, mid-season crop and weed biomass, crop and weed biomass at maturity, grain yield, pea and companion crop harvest index, pea plant height, pea thousand kernel weight (TKW), pea days to maturity (DTM), pea protein content, and net returns. Site-year was a combination of site and/or year, resulting in three separate site-years (Carman 2019, Carman 2020-1, and Carman 2020-2). Site-years were combined for the analysis and when site-year x treatment interactions were detected, data were analyzed separately. Treatments, site-years, and site-year x treatment were considered fixed effects and replicates nested within site-years were considered random effects.

The PROC Univariate procedure was used to test for the normality of residuals. When normality was not met, log or square root transformations were used depending on the model fit. Log transformed data were back transformed when presented in tables and figures. If homogeneity of the residuals was not met upon visual inspection of the residual panel of the predicted values vs. the residual values, a repeated/group statement (group=treatment, group=site-year, group=site-year x treatment) was used to account for heterogeneity of variance. Following the visual inspection, the best fit was identified by using the lowest AIC values. Means were separated using the lsmeans statement and considered significant at $P<0.05$ using the Tukey test.

4 RESULTS AND DISCUSSION

4.1 Climate

The 2019 and 2020 growing season mean temperatures were the same (13.9 °C), resulting in temperatures that were 98% of the long-term mean temperature (Table 3). The mean monthly temperatures from May to August were similar between 2019, 2020, and long-term mean temperatures. However, the mean temperature in April of 2020 was 33% and 36% of the 2019 and long-term mean temperatures, respectively.

Due to significant precipitation in the fall of 2019, September 2019 to April 2020 precipitation was 19% greater than the long-term average. From September 2018 to April 2019, precipitation was 85% of the long-term average (Table 4). Growing season precipitation in 2019 and 2020 was 64% and 61% of the long-term precipitation, respectively. Below-average total precipitation was especially evident in the months of April and May in 2019 and 2020: in April, the 2019 and 2020 total monthly precipitation was 37% and 55% of the long-term average, respectively. In May, the 2019 and 2020 monthly precipitation was 62% and 43% of the long-term average, respectively. June of 2020 was wetter than 2019, with 90% of long-term average in June 2020 compared with 43% in June of 2019.

Table 3. Mean monthly temperature (C°) for September 2018 to August 2020 in Carman Manitoba, Canada.

Location	Sept.-April[֍]	April	May	June	July	August	Growing Season[שׁ]
Carman 2019	-7	4.8	9.6	17.3	19.6	18.1	13.9
Carman 2020	-4	1.6	10.7	18.3	20.2	18.7	13.9
Carman LTA[฿]	-4.2	4.5	11.6	17.2	19.4	18.5	14.2

[֍]September of the previous year until April of the seeding year

[฿]Long term average (1981-2010) for Carman, MB (Environment Canada)

[שׁ]Average temperature over the growing season (April to end of August)

Table 4. Total monthly precipitation (mm) for September 2018 to August 2020 in Carman Manitoba, Canada.

Location	Sept.-April[֍]	April	May	June	July	August	Growing Season[ש]
Carman 2019	167	17	37	37	57	61	209
Carman 2020	234	24	26	70	54	24	198
Carman LTA[฿]	196	44	60	78	76	67	325

[֍]September of the previous year until April of the seeding year

[฿]Long term averages (1981-2010) for Carman, MB (Site-year Canada)

[ש]Total precipitation over the growing season (April to end of August)

4.2 Soil Nutrient Status and pH

The soil pH levels across all three site-years were similar and were within the ideal pH range for field pea production (5.5 to 7 pH) (North Dakota State University Extension, 2018). It is recommended that field peas be planted in soils with levels of residual soil nitrate below 30 ppm in the 0-60 cm depth. Across all site-years soil nitrate levels were found to be low: in 2019 nitrogen at the 0-60 cm depth was found to be 26 ppm (Table 5). In 2020, the early-seeded trials (Carman 2020-1) and late-seeded trials (Carman 2020-2) were found to have 12.5 and 13 ppm of nitrogen at the 0-30 cm depth, respectively. Across all site-years phosphorous levels were moderate (10-11 ppm range), falling below the recommended level (16 ppm) whereat phosphorous fertilizer would be recommended in non-organic field pea production. Field peas require little potassium (K) and it is recommended that levels should fall above 100 ppm (North Dakota State University Extension, 2018). Across all three site-years potassium levels were above 100 ppm (205 to 368 ppm range). In conclusion, the soil analyses of the three site-years represent adequate conditions for organic field pea production.

Table 5. Soil nutrient status and pH of three site-years for three pea intercrop experiments (pea-barley, pea-mustard, and pea-oat) at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020, located in Carman Manitoba, Canada.

Site-year	**N֍**	**Pש**	**K**	**S**	**pH฿**
	------------------------------------Ppm-------------------------------------				
Carman 2019 (0-60 cm)	26	10	205	25	6.0
Carman 2020-1 (0-30 cm)	12.5	10	246	13	5.9
Carman 2020-2 (0-30 cm)	13	11	368	8	6.1

֍N=ppm in nitrate

שP measured using Olsen phosphorous analysis method

฿pH measurements were taken at the 0-15 cm soil depth for all site-years

*2020 soil nutrient status measurements were taken at a depth of 0-30 cm while the 2019 soil analysis measurements were taken at a depth of 0-60 cm

4.3 Weed Populations

The level and diversity of weeds was different among the three site-years. The Carman 2020-1 site-year contained a more diverse community of weeds with the dominant weeds consisting of lambs quarter’s, smart weed (*Polygonum pensylvanicum)*, wild buckwheat *(Fallopia convolvulus*), and Canada thistle (Table 6). The Carman 2019 and Carman 2020-2 site-years contained similar weed communities with green foxtail (*Setaria viridis*) as the most dominant weed.

Although the weed community composition was different between the Carman 2019 and Carman 2020-1 site-years, the level of weed biomass at maturity was similar, with site-years containing 1216 kg ha^{-1} and 1176 kg ha^{-1} of weed biomass, respectively (Table 6). The level of weed biomass throughout the 2020-2 site-year was greater, with a weed biomass at maturity of 2412 kg ha^{-1}.

Table 6. Dominant weed species observed at three site-years for three pea intercrop experiments (pea-barley, pea-mustard, and pea-oat) at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020, located in Carman Manitoba, Canada.

Site-year	Dominant Weed Species	Mean Weed Density (m^{-2})	Mean Weed Biomass (kg ha^{-1})
Carman 2019	Green foxtail	-	1216
Carman 2020-1	Lambs quarter's, smart weed (*Polygonum pensylvanicum*), wild buckwheat (*Fallopia convolvulus*), Canada thistle	139	1176
Carman 2020-2	Green foxtail	800	2412

4.4 Seeding Depth

The recommended seeding depth for field peas is 3 to 8 cm, whereas oats and barley should be planted at 3.8 to 7.6 cm, and 3.8 to 5 cm, respectively (Province of Manitoba, 2020a, 2020d; Saskatchewan Pulse Growers, 2019a). Due to the small seed size of mustard it is recommended that mustard be seeded to depths of 1.3 to 3.8 cm (Manitoba Agriculture and Resource Development, 2020b). Therefore, the different crops in the intercrops had different optimum seeding depths. The seeder used in this research project could only seed the pea and companion crop seeds at the same depth, thus the seeding depth of the intercrop mixture had to fall somewhere in the middle of optimal depths for both crops. A detailed assessment of seeding depth was measured in 2020 only. Seeding depths were similar across site-years and experiments (Table 7).

Table 7. Average seeding depth of pea and companion crop across two site-years for two pea intercrop experiments (pea-barley, pea-mustard, and pea-oat) at the University of Manitoba Ian N. Morrison Research Farm in 2020, located in Carman Manitoba, Canada.

Site-year	**Pea-barley experiment**		**Pea-oat experiment**		**Pea-mustard experiment**	
	Mean pea depth	Mean barley depth	Mean pea depth	Mean oat depth	Mean pea depth	Mean mustard depth
	(cm)					
Carman 2020-1	3.1	2.8	3.2	3.1	2.9	2.7
Carman 2020-2	3.2	2.9	3.4	3.2	2.9	2.6

4.5 Pea-Barley Intercrop Experiment

4.5.1 Crop Density

Due to the weak competitive ability of peas, high seeding rates and emergence are important to ensure the earliest canopy closure possible. Baird et al. (2009) found that the optimal target plant density for organic field pea producers is 120 plants m^{-2}. In the present study, pea density ranged from 73% to 89% of this target plant density. Pea density was significantly greater in 2019 than in 2020 (Table 8). Although pea density was found to be below the target plant density of 120 plants m^{-2} , at all three site-years, pea density was still greater than the recommended seeding rate for non-organic pea production (75 to 85 plants m^{-2}) (Saskatchewan Pulse Growers, 2019b). Pea population density was unaffected by barley intercropping and the lack of a significant intercrop by site-year interaction indicated that pea plant population response to barley intercrops was stable among the three site-years. The lack of intercrop effect on pea density indicates that pea and barley were not competing for resources at this early stage in the crop-cycle.

Barley plant population density was significantly greater in 2019 compared to 2020 (Table 8). The high barley plant density in 2019 was attributed to a planting error that resulted in over-seeding. Barley plant population density was significantly greater at the high seeding rate, but not different between the low and medium seeding rates (Table 8). No significant intercrop treatment by site-year interaction was observed indicating the effects of different barley seeding rates on plant population were similar for the three site-years.

Table 8. Mean pea and barley plant population of pea monoculture and three pea-barley intercrop treatments (pea + low barley, pea + medium barley, and pea + high barley), averaged across site-years and treatments at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020.

	Pea Density	**Barley Density**[฿]
	Plants m^{-2}	
Site-year		
Carman 2019	105a[֍]	119a
Carman 2020-1	87b	56b
Carman 2020-2	91ab	74b
Treatment		
Pea	101a	-
Pea + low barley	86a	47c
Pea + med. barley	99a	75b
Pea + high barley	92a	139a
Fixed Effect P-Values		
Site-year	**0.0230**	**0.0151**
Treatment	0.0757	**<0.0001**
Site-year*Treatment	0.7111	0.5223

[֍]Barley and pea density means with different letters in the same column are significantly different (Tukey's HSD, $p<0.05$).
[฿]Barley data were log transformed with back transformed data presented in table.

4.5.2 Mid-Season Crop and Weed Biomass

Plant shoot biomass samples were taken at flower bud and beginning of bloom (59 to 62 BBCH development stage) of peas, and stem elongation (Zadok stage 30-32) in barley to understand the growth of three main plant components: peas, barley, and weeds. Mid-season biomass was measured in 2020 only.

Pea, barley and total crop biomass levels were significantly higher at the earlier compared to the late-seeded site-year in 2020 (Table 9). Carman 2020-1 was seeded on May 7, 2020, 14 days before Carman 2020-2. Early seeding is known to favour greater plant biomass accumulation in cool season crops such as peas and barley (Chen et al., 2006; Juskiw & Helm, 2003). The biomass values for pea in the present study at the flower bud and beginning of bloom stages, were similar to previous pea growth studies in Manitoba (Borstlap & Entz, 1994).

Pea biomass was significantly lower at the high barley seeding rate compared with the pea monoculture and medium barley seeding rate. Therefore, the high seeding rate of barley had a negative effect on early season pea biomass, reducing it by 17%. Past research has found that in low nitrogen soils interspecific competition can be high early in the crop-cycle when both peas and the non-legume crop are competing for the same chemical form of nitrogen (Bedoussac et al., 2015). The similarity in pea biomass for the lowest and highest barley seeding rate remains unexplained. Biomass results in barley were opposite those of peas, with the highest barley seeding rate resulting in significantly more biomass than the low and medium seeding rates (Table 9). Past research has found that increasing barley seeding rate in monoculture barley production can result in greater barley shoot biomass (Kumar & Jha, 2017).

Total crop biomass was significantly greater for the three pea-barley intercrops compared with the pea monoculture (Table 9). Therefore, results showed that net primary productivity was increased with intercropped barley. The proportion of total crop biomass contributed by the barley intercrop was 30%, 35%, and 35% for the low, medium, and high seeding rates, respectively.

A significant site-year by treatment interaction was detected in total crop biomass (Figure 1). At the Carman 2020-1 site-year total crop biomass was significantly greater for all intercrops compared with the pea monoculture. At the Carman 2020-2 site-year, total crop biomass was only greater than the pea monoculture at the medium seeding rate. One explanation for these results is that the late seeding at the Carman 2020-2 site-year provided green foxtail – the dominant weed of the site-year – with more niche space that green foxtail was able to exploit due to warmer weather conditions. Green foxtail is a C_4 grass species and is known to be highly productive in low moisture and high temperatures (Taylor et al., 2014). An explanation for the greater biomass contribution from barley at the Carman 2020-1 site-year may be because weed biomass levels were significantly lower at the Carman 2020-1 site-year, Furthermore, barley is a cool season annual and is known to generate high levels of early season biomass that can lead to weed biomass reductions (Didon & Hansson, 2002; Sustainable Agriculture Research and Education, 2021a). Therefore, the early seeding date and low weed biomass levels may have resulted in greater levels of barley biomass at the Carman 2020-1 site-year compared to the Carman 2020-2 site-year.

Boerboom & Young (1995) observed that slow canopy closure in semi-leafless field peas resulted in yield losses due to early season weed competition. Therefore, I hypothesized that intercropping barley would reduce weed biomass in the present study. Carman 2020-2 had 66% greater weed biomass than Carman 2020-1 (Table 9), but no significant difference was observed in weed biomass due to barley intercrop seeding rates (Table 9). It was notable that the highest barley seeding rate resulted in fewer weeds than pea monoculture (P=0.0627).

Table 9. Mean pea, barley, total crop (pea + barley), and weed biomass of pea monoculture and three pea-barley intercrop treatments (pea + low barley, pea + medium barley, and pea + high barley) at early stages[ש] in the crop cycle, averaged across site-years and treatments at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020.

	Pea	**Barley**	**Total Crop**	**Weed**
		Kg ha^{-1}		
Site-year				
Carman 2020-1	1511a[֍]	909a	2192a	211b
Carman 2020-2	606b	355b	872b	621a
Treatment				
Pea	1107a	-	1107b	493a
Pea + low barley	1081ab	510b	1591a	433ab
Pea + med. barley	1130a	585b	1715a	412ab
Pea + high barley	915b	800a	1715a	327b
Fixed Effect P-Values				
Site-year	**<0.0001**	**<0.0001**	**<0.0001**	**0.0001**
Treatment	**0.0087**	**<0.0001**	**0.0002**	0.0627
Site-year*Treatment	0.4379	0.7791	**0.0077**	0.5488

[֍]Means with different letters in the same column are significantly different (Tukey's HSD, p<0.05).
[ש]At time of early biomass sampling, peas had begun to flower (R1 and R2 growth stage), and barley had reached stem elongation (Zadok stage 30-32).

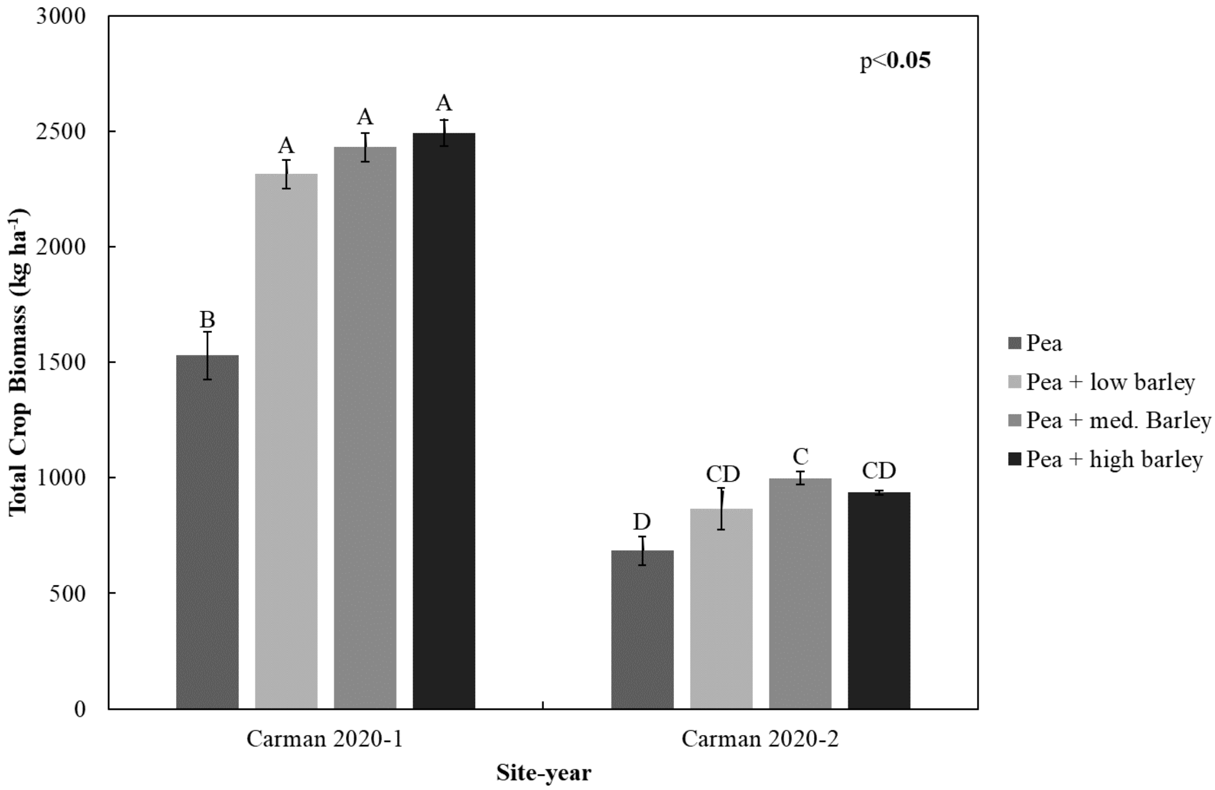

Figure 1. Early season total crop biomass (pea + barley) of pea monoculture and three pea-barley intercrop treatments (pea + low barley, pea + med. barley, and pea + high barley) at the University of Manitoba Ian N. Morrison Research Farm in 2020. Error bars represent standard errors of the least-squares means. Treatments are clustered by site-year. Means with different letters are significantly different (Tukey's HSD, $p<0.05$).

4.5.3 Maturity Crop and Weed Biomass

Biomass samples were taken when peas had reached full pod (BBCH 79 development stage), and barley had begun to ripen (Zadok stage 90) (Government of Western Australia, 2018; Manitoba Pulse & Soybean Growers, 2018). Carman 2020-1 contained significantly greater pea and total crop biomass than Carman 2019 and Carman 2020-2 (Table 10). The early seeding in Carman 2020-1 allowed for greater early season growth of the pea crop and may have outcompeted the barley crop, later in the crop-cycle. Furthermore, Carman 2020-1 contained comparatively lower levels of nitrogen which may have benefited early season pea growth over barley (Table 5). This is common in intercrop systems, because when one crop establishes greater access to a resource the crop tends to become even more dominant as greater resources are captured, acting as a positive feed back mechanism for the dominant crop (Donald, 1958). Carman 2019 contained significantly greater barley biomass than 2020. One explanation for this is that overseeding in 2019 led to greater barley biomass.

The barley crop contributed 8%, 5%, and 5% to the total crop biomass at the low, medium, and high barley seeding rates, respectively (Table 10). The medium and high barley seeding rates contained significantly greater barley biomass than the low barley seeding rate, and the high barley seeding rate significantly reduced pea biomass by 25%, compared to the pea monoculture. This result supports the hypothesis that barley intercropping has a negative effect on pea growth. The range of pea biomass results (3165 kg ha^{-1} to 4198 kg ha^{-1}) were similar to those found in Baird et al., (2009).

Weed biomass was significantly greater in Carman 2020-2 compared with the other two site-years. Due to the high level of green foxtail, Carman 2020-2 contained 48% and 53% greater weed biomass than Carman 2019 and Carman 2020-1. In addition, Carman 2020-2 was seeded approximately 14 days later than the other site-years which may have contributed to a significantly greater level of weed biomass. Fernandez et al. (2012) found that a delayed seeding date of 4 weeks in organic field pea production led to a 36% increase in weed biomass at the time of crop maturity. Thiessen Martens et al. (2019) found that organic fields across Manitoba and Saskatchewan contained an average weed biomass of 675 kg ha^{-1} (0 to 3266 kg ha^{-1} range). Therefore, weed biomass levels in the present study (1092 kg ha^{-1} to 1952 kg ha^{-1}) may be considered slightly above-average for organic fields in the region.

Weed biomass was significantly lower for the medium and high barley seeding rates compared to the pea monoculture and low barley seeding rate (Table 10). The reduction was 35% and 44%, respectively. These, observations support the study hypothesis that barley intercrops reduce weed biomass. The differences in aboveground leaf architecture between pea and barley may have led to increased light interception, reducing light availability for weeds (Bedoussac & Justes, 2010a; Corre-Hellou et al., 2006). Furthermore, in the present study, it was observed that barley germinated and emerged quicker than pea which may have resulted in an earlier canopy closure when compared to the pea monoculture, giving the intercrop a size advantage over weeds.

No significant interaction was observed in either barley, weed, pea or total biomass (Table 10). This indicates that the relationship between these components was stable across the three different site-years. These results suggest that barley intercropping may produce a predictable response to reduce weed populations in barley-pea intercrops.

Table 10. Mean pea, barley, total crop (pea + barley), and weed biomass at maturity[฿] of pea monoculture and three pea-barley intercrop treatments (pea + low barley, pea + medium barley, and pea + high barley), averaged across site-years and treatments at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020.

	Pea	**Barley**[ʋ]	**Total Crop**	**Weed**
	Kg ha^{-1}			
Site-year				
Carman 2019	2959b[֍]	1520a	4268b	1197b
Carman 2020-1	5658a	304b	5924a	1069b
Carman 2020-2	2504b	574b	3010b	2286a
Treatment				
Pea	4198a	-	4198a	1952a
Pea + low barley	3983ab	373b	4545a	1544ab
Pea + med. barley	3481ab	679a	4434a	1261bc
Pea + high barley	3165b	1009a	4426a	1092c
Fixed Effect P-Values				
Site-year	**<0.0001**	**0.0029**	**0.0011**	**0.0023**
Treatment	**0.0184**	**0.0002**	0.7658	**<0.0001**
Site-year*Treatment	0.6055	0.0753	0.7944	0.0968

[֍]Means with different letters in the same column are significantly different (Tukey's HSD, p<0.05).
[ʋ]Barley and weed biomass were log transformed with back transformed data presented in table.
[฿]At time of biomass at maturity sampling peas had reached pod-fill stage and barley had begun to ripen (Zadok stage 90).

4.5.4 Grain Yield and Harvest Indices

Pea grain yield was affected significantly by site-years (Table 11). The site-year effect showed that Carman 2020-1 (2867 kg ha^{-1}) yielded significantly more than Carman 2019 (1949 kg ha^{-1}), which yielded significantly more than Carman 2020-2 (1063 kg ha^{-1}). The pea yields observed in the present study were similar to those reported by participants in the accompanying pea intercropping survey (1008 kg ha^{-1} to 4033 kg ha^{-1} range) (Appendix 8.7). Pea yield results in the present study also corresponded to those of Boerboom & Young (1995) and Santín-Montanyá et al. (2014) whereby field pea yields were found to be reduced by low precipitation and high weed populations. Boerboom & Young (1995) experienced growing conditions that were similar to the low precipitation in June in the Carman 2019 site-year (Table 4), and the high levels of weeds found in the Carman 2020-2 site-year (Table 6).

Barley grain yield was affected significantly by site-year, with the highest yield at Carman 2019 (1012 kg ha^{-1}), while Carman 2020-1 and 2020-2 yielded 30 kg ha^{-1} and 120 kg ha^{-1}, respectively (Table 11). One explanation for the low 2020 barley grain yields is grasshopper damage. Grasshoppers were observed in 2020 and can reduce yields in cereal crops by consuming photosynthetic tissue reducing the crops ability to maintain metabolic processes that contribute to the development of grain, or by chewing directly through the peduncle removing the entire cereal spike from the plant (head clipping) (Begna & Fielding, 2008; Pickford & Mukerji, 1974). The grasshopper damage in 2020 may have strongly influenced the growth trajectory of the plant community. For example, strong early growth allowed the barley to suppress weeds, but then after being reduced by grasshoppers the competitive effect that barley was exerting on the peas may have been reduced resulting in greater pea yield. In order to verify this theory, a more detailed study with a more intensive biomass sampling regime would be required.

Pea grain yield declined as the density of barley increased within the intercrop. From the pea monoculture to high barley rate, pea grain yield significantly declined by 15% from 2129 kg ha^{-1} to 1801 kg ha^{-1}. (Table 11). The decline in pea grain yield indicates that the barley crop was interfering with the pea crop for resources in the same environmental niche, which led to reduced pea grain yields. The opposite trend was observed for barley. For example, barley grain yield increased as the density of barley within the intercrop increased. The grain yield increase was

76% from the lowest to highest barley seeding rate. Past research has found that increasing the seeding rate of barley in a barley monoculture from 300 to 600 seeds m^{-2} can lead to greater grain yields (Mason et al., 2007).

Site-year by treatment interactions were observed for both pea and barley grain yields (Figure 2 and Figure 3). For pea, the interaction was due to a reduction in grain yield with increasing rates of barley intercrop in 2019, while barley presence did not affect pea grain yield at the other two site-years (Figure 2). For barley, the interaction was attributed to an increase in barley yield with increasing rate in Carman 2019 and 2020-2 but no effect was detected in Carman 2020-1 (Figure 3). In Carman 2019, where barley had the greatest establishment and yields, the magnitude of differences in pea and barley grain yields across treatments were significant and much greater than the other site-years (Figure 2 and Figure 3). An explanation for the greater barley yields and greater reductions in pea grain yield at the Carman 2019 site-year is that the over-seeding of barley led to greater establishment of barley, and thus greater barley yields and reduced pea yields. However, this does not explain the high barley grain yields at the Carman 2020-2 site-year, compared to the Carman 2020-1 site-year. An explanation for this is that barley has been found to tolerate environmental conditions such as low soil moisture and is highly competitive against weeds (Beres et al., 2010; Blackshaw et al., 2002; Wallace & Canadian Organic Growers, 2001). Therefore, the barley crop may have outcompeted the pea crop at the Carman 2020-2 and Carman 2019 site-years where growing conditions were sub-optimal for peas, resulting in greater barley yields and lower pea grain yields. Whereas, at the Carman 2020-1 site-year, optimal pea growing conditions led to pea outcompeting barley. In summary, the intercrop systems functioned differently across different site-years and the site-year by treatment interactions indicated that the grain yield response to barley intercrops was unstable across the three site-years.

The harvest index (HI) is the ratio of grain yield to total aboveground biomass and is a measure of the efficiency of plants to produce seed. The pea harvest index in 2020 fell within the range found in past pea intercrop research (Bedoussac & Justes, 2010b). Harvest index was significantly greater for pea in 2019 compared with the other two site-years. However, between-year comparisons in HI may be problematic here owing to different approaches for establishing crop biomass measurements. There were no significant differences in pea harvest indices among intercrop treatments (Table 11). Of interest to note is that as the seeding rate of barley increased within the intercrop mixture the pea harvest index increased, indicating an increase in pea crop efficiency to produce seed. Similar results have been observed in past research (Bedoussac & Justes, 2010b).

In 2019, the barley harvest index (0.69) was significantly greater than 2020. The Carman 2020-1 barley harvest index was 0.10 and the Carman 2020-2 harvest index was 0.23 (Table 11). The grasshopper damage observed in 2020 would have caused the barley crop to accumulate biomass, but head clipping may have reduced grain yields, resulting in a low harvest index. This was observed by Begna & Fielding (2005) whereby greater densities of grasshopper, resulted in a greater level of head clipping and reduced the monoculture barley harvest index (0.41 to 0.48 range).

Table 11. Mean pea and barley grain yields, and pea and barley harvest indices of pea monoculture and three pea-barley intercrop treatments (pea + low barley, pea + medium barley, and pea + high barley), averaged across site-years and treatments at the University of Manitoba Ian N. Research Farm in 2019 and 2020.

	Pea	**Barley**[ש]	**Pea Harvest Index**	**Barley Harvest Index**
	Kg ha^{-1}			
Site-year				
Carman 2019	1949b[֍]	1012a	0.70a	0.69a
Carman 2020-1	2867a	30c	0.52b	0.10b
Carman 2020-2	1063c	120b	0.44b	0.23b
Treatment				
Pea	2129a	-	0.53a	-
Pea + low barley	1984ab	78c	0.51a	0.21b
Pea + med. barley	1924ab	141b	0.57a	0.21b
Pea + high barley	1801b	320a	0.60a	0.32a
Fixed Effect P-Values				
Site-year	**<0.0001**	**<0.0001**	**0.0039**	**0.0031**
Treatment	**0.0032**	**<0.0001**	0.5251	**0.0233**
Site-year*Treatment	**0.0002**	**0.0040**	0.8888	0.7348

[֍]Means with different letters in the same column are significantly different (Tukey's HSD, p<0.05).
[ש]Barley yield data were log transformed with back transformed data presented in table.

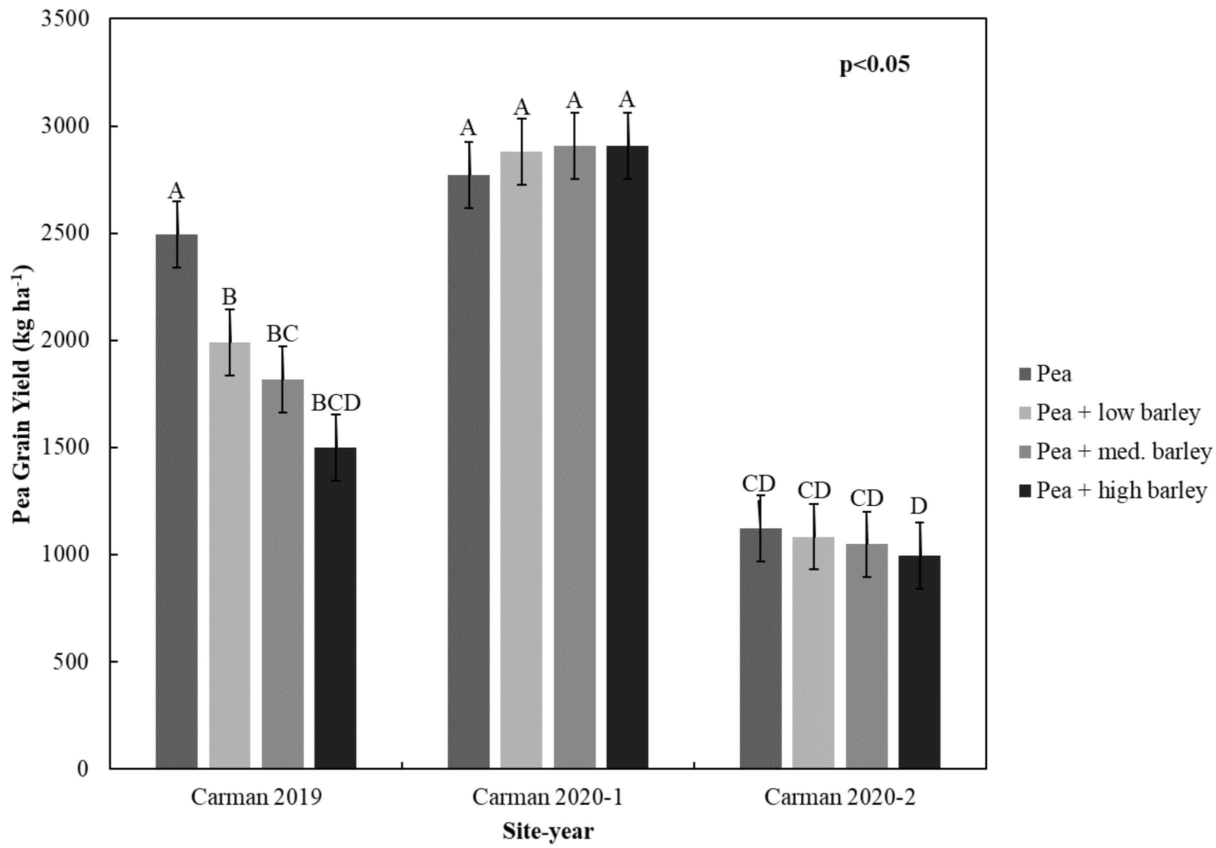

Figure 2. Pea grain yield of pea monoculture and three pea-barley intercrop treatments (pea + low barley, pea + med. barley, and pea + high barley) at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020. Error bars represent standard errors of the least-squares means. Treatments are clustered by site-year. Means with different letters are significantly different (Tukey's HSD, $p<0.05$).

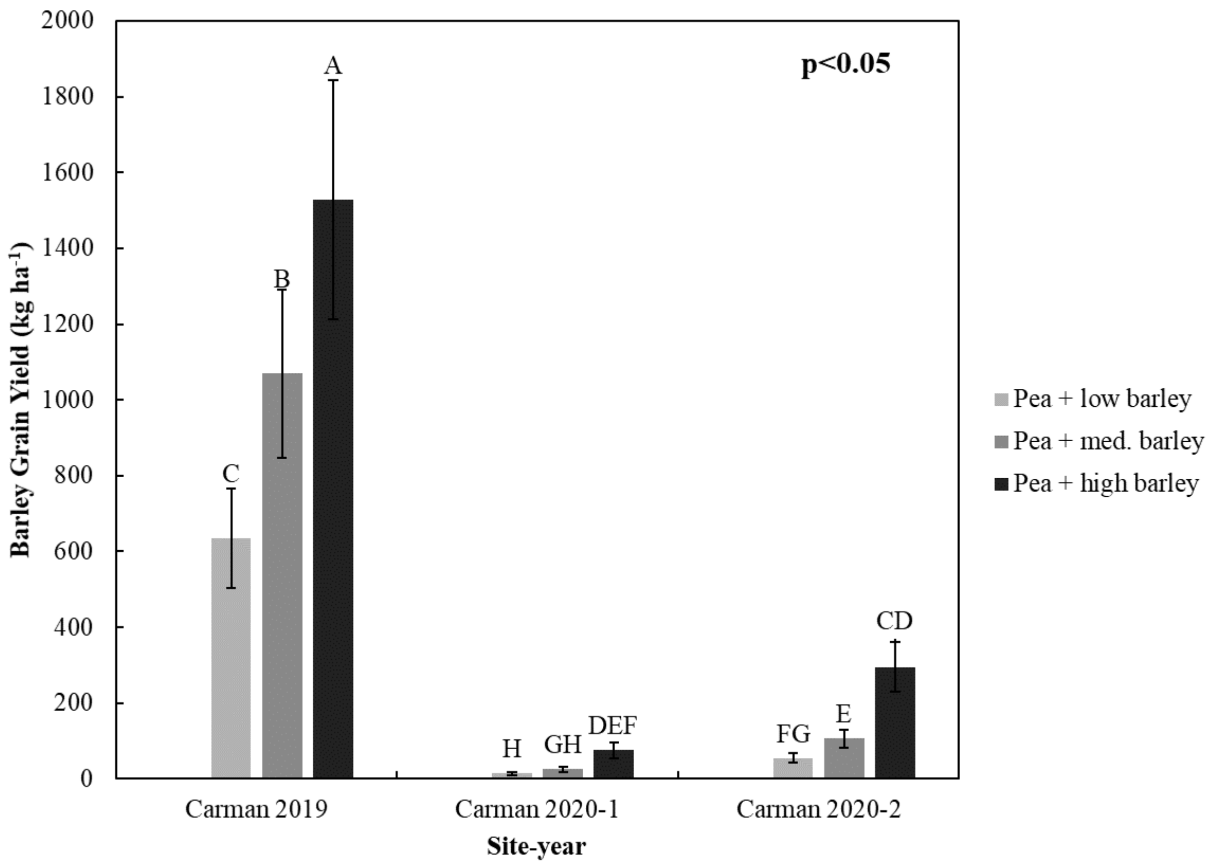

Figure 3. Barley grain yield of three pea-barley intercrop treatments (pea + low barley, pea + med. barley, and pea + high barley) at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020. Error bars represent standard errors of the least-squares means. Treatments are clustered by site-year. Barley yield data were log transformed with back transformed data presented in figure. Means with different letters are significantly different (Tukey's HSD, $p<0.05$).

Grain yield and weed biomass components were compared in an effort to better understand their response across the intercrop treatments. Averaged across site-years, the high and medium barley seeding rates significantly reduced weed biomass by 44% and 35%, with 15% and 10% pea grain yield reductions, from an initial pea grain yield of 2129 kg ha^{-1}, respectively (Figure 4). Thus, pea yields were not improved by intercropping indicating that the presence of barley was more detrimental to pea yields than the presence of greater weed biomass in the pea monoculture. However, this observation does not take into account the long-term benefit of the potential reduction in weed seed production through reduced weed biomass. Corre-Hellou et al. (2011) found that pea-barley intercrops that were established to densities similar to the high barley treatment in the present study significantly reduced ($P<0.05$) weed biomass by

72%, when compared to a pea monoculture control. Using a replacement pea-barley intercrop design, Hauggaard-Nielsen et al. (2006) found that pea grain yield was reduced by 26%, from 4760 kg ha^{-1} to 3530 kg ha^{-1}, compared with a pea monoculture control. These scientific observations are supported by a survey participant who reported that a pea-barley intercrop with 66:33 plant density ratio consistently yielded approximately 1680 kg ha^{-1} peas and 1344 kg ha^{-1} barley (Appendix 8.7.1). Therefore, in the present study, the effect of intercropping on weed biomass and pea grain yield may be considered low in comparison to similar pea-barley intercrop research.

It was interesting to observe that total grain yield in all intercrop treatments (pea + barley) was found to be greater than total grain yield in the pea monoculture. This may represent the competitive nature and high yield potential of the high barley seeding rate intercrop, as the high barley seeding rate resulted in the greatest reduction in weed biomass and pea grain yield and also contained the greatest barley yield.

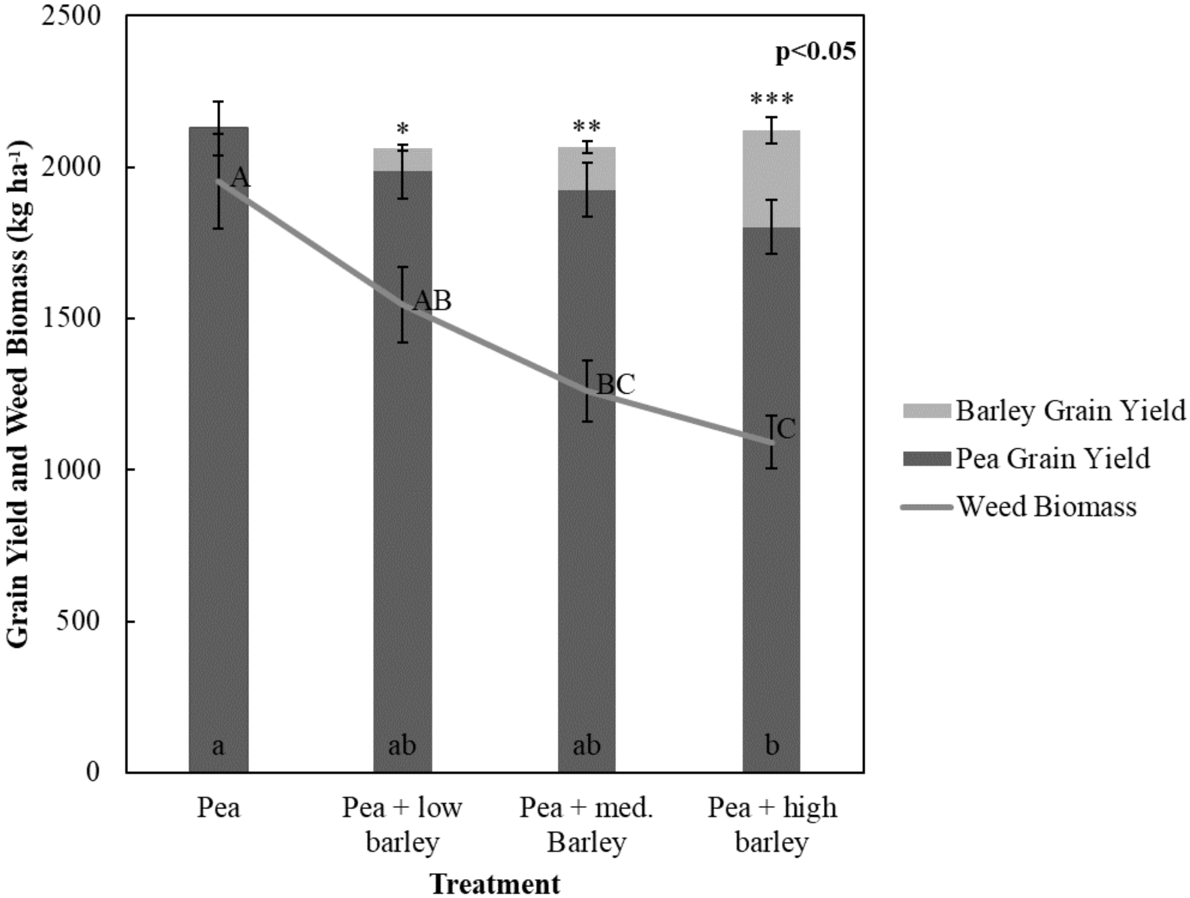

Figure 4. Effect of pea monoculture and three pea-barley intercrop treatments (pea + low barley, pea + med. barley, and pea + high barley) on pea and barley grain yield and weed biomass averaged over three site-years at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020. Error bars represent standard errors of the least-squares means. Barley data were log transformed with back transformed data presented in figure. Means with different letters (pea grain yield and weed biomass) and number of asterisks (barley grain yield) are significantly different (Tukey's HSD, $p<0.05$).

4.5.5 Economic Analysis

Net returns were considered in three different scenarios: standard organic price of peas and barley; a 50% increase in the price for peas; and a 50% increase in the price for barley. In the present study, when using a pea market price of \$0.53 kg a farmer must achieve pea yields over 2208 kg ha^{-1} in order to achieve positive net returns. The Carman 2019 and 2020-1 site-years were the only site-years that achieved a pea seed yield above this level (Table 11) and as such were the only site-years to register positive net returns (Table 12). Statistically, however, Carman 2020-1 and Carman 2019 had similar net returns.

It is clear that the main factor contributing to net return in this study was pea yield. Greater weed pressure and late seeding at Carman 2020-2 which resulted in low pea yield directly contributed to significantly lower net returns that year. On the other hand, early seeding, and minimum weed pressure at Carman 2019 and 2020-1 resulted in higher pea yields and greater net returns. The treatment effect of intercropping with barley did not affect net returns; negative net returns were recorded for all treatments (Table 12).

In the survey responses, a range of pea market prices, between $0.37 kg to $0.66 kg, were received by organic farmers, alongside a range of pea yields, from 1008 kg ha^{-1} to 4033 kg ha^{-1} (Appendix 8.7). Therefore, the pea yields observed in the present study fall within the range of yields observed by organic farmers, and the market price for organic peas ($0.53 kg) that was used in the initial economic analysis falls within the range of market prices received by organic farmers.

The second scenario involved a reanalysis based on a 50% increase in the market price for organic peas. Under this second scenario, the ranking of site-years and treatments did not change substantially, as the only difference from the initial analysis was that the Carman 2019 and Carman 2020-1 site-years now contained significantly different net returns (Table 12). What did change substantially is the overall profitability across site-years and treatments, as the Carman 2020-2 site-year was the only site-year that contained negative net returns, and when averaged across treatments, all of the treatments now contained positive net returns. The site-year effect showed that Carman 2020-1 ($1132.85 ha^{-1}) experienced significantly greater net returns than Carman 2019 ($657.62 ha^{-1}), which experienced significantly greater net returns than Carman 2020-2 (-$278.65 ha^{-1}). Intercropping did not affect net returns significantly when the price of peas was increased by 50%. This observation suggests that from a one-year economic analysis, intercropping did not provide any economic benefits.

In a third scenario, the price of barley was increased by 50% while the price of peas remained the same as in the initial scenario. In this scenario, intercropping resulted in positive net returns, while the pea monoculture stayed negative (Table 12). Also, the highest barley seeding rate had a significantly higher net return than the pea monoculture within this 50%

barley price premium scenario. Although intercropping did have a significant effect on net returns, in comparison to the increase in pea price scenario, the net returns using an increase in barley price resulted in low net returns across treatments, which may be evidence that even with an additional price premium there was a limit to which barley helped make pea intercropping profitable.

No significant interactions were detected for net returns across a wide range of market conditions. These results suggest that the lack of any positive barley intercropping returns was observed consistently across all three site-years and lead to a conclusion that as an intercrop, barley produced no positive economic benefit in the year of production.

Table 12. Mean net returns of pea monoculture and three pea-barley intercrop treatments (pea + low barley, pea + medium barley, and pea + high barley), averaged across site-years and treatments at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020.

	Initial Net Return	**50% Increase in Pea Market Price Net Return**	**50% Increase in Barley Market Price Net Return**
		$ $ ha^{-1}$	
Site-year			
Carman 2019	154.54a[֍]	657.62b	284.04a
Carman 2020-1	361.75a	1132.85a	364.92a
Carman 2020-2	(555.77)b[ש]	(278.65)c	(543.71)b
Treatment			
Pea	(24.43)a	532.07a	(24.43)b
Pea + low barley	(32.54)a	509.77a	15.90ab
Pea + med. barley	(2.58)a	486.76a	48.81ab
Pea + high barley	(6.92)a	487.16a	117.48a
Fixed Effect P-Values			
Site-year	**<0.0001**	**<0.0001**	**<0.0001**
Treatment	0.6998	0.8444	**0.0130**
Site-year*Treatment	0.5488	0.2071	0.4966

[֍]Means with different letters in the same column are significantly different (Tukey's HSD, $p<0.05$).
[ש]Parentheses indicate negative values.
*Economic analysis assumes an initial organic pea market price of $0.53 kg, and an initial organic barley price of $0.36 kg.

4.5.6 Summary and Conclusions

Pea-barley intercrops were observed to produce both positive and negative effects. Positive effects of barley included a reduction in weed biomass and an increase in total crop biomass. Negative effects included a reduction in pea growth (biomass) and yield. These results suggest that there was significant niche overlap between peas and barley. Therefore, one of the main conclusions of this study was that barley reduced pea productivity. What was not significantly influenced by intercropping was pea population density, plant height, harvest index, protein content, DTM, and TKW (Appendix 8.1).

Biomass of both pea and barley were stable across site-years, however, that did not translate to stable yields, as a significant site-year by treatment interaction was found for pea and barley grain yield. This may be due to the different growing conditions across site-years resulting in different levels of pea, barley and weed productivity, and thus varied levels of interspecific competition within the intercrop.

Although pea and barley grain yields were found to be unstable across site-years it appears that net returns were found to be stable. Greater pea yields, as well as a greater market price for organic peas translated to positive net returns. That is, positive net returns for pea were achieved when seed yields exceeded 2208 kg ha^{-1} at the standard price and 1462 kg ha^{-1} at the 50% high pea price. Intercropping only had a significant effect on net returns when the market price for barley was increased by 50%, however in that instance, all the treatments contained low net returns. Thus, from a purely economic standpoint it may not be necessary for a farmer to utilize pea-dominant intercrops with high densities of barley, if a farmer is able to manage weeds and ensure high pea grain yields and/or a high pea market price.

In conclusion, barley intercropping led to reduced weed biomass, but resulted in a significant pea yield penalty. An increase in the market price for peas was required to generate positive net returns, however, there was no difference in profitability between the pea monoculture and intercropping. When the market price of barley was increased, intercropping resulted in greater net returns, however the net returns were lower than those found when the pea price was increased.

4.6 Pea-Mustard Intercrop Experiment

4.6.1 Crop Density

Pea plant population density ranged from 71% to 102% of the 120 plants m^{-2} target plant density and was significantly greater in 2019 compared to 2020 (Table 13). The recommended seeding rate for non-organic pea production is 75 to 85 plants m^{-2} (Saskatchewan Pulse Growers, 2019b). The pea monoculture treatment contained significantly greater pea density than the low mustard seeding rate. This could be interpreted as increased interspecific competition, however, given the similarities in pea densities found in the medium and high mustard seeding rates compared to the pea monoculture treatment, the results remain unexplained and do not represent a pattern (Table 13).

Mustard plant population density was affected by site-year and treatment (Table 13). Mustard density was lower in Carman 2020-1 compared to Carman 2020-2 and increased significantly with increasing seed rate. Mustard plant density was 58%, 49%, and 56% of the low, medium, and high mustard seeding rate target plant densities, respectively.

Table 13. Mean pea and mustard plant population of pea monoculture and three pea-mustard intercrop treatments (pea + low mustard, pea + medium mustard, and pea + high mustard), averaged across site-years and treatments at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020.

	Pea Density	Mustard Density
	Plants m^{-2}	
Site-year		
Carman 2019	122a[֍]	47ab
Carman 2020-1	92b	38b
Carman 2020-2	85b	54a
Treatment		
Pea	111a	-
Pea + low mustard	94b	25c
Pea + medium mustard	95ab	43b
Pea + high mustard	98ab	74a
Fixed Effect P-Values		
Site-year	**<0.0001**	**0.0215**
Treatment	**0.0372**	**<0.0001**
Site-year*Treatment	0.1198	0.2582

[֍]Mustard and pea density means with different letters in the same column are significantly different (Tukey's HSD, p<0.05).

4.6.2 Mid-Season Crop and Weed Biomass

Biomass samples were taken at flower bud and beginning bloom (59 to 62 BBCH development stage) of peas, and at early flowering (60-62 growth stage) of mustard. The goal was to understand the growth of three main plant components: peas, mustard, and weeds part way through the growing season. Mid-season biomass was measured in 2020 only.

Mid-season biomass production was affected by site-year and treatment with no interaction recorded (Table 14). Among the two site-years, Carman 2020-1 contained significantly greater pea and total crop biomass (Table 14). Among mustard intercrop seeding rates, pea biomass was similar for the pea monoculture, and the low and medium mustard seeding rates. However, the high mustard seeding rate resulted in less ($P<0.05$) pea biomass than the pea monoculture (Table 14). Therefore, it appears that at mid-season interspecific competition between pea and mustard was present within the high rate mustard intercrop treatment contributing in the observed reduction in pea biomass.

There were no significant differences in mustard biomass among treatments or site-years (Table 14). It was interesting to observe that while the high mustard seeding rate significantly reduced pea biomass (by 31%) compared to the pea monoculture (Table 14), no difference in mustard biomass was observed. One explanation for this observation may be that the higher mustard plant population density for mustard at the highest seeding rate (Table 13) affected pea through root competition which was not measured here. Another explanation was that flea beetle (*Phyllotreta cruciferae*) may have reduced mustard biomass after the mustard exerted competition on the peas. Finally, low levels of soil nitrogen in the present study (Table 5) may have limited mustard biomass production as mustard requires high nitrogen fertility (Manitoba Agriculture and Resource Development, 2020b). Langat (1992) found that pea-mustard intercrops with 90 kg ha^{-1} nitrogen fertilizer increased the competitiveness of the mustard crop to the point where pea biomass productivity was being reduced.

Total crop biomass was significantly greater for the medium and high mustard seeding rates compared to the pea monoculture (Table 14). Therefore, net primary productivity was increased with intercropped mustard. The mustard crop contributed 9%, 28%, and 26% to the total crop biomass of the low, medium, and high mustard rates, respectively.

Weed biomass was significantly greater for Carman 2020-2 than Carman 2020-1 (Table 14) and consisted mostly of green foxtail, a weed species known to produce high levels of biomass (Table 14) (Province of Manitoba, 2020b). Across site-years, the medium and high mustard seeding rates resulted in significantly less weed biomass compared to the pea monoculture (Table 14). The reduction was 33% and 35%, respectively. Therefore, the results in the present study support the hypothesis that mustard intercropping reduces weed biomass.

Table 14. Mean pea, mustard, total crop (pea + mustard), and weed biomass of pea monoculture and three pea-mustard intercrop treatments (pea + low mustard, pea + medium mustard, and pea + high mustard) at early฿ stages in the crop cycle, averaged across site-years and treatments at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020.

	Pea	**Mustard**	**Total Crop**	**Weed**
	Kg ha^{-1}			
Site-year				
Carman 2020-1	863a֍	469a	1215a	282b
Carman 2020-2	538b	333a	788b	619a
Treatment				
Pea	828a	-	828b	567a
Pea + low mustard	697ab	218a	915ab	485ab
Pea + medium mustard	705ab	442a	1147a	381b
Pea + high mustard	572b	542a	1114a	370b
Fixed Effect P-Values				
Site-year	**0.0021**	0.2461	**0.0009**	**<0.0001**
Treatment	**0.0034**	0.0827	**0.0037**	**0.0089**
Site-year*Treatment	0.9580	0.6728	0.6220	0.6468

֍Means with different letters in the same column are significantly different (Tukey's HSD, p<0.05).
฿At time of early biomass sampling, peas and mustard had begun to flower (Pea=R1 and R2 growth stage, mustard=60-62 growth stage).

4.6.3 Maturity Crop and Weed Biomass

Biomass samples were taken when peas had reached full pod (BBCH 79 development stage), and mustard had reached the ripening phase (84-88 growth stage) to understand the growth of three main plant components: peas, mustard and weeds at the end of their growth cycle. Maturity biomass production for pea was affected by site-year (Table 14). Carman 2020-1 contained 5138 kg ha^{-1} average pea biomass, significantly greater than Carman 2019 and Carman 2020-2 which contained biomass levels of 3528 kg ha^{-1} and 2260 kg ha^{-1}, respectively (Table 15). The treatment effect for pea showed a significant (25%) reduction in pea biomass between the pea monoculture (4156 kg ha^{-1}) and the pea-mustard intercrop with the high mustard seeding rate (3130 kg ha^{-1}). This observation supports the hypothesis that mustard intercrops reduce pea biomass, and the absence of a site-year by treatment interaction showed that the negative effect of a high mustard seeding rate on pea yield was observed across a range of growing conditions.

The 2019 site-year contained significantly greater mustard biomass compared to the Carman 2020-1 site-year, and Carman 2020-2 was found to be numerically greater than Carman 2020-1 (Table 15). Averaged across treatments, the medium and high mustard seeding rates contained significantly greater mustard biomass than the low mustard seeding rate. However, overall, mustard was not a major contributor to total crop biomass (Table 15). The low levels of mustard biomass at maturity found among site-years may be due to flea beetle damage and/or low nitrogen fertility. Under organic management, Pridham & Entz (2008) found that mustard in wheat-mustard intercrops was destroyed by flea beetle. Intercropping mustard with peas here did not increase crop net primary productivity.

A significant site-year by treatment interaction was detected for mustard biomass (Figure 5). The basis for this interaction was that at the Carman 2020-1 site-year the high mustard seeding rate resulted in a significantly greater yield compared with the lowest mustard seeding rate, while no differences in seeding rate were observed at the other site-years. The variability in mustard biomass across treatments in 2019 and 2020-2 remains unexplained.

Weed biomass levels at maturity were 1302 kg ha^{-1} at Carman 2019 and 1228 kg ha^{-1} at Carman 2020-1 (Table 15). Increased levels of weed biomass at Carman 2020-2 (2310 kg ha^{-1}) were attributed to high levels of green foxtail biomass. Green foxtail is a grass species which may have resulted in a competitive advantage over the pea and mustard crops. C_4 plant species such as green foxtail can be more productive in low soil moistures and high temperatures, compared to C_3 plant species such as pea and mustard (Peterson & Nalewaja, 1992; Taylor et al., 2014).

Weed biomass was significantly lower for the medium (18%) and high (17%) mustard seeding rates compared to the pea monoculture (Table 15). These observations support the study hypothesis that mustard intercropping reduces weed biomass. Although mustard may not be as competitive as cereal crops such as barley or oats, it is competitive against weeds and has been found to have greater competitive ability in comparison to other brassica crops such as canola (Beckie et al., 2008; Blackshaw et al., 2002). The reductions in weed biomass were greater in the mid-season biomass, as the medium and high mustard seeding rates resulted in 33% and 35% reductions in weed biomass compared to the pea monoculture treatment, respectively (Table 14). The low percent reduction in weed biomass at maturity compared to mid-season biomass levels may be because the flea beetle damage to the mustard crop reduced the plant stand to the point where it was outcompeted by weeds and the pea crop later in the growing season.

The analysis of variance F-test for weed biomass detected a site-year by treatment interaction (P=0.0358) (Table 15). This indicates that the relationship between mustard and weeds may not always be stable across growing environments. However, the Tukey's HSD multi-treatment comparison of least-squares means failed to detect any significant differences among treatments (Figure 6). The Tukey HSD test is considered a conservative pairwise comparison that was unable to detect the differential significant differences among treatments within each site-year that the F-test showed. While Figure 1. does not denote any statistically significant differences among treatments within individual site-years, it is evident that intercropping did not affect weed biomass in 2019, while the medium and high mustard seeding rates in Carman 2020-1, and medium mustard seeding rate in Carman 2020-2 reduced weed biomass. These observations may represent the significant site-year by treatment interaction that was initially detected (Table 15). The low weed biomass found in 2020-1 corresponds to greater mustard biomass, thus may be a result of weed suppression from the mustard crop (Figure 5 and Figure 6).

Table 15. Mean pea, mustard, total crop (pea + mustard), and weed biomass of pea monoculture and three pea-mustard intercrop treatments (pea + low mustard, pea + medium mustard, and pea + high mustard) at maturity[ש], averaged across site-years and treatments at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020.

	Pea	**Mustard**[฿]	**Total Crop**	**Weed**
		Kg ha^{-1}		
Site-year				
Carman 2019	3528b[֍]	758a	4201b	1302b
Carman 2020-1	5138a	341b	5440a	1228b
Carman 2020-2	2260c	361ab	2568c	2310a
Treatment				
Pea	4156a	-	4156a	1804a
Pea + low mustard	3740ab	277b	4119a	1680ab
Pea + medium mustard	3542ab	479a	4052a	1472b
Pea + high mustard	3130b	682a	3951a	1498b
Fixed Effect P-Values				
Site-year	**0.0003**	**0.0335**	**0.0003**	**<0.0001**
Treatment	**0.0277**	**<0.0001**	0.9315	**0.0091**
Site-year*Treatment	0.6810	**0.0236**	0.9766	**0.0358**

[֍]Means with different letters in the same column are significantly different (Tukey's HSD, $p<0.05$).
[฿]Mustard biomass data were log transformed with back transformed data presented in table.
[ש]At time of biomass at maturity sampling peas had reached full-pod stage (R4 growth stage) and mustard had begun to ripen (84-99 growth stage).

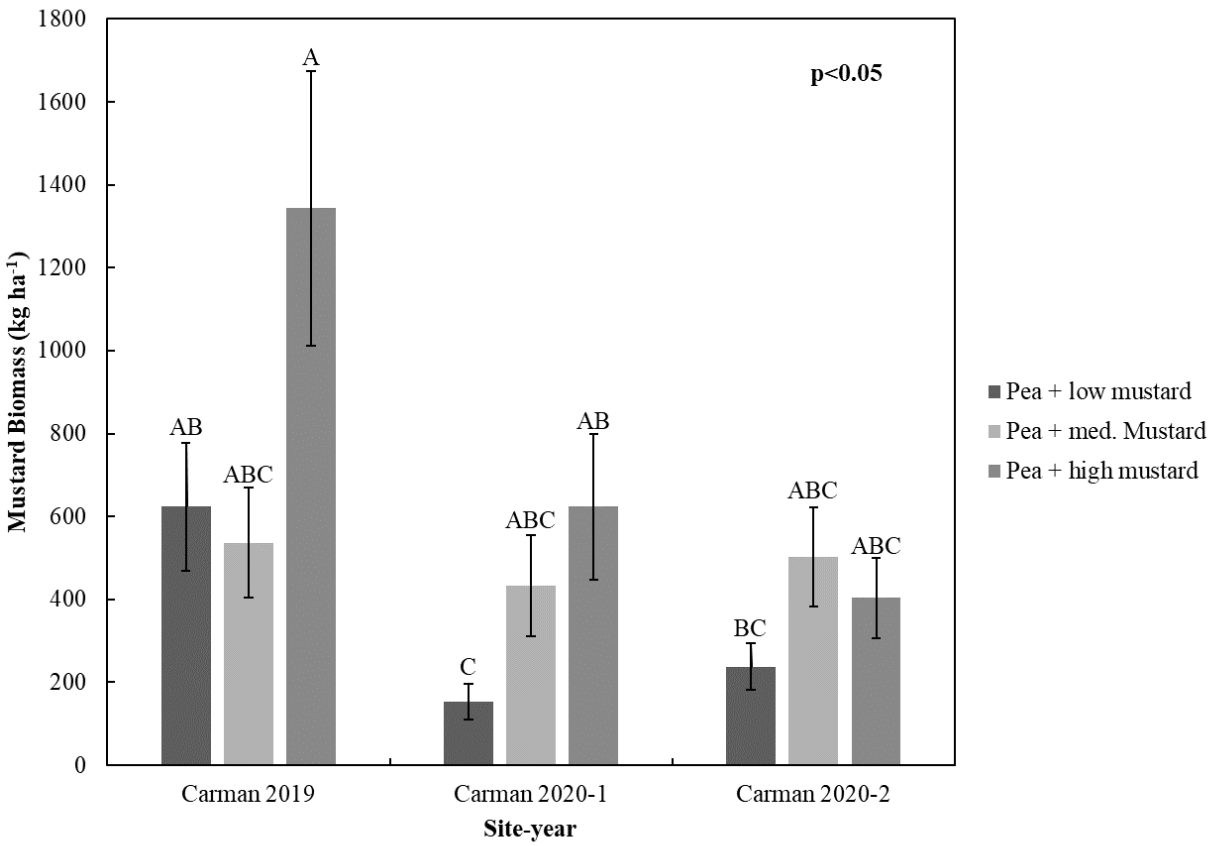

Figure 5. Mustard biomass of three pea-mustard intercrop treatments (pea + low mustard, pea + med. mustard, and pea + high mustard) at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020. Error bars represent standard errors of the least-squares means. Treatments are clustered by site-year. Data were log transformed with back transformed data presented in figure. Means with different letters are significantly different (Tukey's HSD, $p<0.05$).

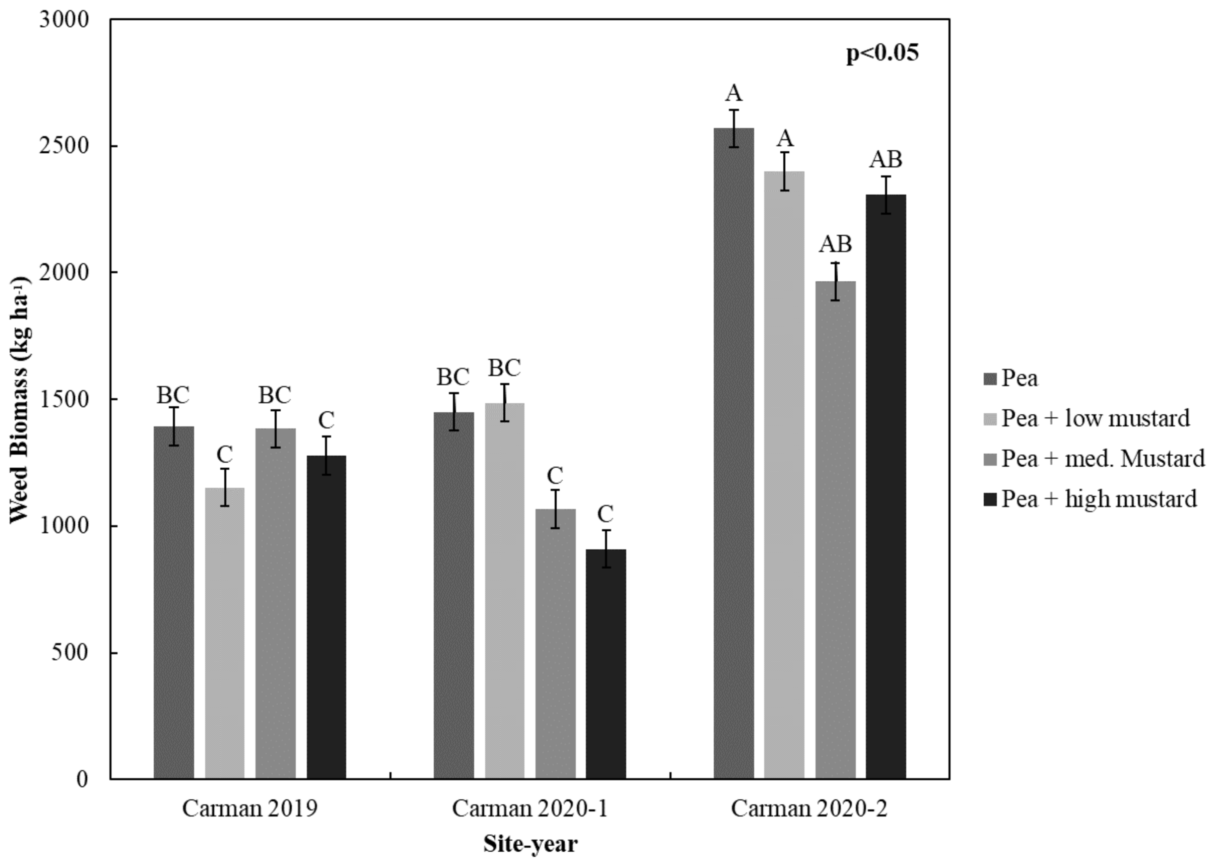

Figure 6. Weed biomass of pea monoculture and three pea-mustard intercrop treatments (pea + low mustard, pea + med. mustard, and pea + high mustard) at the University of Manitoba Ian N. Research Farm in 2019 and 2020. Treatments are clustered by site-year. Error bars represent standard errors of the least-squares means. Means with different letters are significantly different (Tukey's HSD, $p<0.05$).

4.6.4 Grain Yield and Harvest Indices

Pea grain yield was significantly affected by site-year and treatments (Table 16). The site-year effect showed that Carman 2020-1 (2727 kg ha^{-1}) yielded significantly more than Carman 2019 (2124 kg ha^{-1}), which yielded significantly more than Carman 2020-2 (1033 kg ha^{-1}). The treatment effect showed that pea grain yield was significantly reduced with mustard intercropping, thereby supporting the hypothesis that mustard intercropping has a negative effect on pea grain yields. The highest mustard seeding rate significantly reduced pea yield by 9% and 11% when compared to the medium and low seeding rates, respectively (Table 16).

A site-year by treatment interaction was observed for pea grain yield (Figure 7.). The basis of the interaction was that the presence of the mustard intercrop resulted in significant pea yield decreases at two site-years but not at the third site-year. For example, the high mustard seeding rate in 2019, and medium and high mustard seeding rates in 2020-1 significantly reduced pea grain yields compared to the pea monoculture, but intercropping did not affect pea grain yields in 2020-2. The Carman 2019 and 2020-1 site-years contained similar levels of weed biomass, however the weed community composition was different (Table 6). The Carman 2020-1 contained a diverse community of broadleaf weeds such as lamb's quarters, and the Carman 2019 site-year was dominated by green foxtail. The Carman 2020-2 site-year was also dominated by green foxtail, however the level of weed biomass was significantly greater than the Carman 2019 and 2020-1 site-years. At low densities, Weaver, (2001) found that lamb's quarters was more competitive than green foxtail. However, at high densities green foxtail and lamb's quarters resulted in similar yield reductions. Therefore, the significant yield reductions at Carman 2020-2 may be attributed to the substantial level of green foxtail at that site, resulting in little competitive effect on weed biomass from the mustard crop.

The pea harvest index in 2020 fell within the range found in past pea intercrop research (Bedoussac & Justes, 2010b). The pea harvest index in 2019 was significantly greater than in 2020 (Table 16). However, between-year comparisons in harvest index may be problematic here owing to different approaches for establishing crop biomass measurements. Bedoussac & Justes (2010b) found that intercropping peas resulted in a numerically greater harvest index, and between the sole crop and intercrop treatments the pea harvest index was 0.47 to 0.54. Thus, based on Bedoussac & Justes (2010b) findings, it appears that in the present study peas exhibited a similar response to intercropping.

Mustard yields were very low at all site-years and differed between site-years (Table 16). Mustard yields ranged from 19 kg ha^{-1} to 83 kg ha^{-1}, alongside a pea yield range of 1034 kg ha^{-1} to 2124 kg ha^{-1}. The approximate seeding rates for the pea-mustard intercrops in the present study were 181.5 kg ha^{-1} peas, with 2.6 kg ha^{-1} to 7.9 kg ha^{-1} mustard from the low to high seeding rates, respectively. In comparison, in the survey of organic farmers using pea intercrops three participants responded that when using a pea rate of 133 kg ha^{-1} to 266 kg ha^{-1}, with a mustard rate of 2.8 kg ha^{-1} to 22.4 kg ha^{-1}, average pea and mustard yields were approximately

1008 kg ha^{-1} to 2285 kg ha^{-1}, and 111 kg ha^{-1} to 672 kg ha^{-1}, respectively (Appendix 8.7.2, 8.7.3, and 8.7.8). There were significant differences between 2019 and 2020 mustard yields (Table 16). Carman 2019 yielded 74 kg ha^{-1}, while Carman 2020-2 and Carman 2020-1 yielded 43 kg ha^{-1} and 27 kg ha^{-1}, respectively. Mustard grain yield was significantly affected by mustard rate and increased as the density of mustard within the intercrop increased. The grain yield increase was 78% from the lowest to highest mustard rate. Increasing the mustard seeding rate up to 125 seeds m^{-2} has been found to increase mustard grain yield in monoculture mustard production (McKenzie et al., 2006). Pridham & Entz (2008) found that intercropping mustard with wheat reduced ($P<0.05$) wheat yields by an average of 26% and 41% over two of the three site-years, respectively. Langat (1992) found that intercropping peas with mustard resulted in the opposite effect, whereby peas, which were the dominant crop in the intercrop, appeared to outcompete the mustard crop reducing mustard yields by 87%.

A significant site-year by treatment interaction for mustard HI was observed (Figure **8**). The medium mustard seeding rate HI was significantly greater than the low and high mustard seeding rates in 2019, but intercropping did not affect the mustard harvest index in 2020. Across site-years, mustard HI was between 0.09 to 0.14. Angadi et al., (2000) found that mustard under different levels of temperature stress exhibited a range of harvest indices between 0.19 and 0.34. If the harvest index is low it may suggest that the crop is under stress (Unkovich et al., 2010). Therefore, the results in the present study suggest that the mustard crop was under stress and not able to have a high reproductive efficiency. The stress that the mustard crop may have been subjected to may be due to a combination of factors such as flea beetle damage, competition from weeds and the pea crop, and high temperatures at flowering (Table 3).

Table 16. Mean pea and mustard grain yields and pea and mustard harvest indices of pea monoculture and pea-mustard intercrop treatments (pea + low mustard, pea + medium mustard, and pea + high mustard), averaged across site-years and treatments at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020.

	Pea	**Mustard**[ʮ]	**Pea Harvest Index**[฿]	**Mustard Harvest Index**
	Kg ha^{-1}			
Site-year				
Carman 2019	2124b[֍]	74a	0.65a	0.14a
Carman 2020-1	2727a	27b	0.54ab	0.09a
Carman 2020-2	1034c	43b	0.47b	0.14a
Treatment				
Pea	2125a	-	0.50a	-
Pea + low mustard	1990b	19c	0.57a	0.09a
Pea + medium mustard	1954b	55b	0.55a	0.14a
Pea + high mustard	1776c	83a	0.58a	0.13a
Fixed Effect P-Values				
Site-year	**<0.0001**	**0.0010**	**0.0520**	0.2886
Treatment	**<0.0001**	**<0.0001**	0.3875	0.0655
Site-year*Treatment	**0.0347**	0.1764	0.8986	**0.0065**

[֍]Means with different letters in the same column are significantly different (Tukey's HSD, p<0.05).
[ʮ]Mustard yield data were log transformed with back transformed data presented in table.
[฿]Pea harvest index yield data were log transformed with back transformed data presented in table.

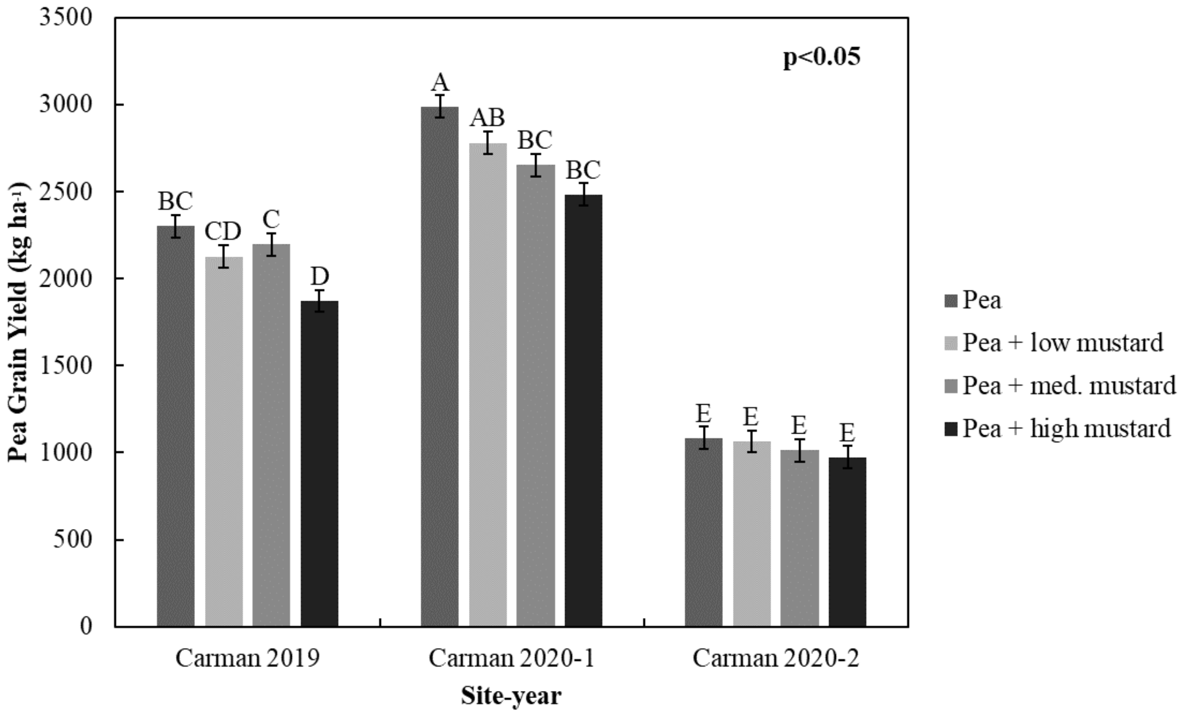

Figure 7. Pea grain yield of pea monoculture and three pea-mustard intercrop treatments (pea + low mustard, pea + med. mustard, and pea + high mustard) at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020. Error bars represent standard errors of the least-squares means. Treatments are clustered by site-year. means with different letters are significantly different (Tukey's HSD, $p<0.05$).

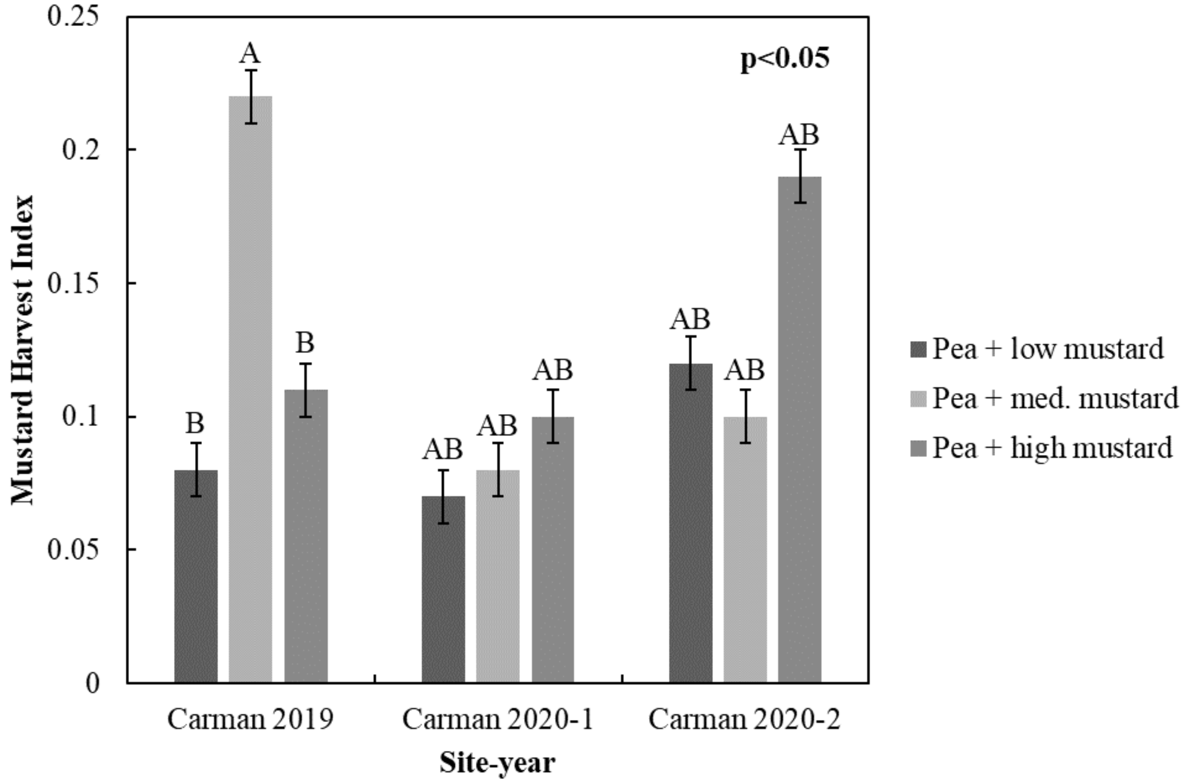

Figure 8. Mustard harvest index of three pea-mustard intercrop treatments (pea + low mustard, pea + med. mustard, and pea + high mustard) at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020. Error bars represent standard errors of the least-squares means. Treatments are clustered by site-year. Means with different letters are significantly different (Tukey's HSD, $p<0.05$).

Grain yields and weed biomass components were compared in an effort to better understand their response across intercrop treatments. Averaged across site-years, mustard yields were very low and contributed very little to total grain production (Figure 9.). Despite the limited grain yield contribution, however, the high and medium mustard seeding rates significantly reduced weed biomass by 17% and 18%, respectively (Figure **9**). Unfortunately, the presence of mustard intercrops also reduced pea grain yield, with 8% and 16% reductions from the medium and high mustard seeding rates, respectively (Figure 9.). Pea yields were not improved by intercropping indicating that the presence of mustard was more detrimental to pea yields than the presence of greater weed biomass in the pea monoculture. Similarly, Fernandez et al. (2015) found that pea-oilseed radish (*Raphanus sativus* L.) reduced weed biomass by 39%. Across three site-years, pea grain yield was reduced by 11%, 46%, and 12%, respectively.

Therefore, in the present study, although weed biomass was reduced significantly by intercropping, weed suppression may be considered low in comparison to results from similar pea-oilseed intercrop research. Pridham & Entz (2008) found that wheat-mustard intercrops failed to suppress weeds, due to flea beetle reducing the mustard stand. However, similar to the grasshopper damage in the 2020 pea-cereal site-years, further research is required to understand if the flea beetle damage to the mustard crop removed the mustards competitive effect on pea growth, resulting in early season weed suppression and greater pea yields. Langat (1992) found that intercropping peas with mustard did not affect pea yields, however the mustard yields were reduced, when compared to the mustard monoculture crop seeded at the same rate. In Langat (1992) study, peas were seeded approximately 37% lower than the pea seeding rate in the present study, and mustard was seeded at a similar rate to the low mustard rate treatment. The results from the present study and Langat (1992) may reflect the weaker competitive ability of mustard when compared to other intercrop component crops such as barley and oats, but further study is required to verify this theory.

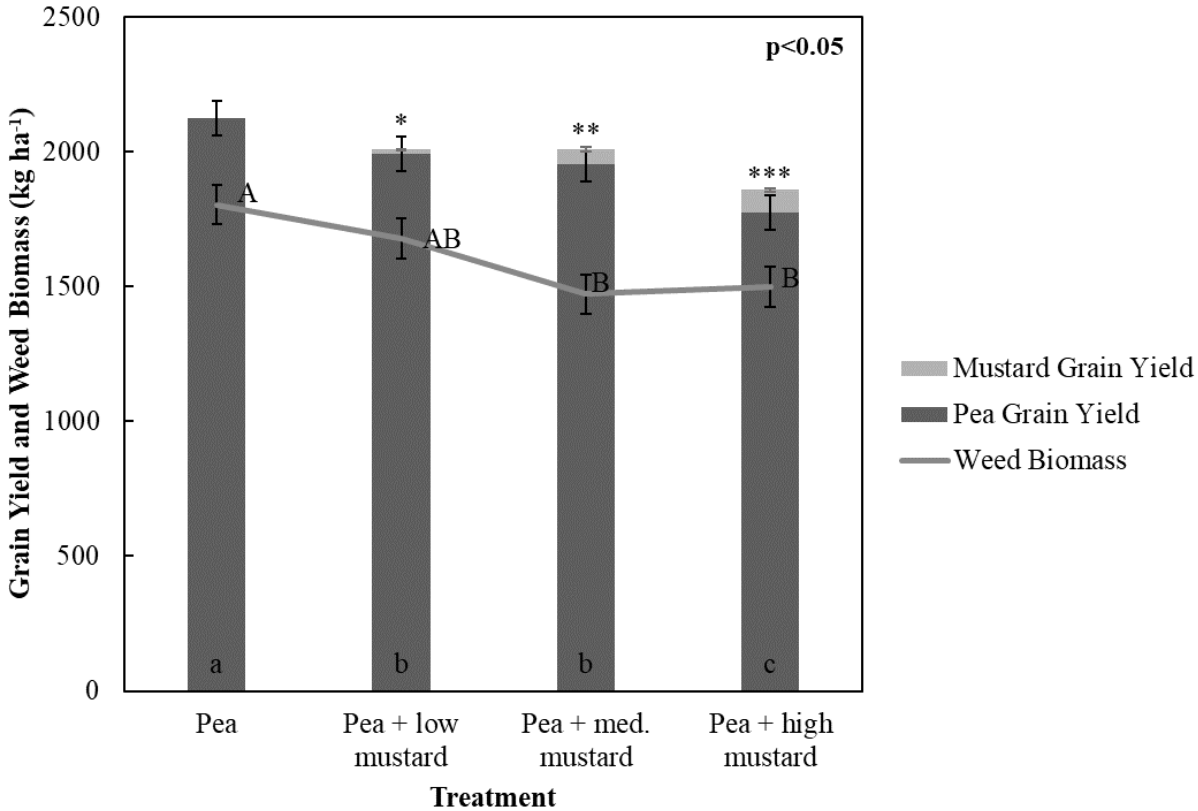

Figure 9. Effect of pea monoculture and three pea-mustard intercrop treatments (pea + low mustard, pea + med. mustard, and pea + high mustard) on pea and mustard grain yield and weed biomass averaged over three site-years at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020. Error bars represent standard errors of the least-squares means. Mustard yield data were log transformed with back transformed data presented in figure. Means with different letters (pea grain yield and weed biomass) and number of asterisks (mustard grain yield) are significantly different (Tukey's HSD, $p<0.05$).

4.6.5 Economic Analysis

Net returns were considered in three different scenarios: standard organic price of peas and mustard; a 50% increase in the price of peas; and a 50% increase in the price for mustard. In the present study, when using a standard organic price of peas and mustard, Carman 2019 and 2020-1 were the only site-years that achieved pea yields that resulted in positive net returns. However, net returns were significantly influenced by site-year, treatment, and their interaction. In terms of site-years, the initial net return using standard grain prices was significantly greater for Carman 2020-1 (\$297.91 ha^{-1}), than Carman 2019 (\$55.23 ha^{-1}), which was greater than

Carman 2020-2 (-\$585.87 ha^{-1}) (Table 17). The higher (less negative) net returns for Carman 2020-1 reflects the high pea yields that were achieved (Table 16). Significantly lower net returns at Carman 2019 and Carman 2020-2 were attributed to low pea yields, due to greater weed pressure and sub-optimal growing conditions. Across treatments, net returns ranged from -\$129.19 ha^{-1} to -\$44.11 ha^{-1}. (Table 17). The pea monoculture and medium mustard seeding rates were found to be significantly more profitable than the high mustard seeding rate. Fernandez et al. (2015) found no difference in profitability between a pea-oilseed radish intercrop and an unweeded pea monoculture control. Although pea yields were reduced by the presence of oilseed radish, they attributed the high net returns to the high market price for oilseed radish seed (\$3.31 kg^{-1}).

In the initial net return analysis a site-year by treatment interaction was detected for net returns (Figure 10). At the Carman 2020-1 site-year, net returns for the high mustard seeding rate were significantly lower than the pea monoculture. In 2019, the medium mustard seeding rate net returns were significantly lower than the low and high mustard seeding rates. The pea grain yield and weed biomass results suggest that where weed biomass was lower, pea grain yields were greater, resulting in greater net returns (Figure 1. , Figure *7.* , and Figure 10). Of interest to note is that the most profitable treatment of all three site-years was the pea monoculture in Carman 2020-1, where pea yields were found to be the greatest (Figure ***7.***). These results suggest that greater pea yields appear to be the main contributor to profitability within pea-mustard intercropping systems. The added mustard yield, on the other hand, added very little to profitability.

The second scenario involved a reanalysis based on a 50% increase in the market price for peas. Under this second scenario, the ranking of site-years and treatments did not change, but the overall profitability across site-years and treatments increased (Table 17). Net returns were significantly affected by site-year and treatment. The site-year effect showed that Carman 2020-1 (\$1033.23 ha^{-1}) was significantly more profitable than Carman 2019 (\$627.29 ha^{-1}), which was significantly more profitable than Carman 2020-2 (-\$307.27 ha^{-1}). Across treatments, the pea monoculture, and low and medium mustard seeding rates were found to be significantly more profitable than the high mustard seeding rate. This observation suggests that from a one-year economic analysis, intercropping did not provide any economic benefits.

In this second scenario, net returns were affected by a site-year by treatment interaction (Figure 11.). At the Carman 2020-1 site-year, net returns in the medium and high mustard seeding rates were significantly lower than the pea monoculture. In 2019, the medium mustard seeding rate net returns were significantly greater than the low and high mustard seeding rates. These results contain the same trends across treatments as found in Figure 10, however, net returns were increased substantially at every site-year, further confirming that greater pea yields appear to be the main contributor to profitability within pea-mustard intercropping systems.

In a third scenario, the price of mustard was increased by 50%. In this scenario, the net return results compared with the base price scenario. For example, the average net returns were approximately $0.08 to $85 per hectare less negative across all treatments when mustard was priced at a 50% premium compared with the base scenario (Table 17). Also, under this scenario the pea monoculture was no longer more profitable and there were no significant differences in net returns among treatments. The observation that mustard did not improve the economic performance of intercropping even with an additional price premium demonstrated the limit to which mustard helped make pea intercropping profitable.

In the third scenario, net returns were affected by a site-year by treatment interaction (Figure 12). At the Carman 2020-1 site-year, net returns in the high mustard seeding rate were significantly lower than the pea monoculture. In 2019, the medium mustard seeding rate net returns were significantly greater than the low mustard seeding rate. These results contain the same trends across treatments as found in Figure 10 and Figure 11, further confirming that greater pea yields appear to be the main contributor to profitability within pea-mustard intercropping systems.

A significant interaction was detected for net returns across all three economic scenarios, indicating that net returns were unstable across the three different site-years, across a wide range of market conditions. These results suggest that mustard intercropping may not produce a predictable net return outcome, regardless of substantial changes in market conditions.

Table 17. Mean net returns of pea monoculture and three pea-mustard intercrop treatments (pea + low mustard, pea + medium mustard, and pea + high mustard), averaged across site-years and treatments at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020.

	Initial Net Return	50% Increase in Pea Market Price Net Return	50% Increase in Mustard Market Price Net Return
		$\$ ha^{-1}$	
Site-year			
Carman 2019	55.23b[֍]	627.29b	121.51b
Carman 2020-1	297.91a	1033.23a	322.4a
Carman 2020-2	(585.87)c[ש]	(307.27)c	(554.27)c
Treatment			
Pea	(44.11)a	528.98a	(44.11)a
Pea + low mustard	(84.22)ab	451.81a	(64.44)a
Pea + medium mustard	(52.80)a	474.15a	5.65a
Pea + high mustard	(129.19)b	349.4b	(44.19)a
Fixed Effect P-Values			
Site-year	**<.0001**	**<.0001**	**<.0001**
Treatment	**0.0053**	**0.0003**	0.0673
Site-year*Treatment	**0.0008**	**0.0031**	**0.0008**

[֍]Means with different letters in the same column are significantly different (Tukey's HSD, $p<0.05$).
[ש]Parentheses indicate negative values.
*Economic analysis assumes an initial organic pea market price of $0.53 kg, and an initial organic mustard price of $1.78 kg.

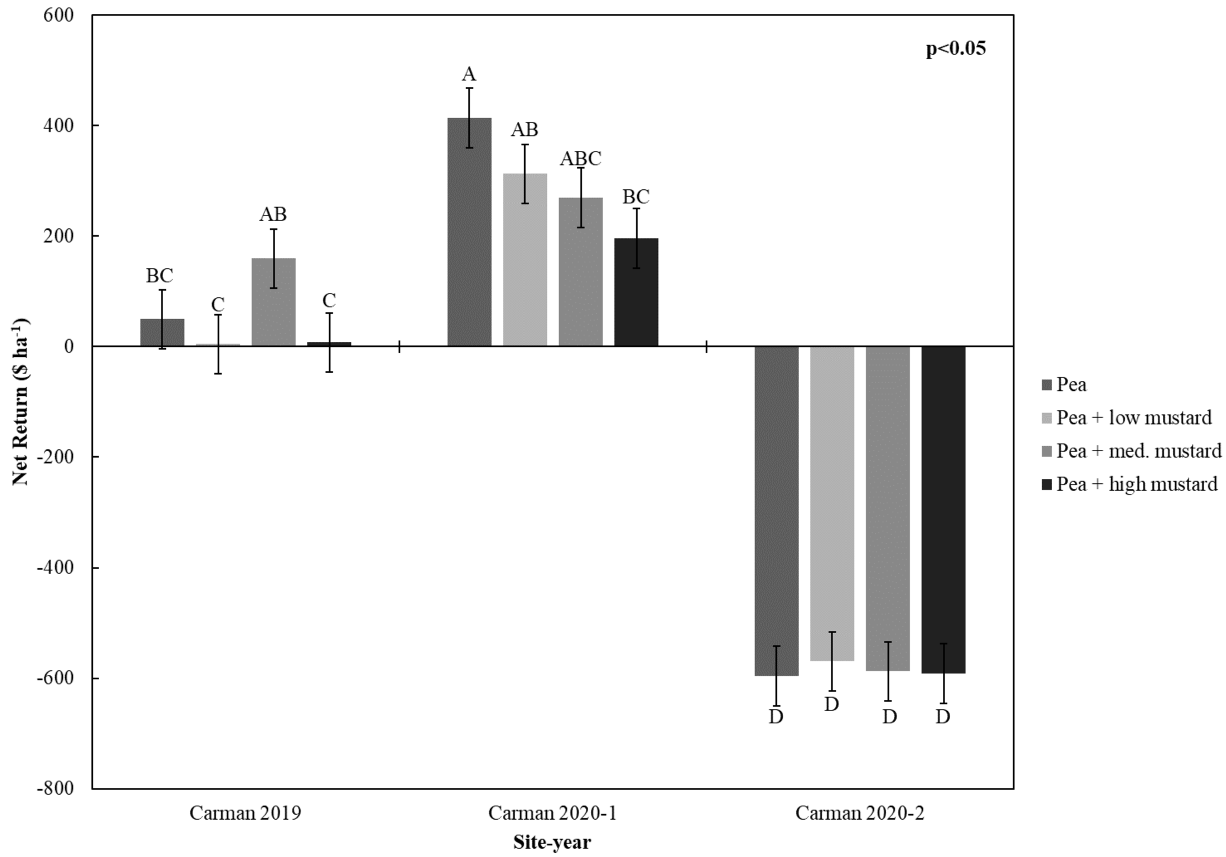

Figure 10. Initial net returns of pea monoculture and three pea-mustard intercrop treatments (pea + low mustard, pea + med. mustard, and pea + high mustard) at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020. Error bars represent standard errors of the least-squares means. Treatments are clustered by site-year. Means with different letters are significantly different (Tukey's HSD, $p<0.05$).

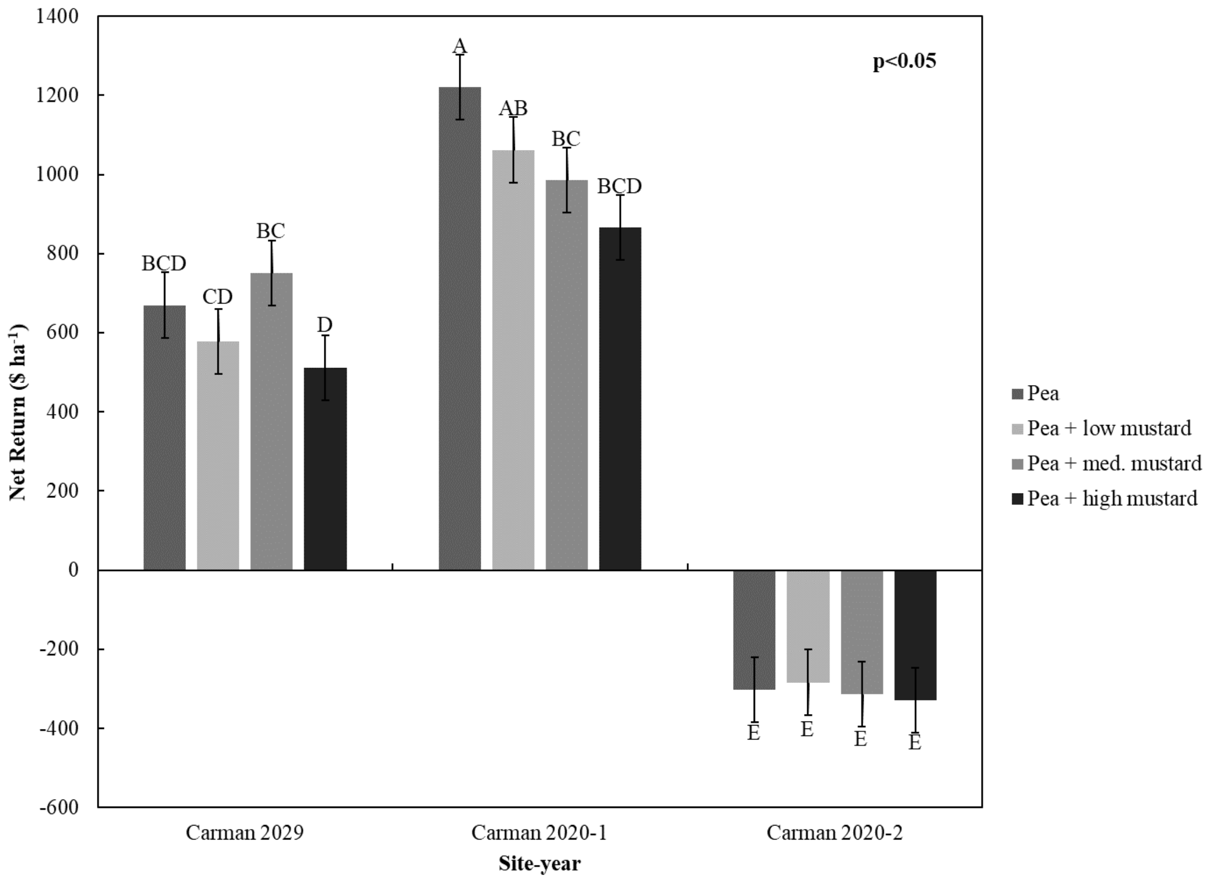

Figure 11. Net returns of pea monoculture and three pea-mustard intercrop treatments (pea + low mustard, pea + med. mustard, and pea + high mustard) using a 50% increase in pea market price at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020. Error bars represent standard errors of the least-squares means. Treatments are clustered by site-year. Means with different letters are significantly different (Tukey's HSD, $p<0.05$).

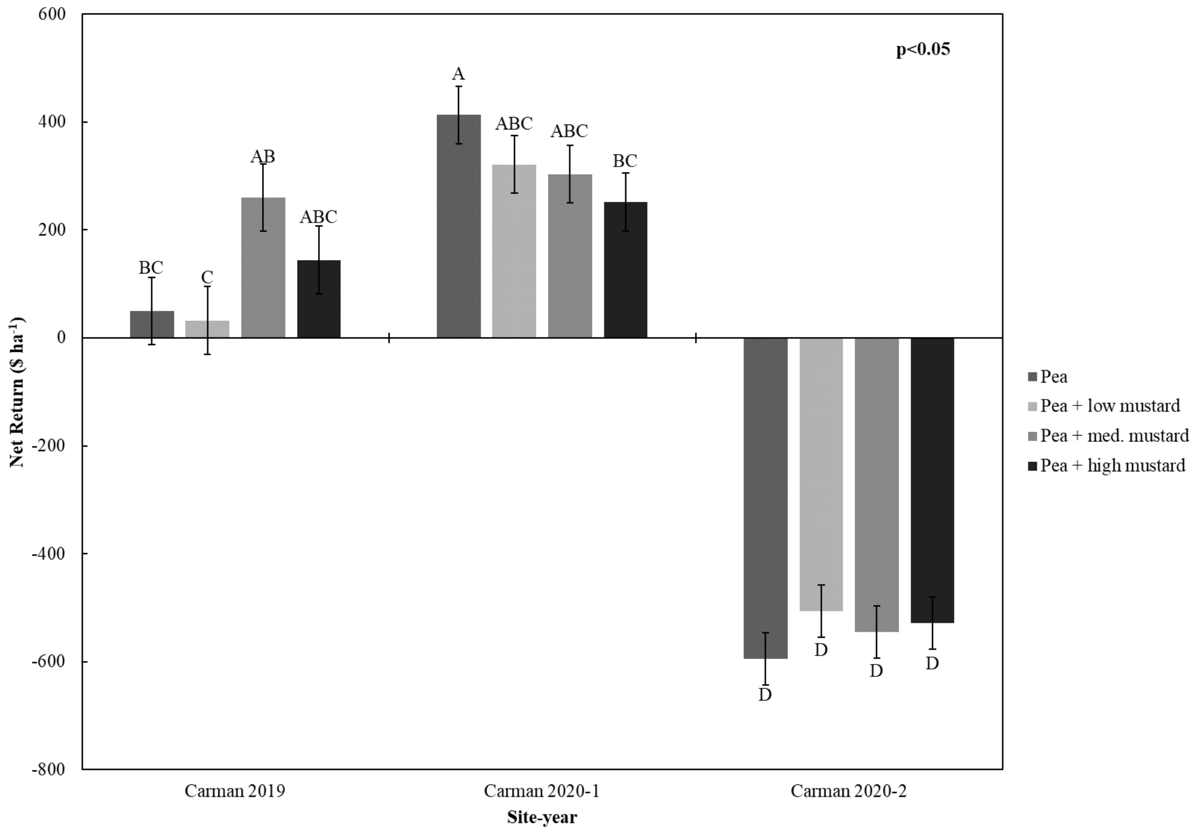

Figure 12. Net returns of pea monoculture and three pea-mustard-intercrops (pea + low mustard, pea + med. mustard, and pea + high mustard) using a 50% increase in mustard market price at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020. Error bars represent standard errors of the least-squares means. Treatments are clustered by site-year. Means with different letters are significantly different (Tukey's HSD, $p<0.05$).

4.6.6 Summary and Conclusions

Positive effects of mustard intercropping included a reduction in weed biomass. In the present study weed biomass reductions were low in comparison to Fernandez et al. (2015) findings, however flea beetle damage did not appear to be a problem in this particular study. This was not the case in Pridham & Entz (2008) study, whereby flea beetle damage reduced the mustard crop to the point where no weed suppression effect was detected.

Negative effects of intercropping included a reduction in pea growth (biomass) and grain yield. Therefore, one of the main conclusions of this study was that mustard reduced pea yield.

Mustard intercropping did not affect pea plant height, pea protein content, pea DTM, or pea TKW (Appendix 8.3).

In the initial net return analysis, all treatments contained negative net returns. Also, the high mustard seeding rate was significantly less profitable than the pea monoculture, indicating that the contribution of mustard grain to total yield was not beneficial to per hectare profitability. Increasing the market price of peas by 50% resulted in similar treatment trends as were observed in the initial net return analysis, however all of the treatments contained positive net returns. These observations demonstrate that common organic pea yields may not translate to positive net returns, and a greater pea market price is a major contributor to profitability in organic pea production. Increasing the market price for organic mustard by 50% resulted in similarly low net returns as were found in the initial net return analysis, however there were no significant differences among treatments, suggesting that increasing the market price of mustard increased the overall profitability of the intercrop mixtures, but not to the point where net returns were more profitable than the pea monoculture.

Increasing the mustard seeding rate from low to high did not always show the same pea response as was hypothesized. Of importance to note is the quantity of site-year by treatment interactions detected across a wide range of agronomic parameters. The treatment effects and interactions in the present study indicates that pea-mustard intercrops were unstable across the three different site-years and suggests that using pea-mustard intercrops in organic production may result in unpredictable outcomes. This may be due to flea beetle damage and/or the low levels of nitrogen found in the experimental soils. Mustard requires high levels of nitrogen to ensure productivity, thus the low levels of nitrogen found in the experimental soils may have inhibited mustard productivity.

In conclusion, mustard intercropping led to reduced weed biomass, but resulted in a significant pea yield penalty. The pea monoculture was more profitable than intercropping and resulted in unpredictable outcomes across a wide range of agronomic parameters including pea yield and net returns.

4.7 Pea-Oat Intercrop Experiment

4.7.1 Crop Density

Pea plant population density was significantly greater in 2019 than 2020 and fell within 76% to 97% of the 120 plants m^{-2} target plant density (Table 18). Pea population density was unaffected by oat intercrop seeding rate and the lack of a significant intercrop by site-year interaction indicated that plant population response to oat intercrops was stable across the three site-years.

Oat plant population was significantly different across all site-years and treatments (Table 18). The high oat plant density in 2019 was attributed to a planting error that resulted in over-seeding. Oat density significantly increased from the low to high rate oat treatment. No significant intercrop treatment by site-year interaction was observed indicating the effects of different oat densities on plant population were similar among the three site-years.

Table 18. Mean pea and oat plant population densities of pea monoculture and three pea-oat intercrop treatments (pea + low oat, pea + medium oat, and pea + high oat), averaged across site-years and treatments at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020.

	Pea Density	Oat Density
	Plants m^{-2}	
Site-year		
Carman 2019	116a֍	177a
Carman 2020-1	91b	60c
Carman 2020-2	92b	78b
Treatment		
Pea	103a	-
Pea + low oat	99a	57c
Pea + medium oat	92a	94b
Pea + high oat	104a	163a
Fixed Effect P-Values		
Site-year	0.0006	**<0.0001**
Treatment	0.1584	**<0.0001**
Site-year*Treatment	0.5816	0.0638

֍Oat and pea density means with different letters in the same column are significantly different (Tukey's HSD, $p<0.05$).

4.7.2 Mid-Season Crop and Weed Biomass

Biomass samples were taken at flower bud and beginning bloom (R1 and R2 growth stage) of peas, and stem elongation (Zadok stage 30-32) in oat. The goal was to understand the growth of three main plant components: peas, oat, and weeds. Mid-season biomass was measured in 2020 only.

Pea, oat, and total crop biomass levels were significantly higher for Carman 2020-1 compared to Carman 2020-2 (Table 19). Pea and oat biomass were 64% and 49% greater in Carman 2020-1, respectively. The range of pea (991 kg ha^{-1} to 1201 kg ha^{-1}) and oat (537 kg ha^{-1} to 939 kg ha^{-1}) biomass recorded were similar to previous Canadian studies. For example, Borstlap & Entz (1994) observed a range of mid-season pea monoculture biomass from approximately 700 kg ha^{-1} to 1500 kg ha^{-1}, while Li et al. (2018) observed a range of oat monoculture biomass yields at mid-season from approximately 600 kg ha^{-1} to 1000 kg ha^{-1}.

Pea biomass yield was not affected by any intercrop treatment (Table 19). This observation did not support my hypothesis that oat intercrops would have a negative effect on pea growth. The lack of intercrop effect on pea biomass indicates that pea and oat were not competing for resources at early stages in the crop-cycle. Oat biomass increased as the density of oat increased within the intercrop. From the low oat seeding rate to the high oat seeding rate, oat biomass increased by 43%.

Intercropping significantly increased total crop biomass, with all oat/pea intercrop treatments producing more biomass than the pea monoculture (Table 19). The highest seeding rate resulted in significantly greater total crop biomass than the lowest pea seeding rate treatments. Therefore, the results showed that net primary productivity at the mid-season growth phase was increased with intercropped oat compared to pea monoculture control. Intercropping did not significantly reduce pea biomass when compared to the pea monoculture allowing the high oat seeding rate to contribute significant levels of biomass to total crop biomass. The lack of a significant treatment by site-year interaction indicated that total crop biomass response to oat was stable across the two site-years.

Mid-season weed biomass was 72% greater at Carman 2020-2 vs. Carman 2020-1, but intercropping did not elicit a significant reduction in weed biomass (Table 19). Therefore, the mid-season biomass results did not support the hypothesis that oat intercrops would reduce weed biomass. In the survey of organic farmers using pea intercrops, one participant responded that oat variety choice can contribute greatly to weed suppression in pea-oat intercrops, as different oat varieties have different plant growth habits and may result in earlier canopy closure (Appendix 8.7.3). Li et al. (2018) further confirms this observation as they found that “droopy-leaf” oat varieties suppressed weeds to a greater extent when compared with "erect-leaf" oat varieties. Therefore, future studies on organic pea-oat intercropping should consider oat cultivar.

Table 19. Mean pea, oat, total crop (pea + oat), and weed biomass of pea monoculture and three pea-oat intercrop treatments (pea + low oat, pea + medium oat, and pea + high oat) at early stages[฿] in the crop cycle, averaged across site-years and treatments at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020.

	Pea	**Oat**	**Total Crop**	**Weed**
	Kg ha^{-1}			
Site-year				
Carman 2020-1	1580a[֍]	938a	2284a	182b
Carman 2020-2	575b	477b	933b	660a
Treatment				
Pea	1201a	-	1201c	476a
Pea + low oat	1051a	537b	1588b	421a
Pea + medium oat	1068a	647ab	1715ab	421a
Pea + high oat	991a	939a	1929a	367a
Fixed Effect P-Values				
Site-year	**<0.0001**	**0.0005**	**<0.0001**	**<0.0001**
Treatment	0.1089	**0.0349**	**<0.0001**	0.1167
Site-year*Treatment	0.8518	0.9437	0.0728	0.9329

[֍]Means with different letters in the same column are significantly different (Tukey's HSD, $p<0.05$).
[฿]At time of early biomass sampling, peas had begun to flower (R1 and R2 growth stage), and oats had reached stem elongation (Zadok stage 30-32).

4.7.3 Maturity Crop and Weed Biomass

Samples were taken when peas had reached full pod (R4 growth stage), and oat had begun to ripen (Zadok stage 90).

The results showed that Carman 2020-1 produced significantly greater pea biomass (5320 kg ha^{-1}) than either Carman 2019 (2962 kg ha^{-1}) or Carman 2020-2 (2287 kg ha^{-1}) (Table 20). Greater pea biomass at Carman 2020-1 may be due to a combination of factors such as early seeding, lower levels of nitrogen, and lower levels of weed biomass (Table 5). The low oat seeding rate contained significantly greater pea biomass than the high oat seeding rate treatment. Therefore, increasing the seeding rate of oat had a negative effect on pea growth.

A site-year by treatment interaction (P=0.0314), was observed for pea biomass, however the Tukey HSD multi-treatment comparison of least-squares means failed to detect any significant differences among treatments (Figure 13). At the Carman 2019 site-year, intercropping resulted in lower pea biomass levels than the pea monoculture. At Carman 2020-1, on the other hand, the pea monoculture and low and medium oat seeding rates contained greater biomass than the high oat seeding rate, while at Carman 2020-2 pea biomass was low and unchanged across treatments. These results suggest that in site-years where oat biomass was found to be greater (Carman 2019 and 2020-2) the negative effect on pea biomass was greater. Oats have been found to be more competitive against weeds than field peas, therefore the greater establishment of oats in the Carman 2019 and Carman 2020-2 site-years, and competitive advantage of oat over peas, may have led to greater reductions in pea biomass (Blackshaw et al., 2002).

Oat biomass at maturity was significantly different for each site-year. Carman 2019 yielded 2164 kg ha^{-1}, while Carman 2020-1 and Carman 2020-2 yielded 458 kg ha^{-1} and 973 kg ha^{-1}, respectively. Greater oat biomass in 2019 was partly due to over seeding. Greater oat biomass at 2020-2 may be because the early season canopy growth found in oats led to oats outcompeting green foxtail (Sustainable Agriculture Research and Education, 2021b). Whereas, the significantly lower oat biomass found in 2020-1 was because optimal pea growing conditions resulted in pea outcompeting oat. Across treatments the high oat seeding rate contained significantly greater oat biomass than the low and medium oat seeding rates (Table 20), with the low, medium, and high oat seeding rates contributing 23%, 21%, and 24% to total crop biomass, respectively. The lack of significant interaction indicated that the effect of oat seeding rate intercrops on oat biomass was stable across site-years.

Weed biomass in the present study was greater than weed biomass observed in a survey of commercial farm fields in Manitoba and Saskatchewan (Thiessen Martens et al., 2019). Among site-years, Carman 2020-2 contained the highest ($P<0.05$) level of weed biomass (2649 kg ha^{-1}). Among treatments the medium rate oat seeding rate treatment significantly reduced weed biomass by 36% compared to the pea monoculture, and the high oat seeding rate significantly reduced weed biomass by 37%, 25%, and 15%, compared to the pea monoculture, and low and medium oat seeding rates, respectively (Table 20). The lack of a significant seeding rate by site-year interaction indicates that the observations of lower weed biomass with higher oat seeding rates was stable across the three site-years. The results here, support the hypothesis that oat intercrops reduce weed biomass. An explanation for the weed suppression may be because oats are tolerant to variable soil and environmental conditions and are competitive against weeds due to rapid biomass production and allelopathic compounds found in their plant residue (Bouhaouel et al., 2015; Satorre & Snaydon, 1992; Wallace & Canadian Organic Growers, 2001). The rapid germination and growth of the oat crop may have reduced available light and resources, providing the intercrop with a size advantage over weeds.

Table 20. Mean pea, oat, total crop (pea + oat), and weed biomass at maturity[ש] of pea monoculture and three pea-oat intercrop treatments (pea + low oat, pea + medium oat, and pea + high oat), averaged across site-years and treatments at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020.

	Pea	**Oat**	**Total Crop**	**Weed**
		Kg ha^{-1}		
Site-year				
Carman 2019	2962b[£]	2164a[֍]	4727a	1150b
Carman 2020-1	5320a	458c	5731a	1232b
Carman 2020-2	2287b	973b	3098b	2649a
Treatment				
Pea	3704ab	-	3704b	2085a
Pea + low oat	3772a	715b	4796a	1753ab
Pea + medium oat	3609ab	886b	4685a	1549b
Pea + high oat	3007b	1489a	4889a	1322c
Fixed Effect P-Values				
Site-year	**<.0001**	**0.0008**	**0.0002**	**<.0001**
Treatment	**0.0226**	**0.0003**	**0.0003**	**0.0002**
Site-year*Treatment	**0.0314**	0.3606	0.0731	0.1260

[֍]Pea, oat, total crop, and weed biomass means with different letters in the same column are significantly different (Tukey's HSD, $p<0.05$).
[฿]Oat biomass data were log transformed with back transformed data presented in table.
[ש]At time of biomass at maturity sampling peas had reached full-pod stage (R4 growth stage) and oat had begun to ripen (Zadok stage 90).

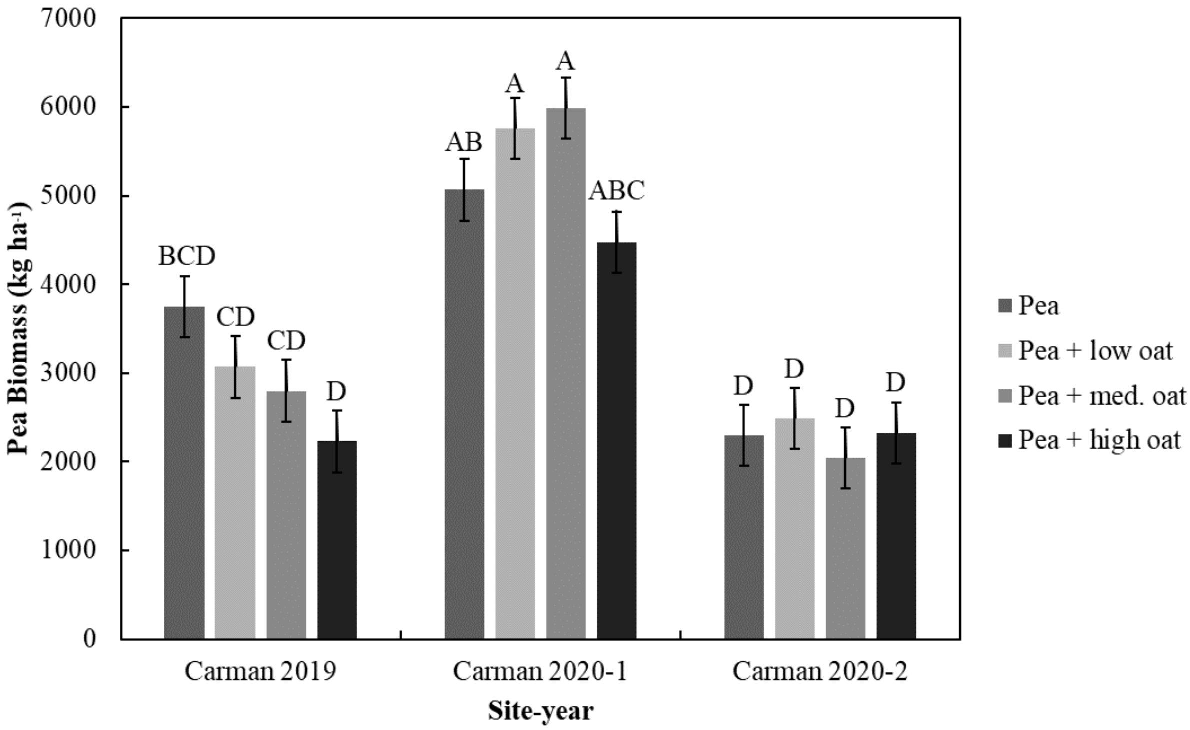

Figure 13. Pea biomass of pea monoculture and three pea-oat intercrop treatments (pea + low oat, pea + med. oat, and pea + high oat) at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020. Error bars represent standard errors of the least-squares means. Treatments are clustered by site-year. Means with different letters are significantly different (Tukey's HSD, $p<0.05$).

4.7.4 Grain Yield and Harvest Indices

Pea grain yield ranged from 1034 kg ha^{-1} to 2921 kg ha^{-1}, and was significantly affected by site-years (Table 21). The site-year effect showed that Carman 2020-1 (2921 kg ha^{-1}) yielded significantly more than Carman 2019 (1838 kg ha^{-1}), which yielded significantly more than Carman 2020-2 (1034 kg ha^{-1}). Greater pea biomass translated to greater pea yields as treatments with high pea dry matter (Table 20) resulted in higher grain yield (Table 21). The pea yields observed in the present study were similar to those reported by participants in the accompanying pea intercropping survey (Appendix 8.7). One survey participant outlined that their pea-oat intercrops seeded in a mixture of 200 kg ha^{-1} peas and 37 kg ha^{-1} oats yielded on average 1714 kg ha^{-1} to 2285 kg ha^{-1} peas, and 302 kg ha^{-1} to 403 kg ha^{-1} oats, respectively (Appendix 8.7.3). In comparison, in the present study, pea-oat intercrops were seeded in a mixture of approximately 181.5 kg ha^{-1} peas with 16.5 kg ha^{-1} to 55.4 ka ha^{-1} oats from the low to high seeding rates, respectively. In the present study, pea had a significant yield response to intercropping, as the low, medium, and high oat seeding rates reduced pea yield by 12%, 17%, and 26%, respectively. Furthermore, yield was significantly reduced by the high oat seeding rate compared to the low and medium oat seeding rates (Table 20). One explanation for the reduced pea yields is that the increased crop densities associated with the additive intercrop design increased both inter and intra-specific competition for resources, thereby reducing pea yields (Vandermeer, 1992).

A significant site-year by treatment interaction was detected for pea grain yield (Table 21). The interaction was due to a reduction in grain yield with increasing rates of oat intercrop in Carman 2019 and 2020-1, while intercropping did not affect pea grain yield at Carman 2020-2 (Figure 14). In conclusion, this interaction indicates that the pea grain yield response to oat intercrops was unstable across the three site-years.

Oat yield was significantly affected by treatment and site-year (Table 21). Carman 2019 yielded 962 kg ha^{-1}, while Carman 2020-2 and Carman 2020-1 yielded 398 kg ha^{-1} and 28 kg ha^{-1}, respectively. Across treatments, oat yield ranged from 151 kg ha^{-1} to 328 kg ha^{-1}. Grasshopper damage to oats was observed across both 2020 site-years and may have contributed to reduced yields. At a seeding rate similar to the high oat rate treatment, Li et al. (2018) found that two different oat varieties yielded approximately 300 kg ha^{-1} to 800 kg ha^{-1} under drought conditions, and 3600 kg ha^{-1} and 3800 kg ha^{-1} under optimal growing conditions. Based on comparison with Li et al. (2018) study, oat yields in the present study can be considered low.

Pea harvest index was significantly lower in the Carman 2020-2 site-year (Table 21). There were no significant differences in pea harvest indices among intercrop treatments and no indication that the pea harvest index increased from the low to high rate oat seeding rate, as was found in past research (Bedoussac & Justes, 2010b). Oat harvest index was significantly lower in the Carman 2020-1 site-year (Table 21). The grasshopper damage observed in 2020 would have caused the oat crop to accumulate biomass, but head clipping may have reduced grain yields, resulting in the unprecedented harvest index. There were no significant differences in oat harvest indices among intercrop treatments. Li et al. (2018) found that harvest indices under drought conditions were approximately 0.24 to 0.28, while under optimal growing conditions the harvest index was 0.45.

Table 21. Mean pea and oat grain yields and pea and oat harvest indices of pea monoculture and three pea-oat intercrop treatments (pea + low oat, pea + medium oat, and pea + high oat), averaged across site-years and treatments at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020.

	Pea	**Oat**[שׁ]	**Pea Harvest Index**	**Oat Harvest Index**[฿]
		Kg ha^{-1}		
Site-year				
Carman 2019	1838b[֍]	962a	0.65a	0.45a
Carman 2020-1	2921a	28c	0.55a	0.06b
Carman 2020-2	1034c	398b	0.46b	0.41a
Treatment				
Pea	2238a	-	0.60a	-
Pea + low oat	1970b	151c	0.54a	0.21a
Pea + medium oat	1866b	212b	0.53a	0.24a
Pea + high oat	1650c	328a	0.56a	0.22a
Fixed Effect P-Values				
Site-year	**<0.0001**	**<0.0001**	**0.0135**	**<0.0001**
Treatment	**<0.0001**	**<0.0001**	0.4683	0.5018
Site-year*Treatment	**<0.0001**	0.7452	0.3645	0.1484

[֍]Means with different letters in the same column are significantly different (Tukey's HSD, $p<0.05$).
[שׁ]Oat yield data were log transformed with back transformed data presented in table.
[฿]Oat harvest index yield data were log transformed with back transformed data presented in table.

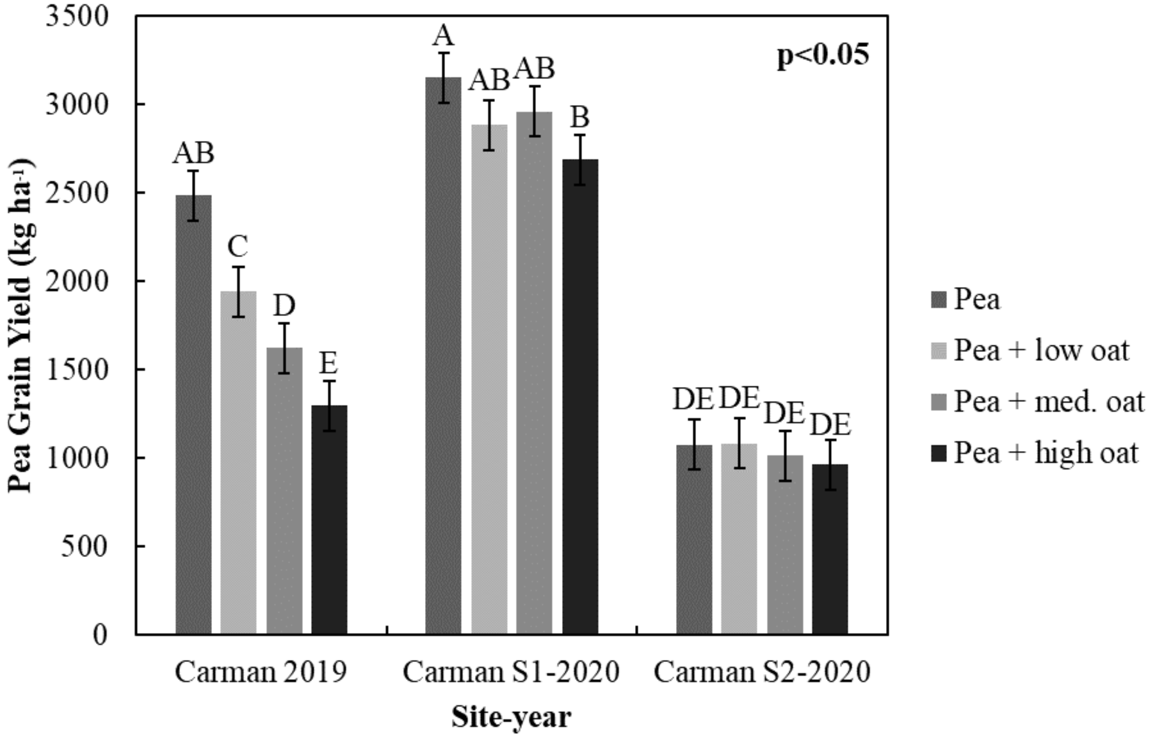

Figure 14. Pea grain yield of pea monoculture and three pea-oat intercrop treatments (pea + low oat, pea + med. oat, and pea + high oat) at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020. Error bars represent standard errors of the least-squares means. Treatments are clustered by site-year. Means with different letters are significantly different (Tukey's HSD, $p<0.05$).

Grain yields and weed biomass components were compared in an effort to better understand their response across intercrop treatments. Figure 15 contains a graphic presentation of the combined site-year data of grain yield and weed biomass that was discussed earlier. Across treatments, pea yields were 1650 kg ha^{-1} to 2238 kg ha^{-1} from the pea monoculture to the high oat seeding rate, and oat yields were 151 kg ha^{-1} to 328 kg ha^{-1} from the low to high oat seeding rate. The high and medium oat seeding rates significantly reduced weed biomass by 37% and 36%, respectively. The low, medium, and high oat seeding rates significantly reduced pea grain yield by 12%, 17%, and 26%, respectively. Pea yields were not improved by intercropping indicating that the presence of oat was more detrimental to pea yields than the presence of greater weed biomass in the pea monoculture. The pea yields and weed biomass reductions noted above may be considered low in comparison to past research (Fernandez et al., 2015). These scientific observations are supported by a survey participant who reported that a pea-oat intercrop seeded to a rate (133 kg ha^{-1} peas and 22 kg ha^{-1} oats) similar to the medium oat seeding rate, yielded approximately 1579 kg ha^{-1} peas and 1238 kg ha^{-1} oats (Appendix 8.7.2).

Pea grain yield and weed biomass reductions in the present study were low in comparison to past research, however the pea grain reductions were still substantial. Therefore, these results indicate that oats provided substantial competition resulting in decreased pea yields. Oats are known to be highly competitive, therefore organic producers should consider potential reductions in pea grain yields when intercropping with oats (Blackshaw et al., 2002).

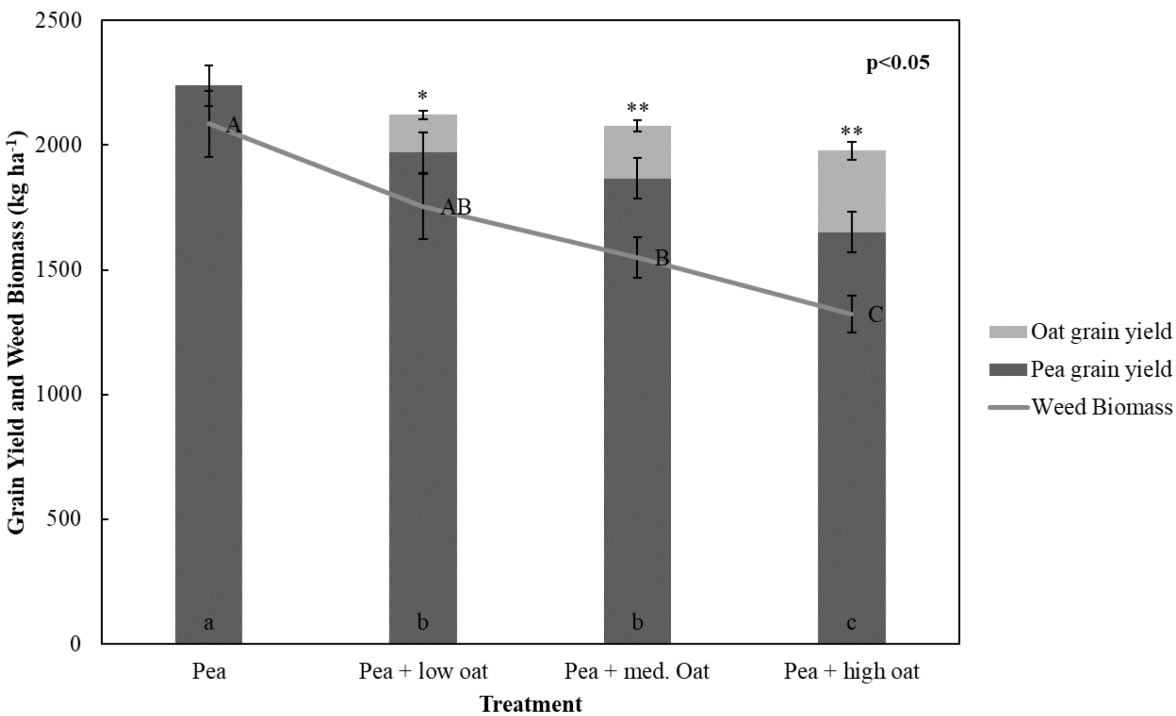

Figure 15. Effect of pea monoculture and three pea-oat intercrop treatments (pea + low oat, pea + med. oat, pea + high oat) on pea and oat grain yield and weed biomass averaged over three site-years at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020. Error bars represent standard errors of the least-squares means. Oat yield data were log transformed with back transformed data presented in figure. Means with different letters (pea grain yield and weed biomass) and number of asterisks (oat grain yield) are significantly different (Tukey's HSD, $p<0.05$).

4.7.5 Economic Analysis

Net returns were considered in three different scenarios: standard organic price of peas and oats; a 50% increase in the price for peas; and a 50% increase in the price for oats. In the present study, when using a standard organic price of peas and oats, net returns were significantly greater at the Carman 2019 (\$182.88 ha^{-1}) and 2020-1 (\$387.58 ha^{-1}) site-years, compared to Carman 2020-2 (-\$462.15 ha^{-1}) (Table 22). The positive net returns found at Carman 2019 and 2020-1 can be attributed to low weed biomass and greater pea yields compared with Carman 2020-2 (Table 20 and Table 21). This observation demonstrates the importance of the local growing conditions for positive net return in organic pea production. In terms of treatments, all treatments contained very low net returns and intercropping did not affect net returns (Table 22). Fernandez et al. (2015) found that intercropping did affect net returns. For example, when using a pea market price that was 46% greater than what was used in the present study, Fernandez et al. (2015) found that pea-oat intercrops were the least profitable (\$1498 ha^{-1}) of five different pea intercrop mixtures studied, with net returns that were 45% less profitable than the unweeded pea monoculture control.

Using the base price for peas and oats, a site-year by treatment interaction was detected (Figure 16). At the Carman 2020-1 site year, net returns for the pea monoculture were significantly greater than the high oat seeding rate. At the Carman 2020-2 site-year the opposite trend was observed, as the pea monoculture net returns were significantly lower than the high oat seeding rate (Figure 16). An explanation for the trend in treatment ranks at the Carman 2020-1 site-year may be that the high level of pea biomass outcompeted oats and led to low oat yields, but the presence of the oat crop still led to reduced pea grain yields when compared to the pea monoculture (Table 20 and Table 21). Therefore, the pea yields were greatest in the pea monoculture and decreased as the seeding rate of oat increased, leading to that same trend occurring across net returns. At the Carman 2020-2 site-year the opposite trend occurred, whereby net returns were lowest in the pea monoculture and increased as the seeding rate of oats increased. An explanation for this is that the high level of weed biomass led to low pea yields, as semi-leafless peas are not competitive with weeds, but oats being more competitive, were able to generate greater yields thereby increasing net returns in the intercropping treatments (Table 20 and Table 21).

A second scenario involved a reanalysis based on a 50% increase in the market price for organic peas. Under this second scenario, net returns were significantly affected by site-years and treatments (Table 22). In terms of site-years, net returns were significantly greater for Carman 2020-1 (\$1161.23 ha^{-1}), than Carman 2019 (\$669.37 ha^{-1}), which was greater than Carman 2020-2 (-\$242.64 ha^{-1}). In terms of treatments, all treatments contained positive net returns and the pea monoculture was significantly more profitable than the high oat seeding rate (Table 22). This observation suggests that from a one-year economic analysis, intercropping did not provide any economic benefits.

In a third scenario, the price of oats was increased by 50%. In this scenario, compared to the base price scenario, the profitability across all treatments increased by \$80 to \$177 per hectare. There were no statistically significant differences between treatment net returns, therefore the treatment ranks did not change from the base price scenario.

The three scenarios that were studied in this economic analysis further confirm that greater pea yields translate to greater net returns. For example, across site-years, where pea grain yields were low and oat yields were high (Carman 2019 and Carman 2020-2), net returns remained low. Whereas, the Carman 2020-1 site-year consistently contained the highest pea yields and lowest oat yields, resulting in the greatest net returns. Furthermore, across treatments, intercropping did not result in statistically greater net returns under all three scenarios.

Table 22. Mean net returns of pea monoculture and three pea-oat intercrop treatments (pea + low oat, pea + medium oat, and pea + high oat), averaged across site-years and treatments at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020.

	Initial Net Return	50% Increase in Pea Market Price Net Return	50% Increase in Oat market Price Net Return
	$ ha⁻¹		
Site-year			
Carman 2019	182.88aש	669.37b	376.29a
Carman 2020-1	387.58a֍	1161.23a	393.06a
Carman 2020-2	(462.15)b	(242.64)c	(379.71)b
Treatment			
Pea	15.91a	608.57a	15.91a
Pea + low oat	41.59a	563.37ab	122.58a
Pea + medium oat	49.30a	543.43ab	165.64a
Pea + high oat	37.61a	401.90b	215.23a
Fixed Effect P-Values			
Site-year	**<0.0001**	**<0.0001**	**<0.0001**
Treatment	0.7372	**0.0239**	0.2609
Site-year*Treatment	**0.0001**	0.2287	0.2967

֍Means with different letters in the same column are significantly different (Tukey's HSD, p<0.05).
שParentheses indicate negative values.
*Economic analysis assumes an initial organic pea market price of $0.53 kg, and an initial organic oat price of $0.49 kg.

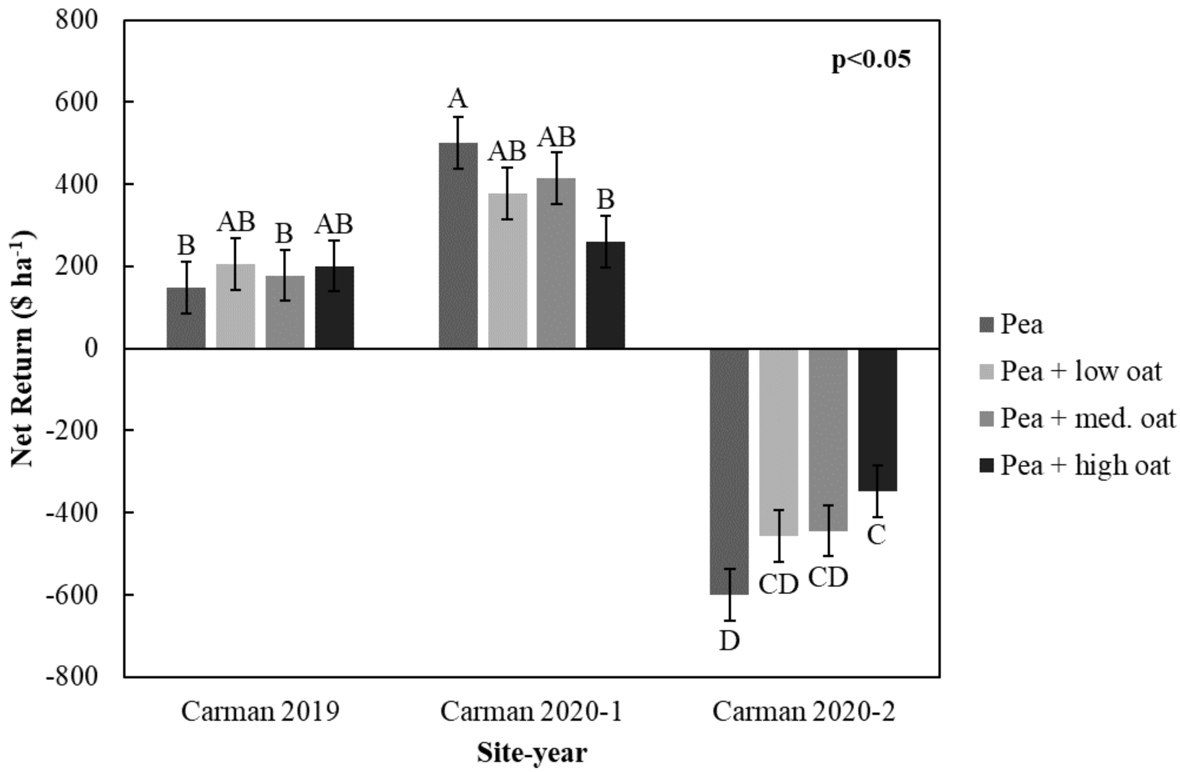

Figure 16. Initial net returns of pea monoculture and three pea-oat intercrop treatments (pea + low oat, pea + med. oat, and pea + high oat) at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020. Error bars represent standard errors of the least-squares means. Treatments are clustered by site-year. Means with different letters are significantly different (Tukey's HSD, $p<0.05$).

4.7.6 Summary and Conclusions

Oat intercropped with pea was observed to produce both positive and negative effects. Positive effects of oat included a reduction in weed biomass and an increase in total crop biomass and TKW (Appendix 8.4). However, weed biomass reductions were low in comparison to Šarūnaitė et al. (2013) findings where mid-season weed biomass reductions averaged 68%.

While oat intercropping did not affect pea and oat harvest indices, pea plant height, DTM, and protein content, it consistently reduced pea growth (biomass) and yield. Therefore, one of the main conclusions of this study was that oat reduced pea productivity. Fernandez et al. (2015) found that intercropping oat with pea reduced pea yields by 17%, 61%, and 24% across three site-years, compared to an unweeded pea monoculture control. However, Fernandez et al.

(2015) observed that both the pea yield potential and level of weeds were exacerbated during optimal pea growing conditions (moderate soil moisture). This may not have been the case in the present study, as it was believed that soil moisture was lowest in the Carman 2019 and Carman 2020-2 site-years, where pea yields were found to be low and weed biomass was found to be high.

Pea biomass and pea grain yields were found to be unstable across site-years, suggesting that the pea crop functioned differently across the three site-years. This may be due to variation in pea, oat and weed productivity across the three site-years due to different growing conditions, resulting in varied levels of interspecific competition within the intercrop.

The instability in pea biomass and pea grain yield may have translated to unstable net returns across site-years, as low pea grain yields and high oat yields resulted in low net returns. Whereas when high pea yields and low oat yields occurred, greater net returns were achieved. The conditions where the highest net returns were consistently achieved was when the market price for peas was increased by 50%. Increasing the market price of oats by 50% did not result in any significant differences across treatments.

In conclusion, oat intercropping led to reduced weed biomass, and pea grain yields also were reduced significantly. The combination of optimal pea growing conditions and an increase in the market price for peas was required for peas to be profitable.

5 GENERAL DISCUSSION

5.1 Stability of Intercrop Mixtures

The unique environmental conditions associated with each site-year influenced intercrop biomass and yield productivity and indicates that the intercrop systems function differently across different environmental conditions. For example, early seeding, greater soil moisture, and low weed biomass may have influenced the greater pea grain yields and net returns that were found at the Carman 2020-1 site-year in all three intercrop experiments (pea-barley, pea-mustard, and pea-oat). In comparison, Carman 2019 contained a similar level of weed biomass, but the low soil moisture may have influenced the lower pea grain yields and net returns. This resulted in pea grain yields that were significantly lower than Carman 2020-1 and did not meet the break-even pea yield in all three intercrop experiments. However, at the Carman 2019 site-year, when compared to Carman 2020-1, net returns did not statistically differ in the pea-barley and pea-oat experiments but were significantly lower in the pea-mustard experiment. An explanation for this is that the overseeding of barley and oats led to greater cereal yields, which compensated for the low pea grain yields, resulting in positive net returns. In contrast, at the Carman 2020-2 site-year, pea yields, and net returns were significantly lower than the Carman 2019 and 2020-1 site-years and net returns were negative across all three experiments. An explanation for the low pea yields and net returns at the Carman 2020-2 site-year is that late seeding reduced the productivity of the intercrop which allowed the high population of green foxtail to significantly reduce grain yields and net returns. Therefore, if pea intercropping is the only weed management tactic that will be used in an organic field pea production system, pea intercrops should be seeded early, in growing conditions with adequate soil moisture and moderate levels of weeds.

Stability in cropping systems is related to resiliency as they both pertain to how a system responds to disturbances. Stability in agriculture is the "constancy of agricultural outputs over long periods of time across various spatial environments" (Urruty et al., 2016) Intercropping has been found to enhance yield stability because of the complementarity in resource use between crop species (Raseduzzaman & Jensen, 2017). However, additive intercrop designs, like what were used in the present study, have been found to provide less yield stability than replacement intercrop designs because resource niche overlap is more likely to occur, leading to greater interspecific competition within the intercrop (Raseduzzaman & Jensen, 2017). In the present study, instability was detected in pea grain yield across all three intercrop experiments. An explanation for this is that because this study used pea-dominant additive intercrop designs, the high plant density per land area may have resulted in a high level of interspecific competition within the intercrop, causing instability within the intercrop systems. Therefore, future studies with organic pea in Manitoba should consider replacement designs.

This study was limited because each intercrop experiment was conducted separately, and a statistical comparison of intercropping mixtures was not possible. However, the number of site-year by treatment interactions detected can help inform the stability of the different intercrop systems. Early crop and weed biomass, pea plant height, pea protein content, and pea TKW were found to be stable across all three intercropping experiments, which suggests that intercropping may produce a predictable response for these agronomic parameters. A site-year by treatment interaction was detected for pea yield in all three intercrop experiments, indicating that the pea grain response to intercropping was unstable, and responded differently to the very different environments found in the study, regardless of non-pea companion crop species. Overall, the pea-barley and pea-oat intercrops appeared to be more stable across the three site-years compared to the pea-mustard intercrop, as instability was detected in the pea-mustard intercrop experiment across a wide range of parameters including mustard biomass, weed biomass, pea yield and net returns across a wide range of market conditions. Based on visual observations throughout the study, it is hypothesized that this instability may have been due to flea beetle damage and low nitrogen fertility, resulting in inconsistent mustard productivity. The stability found across the barley and oat intercrop mixtures may be due to the low nitrogen requirements and competitive advantage against weeds when compared to mustard (Blackshaw et al., 2002; Manitoba Agriculture and Resource Development, 2020b).

In conclusion, the unique environmental conditions associated with each site-year appeared to influence average site-year biomass and yield productivity to a similar degree across all three intercrop experiments, but the pea-mustard experimental treatments appeared to show significant variability in productivity among site-years, indicating a high level of instability. If management practices were developed to mitigate flea beetle damage in organic mustard production this may allow pea-mustard intercrops to be more successful. However, until mustard cultivars are developed for low input agriculture, the high nitrogen fertility requirement will still be a potential issue.

5.2 Weed Suppression by Intercrops: Impact on Grain Yield and Net Returns

In the present study, it was hypothesized that intercropping would reduce weed biomass compared to a pea monoculture control, and that as the rate of companion crop increased within the pea intercrop the reduction in weed biomass would increase. Furthermore, pea grain yield was hypothesized to decline as the rate of companion crop increased within the intercrop. The results from the present study supported these hypotheses. This created a "trade-off" and raised the question of whether any weed suppression benefits would be worth the loss in pea yield. To examine this question in more detail, the weed suppression and yield loss results were presented alongside each other (Figure 17). The main observation here was that barley was most efficient at weed suppression. For example, the high and medium barley seeding rates reduced weed biomass by 44% and 35%, at a cost of 15% and 10% pea grain yield loss, respectively (Figure 17). Intercropping pea with oat only provided 26% and 36% weed suppression at the medium and high seeding rates, respectively, but at a higher pea seed yield cost of 17% and 26%, respectively (Figure 17). Therefore, between the two cereal intercrop options, barley delivered the highest weed control at the lowest pea yield cost. Intercropping pea with mustard resulted in less pea yield loss than oat but did not provide as much weed suppression as either cereal crop. However, of importance to note is that mustard intercropping did not produce a predictable reduction in weed biomass, as weed biomass reductions were unstable across site-years.

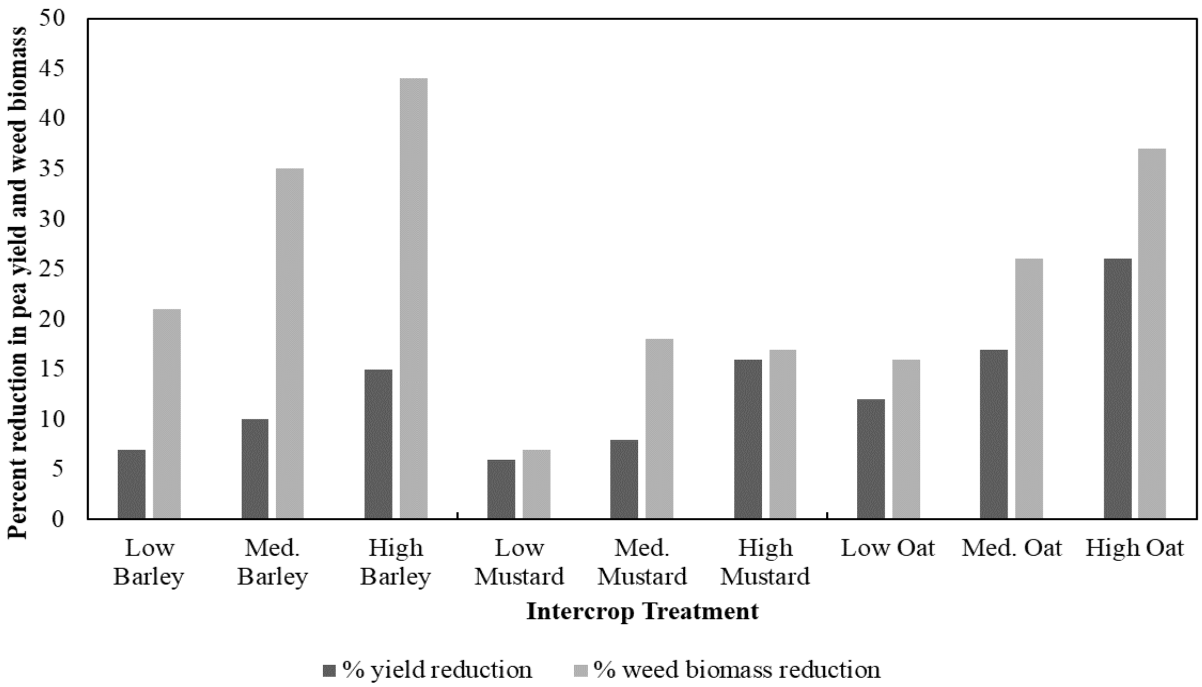

Figure 17. Percent reduction in pea grain yield and weed biomass by three pea-barley, three pea-mustard, and three pea-oat intercrop treatments, compared to pea monoculture, averaged across site-years at the Ian N. Morrison Research Farm in 2019 and 2020.

The seed cost for the high rate barley, mustard, and oat treatments were \$27.31 ha^{-1}, \$75.67 ha^{-1}, and \$32.63 ha^{-1}, respectively. In the present study, the cost of the companion crop seed can be considered the cost of weed management. Alba (2019) found that the cost of using a rotary hoe, harrow, or interrow cultivator in organic field pea production was \$47.20 ha^{-1}, \$30.00 ha^{-1}, and \$34.00 ha^{-1}, respectively. Although the mechanical weed control methods were more expensive than the intercrops used in the present study, the mechanical weed control methods increased pea grain yield compared to an untreated control, and weed biomass reductions ranged from 36% to 69% (Alba, 2019). Therefore, from a weed management viewpoint, mechanical weed control may be a better option when compared to intercropping, as it may benefit pea yields and lead to greater weed suppression. However, in the present study, in addition to weed suppression, many pea-intercropping survey participants outlined that they practice intercropping to suppress plant diseases and reduce lodging (Appendix 8.7). Therefore, recommending that pea-intercropping should not be practiced by organic farmers because of low weed suppression and reduced pea yields does not align with a holistic management framework, and when combined with other weed management methods such as mechanical weed control, pea-intercropping may work very well in an integrated weed management plan.

Profitable cropping systems are integral to the economic sustainability of any farm operation. Intercropping systems have been found to be more profitable than monoculture systems (Martin-Guay et al., 2018; Pelzer et al., 2016). The higher profitability is often associated with replacement designs because interspecific competition is low, and resource complementarity leads to greater yield per land area, when compared to monoculture systems (Martin-Guay et al., 2018). In the present study, grain yields were used to determine the profitability of the different intercrop mixtures in comparison to a pea monoculture control. It was hypothesized that although the non-pea crop may reduce pea grain yields through competition, the non-pea crop yields may compensate for pea yield reductions and result in greater net returns compared to the pea monoculture control. It is evident from the results in the present study that this hypothesis cannot be supported. High pea yields and a high market price for organic peas appears to consistently result in positive net returns in both pea monocultures and additive pea intercropping systems. For example, in the initial economic analysis, using the current market price for peas and non-pea companion crop, intercropping did not result in significantly greater net returns. These results suggest that the reduction in pea yields due to intercropping did not benefit the economic performance of the cropping system. After increasing the market price of peas by 50% in a sensitivity analysis, all of the pea monoculture and intercrop treatments in the three intercrop experiments contained positive net returns, and the pea monoculture was more profitable than intercropping. After increasing the non-pea companion crop market price by 50% there were instances where intercropping was found to be more profitable than the pea monoculture. In these instances, however, the net returns using an increase in non-pea crop price resulted in lower net returns in comparison to the increase in pea price scenario.

In the initial net return analysis, it appears that the pea-mustard experiment yielded the lowest net returns of the three experiments. Of importance to note, is that while net returns between the pea-barley and pea-oat experiments were similar, the pea-oat experiment experienced positive net returns, while the pea-barley experiment experienced negative net returns. Furthermore, the detection of instability found in the pea-oat and pea-mustard intercrops suggests that these two intercrop mixtures did not result in predictable net return outcomes.

The Province of Manitoba estimates that pea monoculture yields must be greater than 2183 kg ha^{-1} to achieve positive net returns when using a pea market price of $0.53 kg. In the present study, using a pea market price of $0.53 kg^{-1}, pea monoculture yields had to reach 2208 kg ha^{-1} to achieve positive net returns. Across all three experiments, the Carman 2020-1 site-year was the only site-year that averaged pea yields above 2208 kg ha^{-1}, suggesting that the break-even yield in organic pea production may be difficult to achieve, and was only achieved when soil moisture levels were was highest and crops were seeded early. These observations are supported by Entz et al. (2001) where it was found that average on-farm organic pea yields were 1257 kg ha^{-1} (201 to 2690 kg ha^{-1} range). If the break-even yield for organic pea production is difficult to achieve, then it appears that the current market price for organic peas may not lead to short-term profitability in pea monoculture systems even when average pea yields are achieved. Therefore, agronomic advancements may be required in organic pea production to increase pea yields. Field peas are known to suffer from poor yield and yield instability, poor disease tolerance, and low competitive ability against weeds (Baird et al., 2009; Watson et al., 2017; Xue & Warkentin, 2001). Breeding to increase yield and yield stability, as well as disease tolerance could lead to greater organic pea yields across the Canadian Prairies. Furthermore, the adoption of advanced weeding technologies such as pre-emergent rotary hoe applications, camera-guided inter-row mechanical weeding, and intra-row mechanical weeding implements such as the harrow may lead to better weed management in organic field pea production, thereby increasing yields.

6 FUTURE RESEARCH

Pea-intercropping resulted in reduced weed biomass levels, and a substantial pea yield penalty. The level of weed biomass suppression observed was low compared to past intercropping research and mechanical weed control methods (Alba, 2019; Corre-Hellou et al., 2011). However, because pea-intercropping was found to reduce weed biomass in the field it deserves further study.

This study was limited because it was three separate experiments. Future research should examine the three different intercrop mixtures (pea-barley, pea-mustard, and pea-oat) that were used in the present study together in the same experiment. This would provide a legitimate comparison of the three different intercrop mixtures.

Future research should examine the application of precision agriculture technologies to organic pea intercropping systems. Precision agriculture is a crop management method that uses field data to make site-specific management decisions. In a pea intercropping system, intercrops could be seeded at variable rates as weed level and community composition changes across a field. This could provide farmers with the ability to control weeds in problem areas, without subjecting their entire field to the yield penalties that were observed in the present study. Furthermore, organic farmers who participated in the pea intercropping survey outlined that they practiced pea intercropping to achieve a multitude of agronomic benefits such as disease suppression, increased organic matter, and reduced lodging (Appendix 8.7). Therefore, if researched further, the application of precision agriculture technologies to organic pea intercropping may allow organic farmers to address this wide range of agronomic goals using a data driven approach, in a holistic management framework.

The three different intercrop mixtures that were used in the present study should be evaluated in a long-term research trial. A long-term research trial could further confirm the stability of the intercrop mixtures across variable environmental conditions. The success of intercrop mixtures is known to be environmentally dependent, thus a long-term research trial could provide insight into how intercropping can be used to be more adaptable to variability in environmental factors such as drought, temperature, soil nutrient status, and pests.

7 LITERATURE CITED

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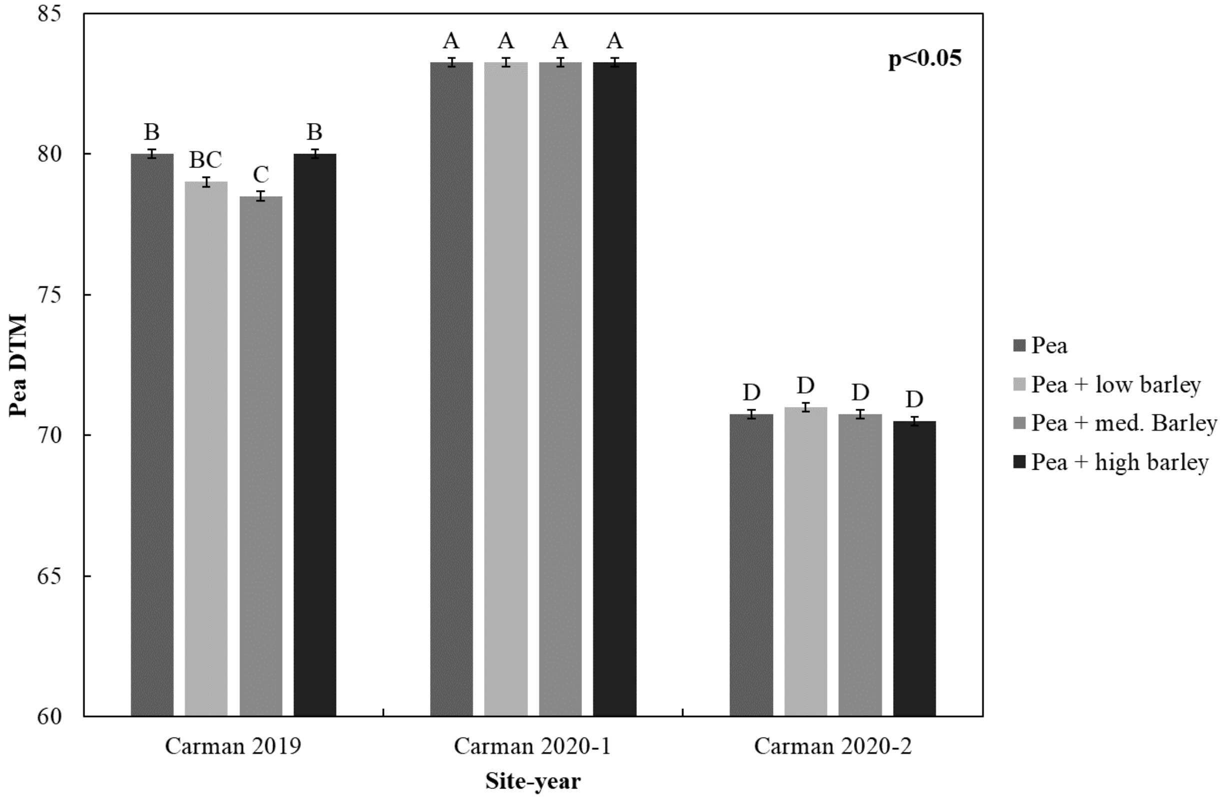
8 APPENDICES

8.1 Mean pea plant height (cm), pea thousand kernel weight (TKW, in g), pea days to maturity (DTM), and pea protein % on a dry matter basis of pea monoculture and three pea-barley intercrop treatments (pea + low barley, pea + medium barley, and pea + high barley), averaged across site-years and treatments at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020.

	Height	TKW	DTM	Protein
Site-year				
Carman 2019	58.0a	247.8a[§]	79.4b	24.0a
Carman 2020-1	66.2a	229.9b	83.3a	24.0a
Carman 2020-2	59.1a	220.2b	70.8c	23.6a
Treatment				
Pea	62.1a	230.5b	77.9a	23.8a
Pea + low barley	61.9a	231.0ab	78.0a	23.8a
Pea + med. barley	60.2a	232.0ab	77.6a	23.8a
Pea + high barley	60.2a	237.0b	77.5a	24.0a
Fixed Effect P-Values				
Site-year	0.0534	**0.0005**	**<0.0001**	0.1074
Treatment	0.4888	**0.0350**	0.1330	0.7745
Site-year*Treatment	0.8017	0.1432	**0.0168**	0.2226

[§]Means with different letters in the same column are significantly different (Tukey's HSD, p<0.05).

8.2 Pea days to maturity (DTM) of pea monoculture and three pea-barley intercrop treatments (pea + low barley, pea + med. barley, and pea + high barley) at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020.



Treatments are clustered by site-year. Error bars represent standard errors of the least-squares means. Means with different letters are significantly different (Tukey's HSD, $p<0.05$).

8.3 Mean pea plant height (cm), thousand kernel weight (TKW, in g), days to maturity (DTM), and protein content on a % dry matter basis of pea monoculture and three pea-mustard intercrop treatments (pea + low mustard, pea + medium mustard, and pea + high mustard), averaged across site-years and treatments at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020.

	Height	TKW	DTM	Protein
Site-year				
Carman 2019	60.5a	236.5a֍	80.1b	23.5b
Carman 2020-1	66.0a	234.8a	83.4a	24.3a
Carman 2020-2	61.0a	209.3b	70.7c	24.2ab
Treatment				
Pea	62.8a	220.4a	78.1a	23.9a
Pea + low mustard	63.3a	227.9a	78.0a	23.9a
Pea + medium mustard	63.3a	227.0a	78.3a	24.2a
Pea + high mustard	60.5a	232.1a	77.8a	24.1a
Fixed Effect P-Values				
Site-year	0.2641	**0.0015**	**<.0001**	**0.0191**
Treatment	0.1580	0.2631	0.2405	0.3473
Site-year*Treatment	0.3319	0.2104	0.2696	0.1795

֍Means with different letters in the same column are significantly different (Tukey's HSD, $p<0.05$).

8.4 Mean pea plant height, thousand kernel weight (TKW, in g), days to maturity (DTM), and protein content on a % dry matter basis of pea monoculture and three pea-oat intercrop treatments (pea + low oat, pea + medium oat, and pea + high oat), averaged across site-years and treatments at the University of Manitoba Ian N. Morrison Research Farm in 2019 and 2020.

	Height	TKW	DTM	Protein
Site-year				
Carman 2019	56.2b[֍]	244.6a	79.4b	23.7a
Carman 2020-1	65.4a	232.1b	82.4a	24.2a
Carman 2020-2	62.8ab	220.2c	71.1c	23.7a
Treatment				
Pea	62.2a	229.2b	77.6a	23.8a
Pea + low oat	62.0a	231.6ab	77.3a	23.7a
Pea + medium oat	60.6a	229.6b	77.5a	23.9a
Pea + high oat	61.2a	238.8a	78.3a	24.1a
Fixed Effect P-Values				
Site-year	**0.0435**	**0.0016**	**<.0001**	0.1201
Treatment	0.7196	**0.0283**	0.1035	0.1105
Site-year*Treatment	0.6723	0.6270	0.9411	0.0854

[֍]Means with different letters in the same column are significantly different (Tukey's HSD, $p<0.05$).

8.5 Summary of Key Survey Findings

The pea intercropping survey found:

- The separation cost of intercrops used in the economic analysis ($0.02 kg) fell within the range of separation costs ($0.01 kg to $0.05 kg) outlined by survey participants.
- The baseline pea market price used in the economic analysis ($0.53 kg) fell within the range of pea market prices ($0.37 kg to $0.66 kg) that were received by organic farmers.
- Many organic farmers who completed the survey outlined that they practice replacement intercrop designs and not additive intercrop designs.
- When averaged across site-years, the pea yields that were observed in the present study fell within the range of pea yields (1008 kg ha^{-1} to 4033 kg ha^{-1}) that were outlined by organic farmers.
- The seeding rate of the non-pea companion crops varied greatly between organic farmers. However, in general, the yields of non-pea companion crops (barley, mustard, oats) that were outlined by organic farmers fell within the range of non-pea companion crop yields that were observed in the present study.
- In addition to weed suppression, many pea-intercropping survey participants outlined that they practice pea intercropping to suppress plant diseases, reduce lodging, and increase soil organic matter.

8.6 Sample Email to Potential Survey Participants

Hello,

My name is Will Bailey-Elkin. I am a graduate student in Plant Science at the University of Manitoba under the supervision of Dr. Martin Entz. My research project is focused on the economics of organic pea intercropping. I am reaching out to farmers that practice certified organic pea intercropping to ask if they would be interested in taking part in a short questionnaire.

Participant Requirements:

- Certified organic
- Farm located in Manitoba, Saskatchewan or Alberta
- Field size of 40 acres or more
- Experience growing pea-intercrops

The overall goal of the questionnaire is to add on-farm information to an economic analysis of different pea intercrop seed mixtures. Because intercropping is a relatively new method of crop production in the Canadian Prairies, the information provided will help develop a greater understanding of the true costs involved in practicing pea intercropping across the Canadian Prairies. This baseline of information will allow agriculturalists to provide extension resources to farmers and foster capacity building within the organic industry.

The questionnaire can simply be filled out and sent directly back to me, via email. All information from the study will be made available to the farmer who is involved in the study.

8.7 Pea Intercropping Survey Responses

8.7.1 Farm 1 - Alberta

Pea-Intercropping Questions:

Please answer the following questions if you practice pea-intercropping on your farm:

1) What is your per bushel cost to separate your harvested pea-intercrop mixtures?

$1/bu

2) What type of pea do you mainly grow in your pea-intercrop?

Common pea

3) What non-pea crop do you mainly grow in your pea-intercrop?

Peas underseeded to clover

Mustard

barley

4) What is the most common seeding rate that you use for your pea-intercrop?

2/3 pulse

1/3 cereal by plant density

Why: word of mouth

5) For that seeding rate, what are average yields for your peas and non-pea crop?

50 bu/ac combined

50/50 in weight of both crops

6) In a poor growing year what would be your expected yield for your peas and non-pea crop?

Primary focus is agronomic practices not economics. Intercropped for four crop years. Lots of work. But love doing for agronomics. Now leaning towards underseeded clover.

7) In an excellent growing year what would be your expected yield for your peas and non-pea

8) In the past two years what price have you received for your peas and non-pea crop?

2018: Had a deal made for $18 bu yellow peas, but was not able to separate the barley out of the intercrop in time and ended up selling for $13 bu.

9) During excellent market conditions what would you expect to sell your peas and non-pea crop for?

10) During weak market conditions what would you expect to sell your peas and non-pea crop for?

$10-13 bu

11) Why do you choose to use a pea-intercrop in your rotation?

-Weed suppression, increase soil microbio diversity and organic matter

-messed around with turnips, and diverse clover crops, but had problems, so then decided to try pea-intercrops

-Have more recently moved towards underseeding crops with clover

12) What is your standard multi-year crop rotation, and where does your pea-intercrop fall in your rotation?

-Rotate brown flax underseeded to red clover, harvest the clover every second year. Pea intercrop is done once every five years. Prefer flax and clover. If done well pea-intercrops may work however the costs are high: two seeds, two rates, harvesting problems, separation, If I could separate grain at harvest it could benefit profits greatly because then I wouldn't have to go back into the bin and separate.

13) Does the use of a pea-intercrop eliminate a green manure crop from your rotation?

No. Because of high costs and inconsistencies in pea-intercrops I have moved towards mainly under-seeding crops to biennial clover.

14) If you use a green manure crop as a source of fertility, how often is a green manure crop used in your rotation and what is the total per/acre cost of the green manure crop?

Every fourth year. Compensate by always having clover intercrop. But when annual clovers go to seed they change taste of intercropped seed and can change the taste of livestock that then consume the feed.

15) If you apply compost to your fields, how often is compost applied and what is the total per/acre cost of compost and compost application?

10 tonnes/ ac try and do every other year.

16) If you apply manure to your fields, how often is manure applied and what is the total per/acre cost of manure and manure application?

$100/ac on manure

If you grow monocrop peas, as well as pea-intercrops, please answer the following questions:

1) What type of pea do you mainly grow in your pea-monocrop?

Common field pea

2) What is the most common seeding rate that you use for your pea-monocrop?

2-3 bu/ac

3) For that seeding rate, what are average yields for your pea-monocrop?

50 bu/ac same as intercrop

4) In a poor growing year, what would be your expected yield for your pea-monocrop?

5) In an excellent growing year, what would be your expected yield for your pea-monocrop?

Irrigation system -natural gas pumping unit, electric pivot, 230 acre cover, low pressure sprinklers.

6) Where does your pea-monocrop fall in your rotation?

One in five years

8.7.2 Farm 2 - Manitoba

Pea-Intercropping Questions:

Please answer the following questions if you practice pea-intercropping on your farm:

1) What is your per bushel cost to separate your harvested pea-intercrop mixtures?

If it is just peas and mustard, it is easy to separate therefore about 500 bu /hr at $150/hr. = 30 cents/ bu.. we usually need to reclean the yellow mustard for market , therefore another 30 cents but only on the mustard If it is pea / oats/ mustard, it is slower to clean and may need to put through twice approximately $1.00

2) What type of pea do you mainly grow in your pea-intercrop?

yellow

3) What non-pea crop do you mainly grow in your pea-intercrop?

Yellow mustard or yellow mustard and oats, considering wheat

4) What is the most common seeding rate that you use for your pea-intercrop?

2 bu/ acre of peas,   mustard 7 to 20 lbs/ acre.,, oats 10 to 30 lbs   10 is lots!

5) For that seeding rate, what are average yields for your peas and non-pea crop?

Low N field 2019 Peas 28 / oats 27/ mustard 7 bu/acre ,   Peas 19/ oats 38 bu/ acre ,   Peas 22/ mustard 12 bu / acre ,   peas alone 40 bu/acre.   Oats at 10 Lbs / acre seed rate

Hi N field 2020 Peas alone 43 bu/acre ,   peas3.2 / mustard 25 bu/acre, peas 1/ mustard 6/ oats 72 bu/ acre, mustard alone 25bu/ acre   Oats at 30 lbs / acre seed rate

6) In a poor growing year what would be your expected yield for your peas and non-pea crop?

The main reason for poor pea yields in the past have been Aphanomyces particularly in wet years, yields have varied from 15 to 60 bushel/ acres over the years for pure stands

7) In an excellent growing year what would be your expected yield for your peas and non-pea crop?

See above

8) In the past two years what price have you received for your peas and non-pea crop?

Peas   organic $ 11.50 to 12

Mustard organic $50/ bu

Oats organic $5.75

9) During excellent market conditions what would you expect to sell your peas and non-pea crop for?

Organic peas $16/ bu

Organic Mustard $50

Organic oats $ 7

10) During weak market conditions what would you expect to sell your peas and non-pea crop for?

> Peas organic $14
>
> Mustard organic $50
>
> Oats organic $6.5

11) Why do you choose to use a pea-intercrop in your rotation?

> Diversity, self insurance, higher income,
>
> Need to watch pea chips in oats, oats discounted to feed from milling, $4 vs $6/ bu

12) What is your standard multi-year crop rotation, and where does your pea-intercrop fall in your rotation?

> Green manure/ hi N using crop , usually wheat, / low N requiring crop , soybeans or pea
>
> Some additional cover crops are added in each year,, catch / smoother crop after GM terminated,,, fall rye or heavy oats based cover crop added after wheat, sweet clover /alfalfa underseeded to soybeans

13) Does the use of a pea-intercrop eliminate a green manure crop from your rotation?

> No

14) If you use a green manure crop as a source of fertility, how often is a green manure crop used in your rotation and what is the total per/acre cost of the green manure crop?

> 1 in 3 years unless we can get liquid hog manure.
>
> Cost of seed varies from $10/ acre for underseeded sweet clover to$40 or more for a cover crop mixture from Imperial seeds. Try to keep it below $30 Total cost is about $300 including land payments, wages, taxes, seed fuel repair, equipment replacement/ depreciation etc

15) If you apply compost to your fields, how often is compost applied and what is the total per/acre cost of compost and compost application?

None applied

16) If you apply manure to your fields, how often is manure applied and what is the total per/acre cost of manure and manure application?

Just starting Pig manure $24/ acre, applied 1 in 2 or 1 in 3 years, should eliminate the green manure year Dried chicken manure pellets $80 to 200/ acre,, only before wheat if green manure is poor Raw hen manure including trucking, $16 to 40/ acre,,,, only before wheat

If you grow monocrop peas, as well as pea-intercrops, please answer the following questions:

1) What type of pea do you mainly grow in your pea-monocrop?

yellow

2) What is the most common seeding rate that you use for your pea-monocrop?

2 bu

3) For that seeding rate, what are average yields for your pea-monocrop?

40

4) In a poor growing year, what would be your expected yield for your pea-monocrop?

15

5) In an excellent growing year, what would be your expected yield for your pea-monocrop?

50

6) Where does your pea-monocrop fall in your rotation?

After wheat, but must be at least 6 years between pea crops , probably should be 9. Interested to know if intercropping and diversity in whole rotation will make pea root diseases worse or better

8.7.3 Farm 3 - Manitoba

Pea-Intercropping Questions:

Please answer the following questions if you practice pea-intercropping on your farm:

1) What is your per bushel cost to separate your harvested pea-intercrop mixtures?

1.00/bu

2) What type of pea do you mainly grow in your pea-intercrop?

-410 forage pea

-Would like to move to yellow field peas

3) What non-pea crop do you mainly grow in your pea-intercrop?

-Oats, barley, yellow mustard, canola

4) What is the most common seeding rate that you use for your pea-intercrop?

-Full rate peas (3 bu/ac)

-1 bushel of other crop and full rate peas

-2.5 lbs. mustard and canola with full rate peas

5) For that seeding rate, what are average yields for your peas and non-pea crop?

-30-40 bu/ac total product

-15% companion crop

6) In a poor growing year what would be your expected yield for your peas and non-pea crop?

NOTE -variety makes bigger difference than seeding rate, long-vine pea, short growing companion

7) In an excellent growing year what would be your expected yield for your peas and non-pea

8) In the past two years what price have you received for your peas and non-pea crop?

Peas (14,15,18)

Mustard (0.85-1.00 lb)

Oat (6.00 bu)

9) During excellent market conditions what would you expect to sell your peas and non-pea crop for?

10) During weak market conditions what would you expect to sell your peas and non-pea crop for?

11) Why do you choose to use a pea-intercrop in your rotation?

-Add more legumes to boost nitrogen fixation

-weed suppression

-lodging, erosion control, organic matter

12) What is your standard multi-year crop rotation, and where does your pea-intercrop fall in your rotation?

-2 years after green manure

-Year before heavy feeder (cereal)

13) Does the use of a pea-intercrop eliminate a green manure crop from your rotation?

-Streched green manure out to every 3-4 years instead of every 2 years

14) If you use a green manure crop as a source of fertility, how often is a green manure crop used in your rotation and what is the total per/acre cost of the green manure crop?

15) If you apply compost to your fields, how often is compost applied and what is the total per/acre cost of compost and compost application?

-Composted cattle manure

16) If you apply manure to your fields, how often is manure applied and what is the total per/acre cost of manure and manure application?

If you grow monocrop peas, as well as pea-intercrops, please answer the following questions:

1) What type of pea do you mainly grow in your pea-monocrop?

Moved away from pea monocrops, only using pea-intercrops

2) What is the most common seeding rate that you use for your pea-monocrop?

3) For that seeding rate, what are average yields for your pea-monocrop?

4) In a poor growing year, what would be your expected yield for your pea-monocrop?

5) In an excellent growing year, what would be your expected yield for your pea-monocrop?

6) Where does your pea-monocrop fall in your rotation?

8.7.4 Farm 4 – Manitoba

Pea-Intercropping Questions:

Please answer the following questions if you practice pea-intercropping on your farm:

1) What is your per bushel cost to separate your harvested pea-intercrop mixtures?

$0.55 for first crop separation per bushel on total bushels.

$0.55 for second crop separation per bushel on subtracted bushels after first crop is removed.

2) What type of pea do you mainly grow in your pea-intercrop?

Yellow Peas – human consumption.

3) What non-pea crop do you mainly grow in your pea-intercrop?

Milling Oats.

4) What is the most common seeding rate that you use for your pea-intercrop?

150 lbs/ac depending on seed size.

Target 8 plants per square foot in final plant stand.

5) For that seeding rate, what are average yields for your peas and non-pea crop?

Cleaned:

Peas – 10 bu/ac Oats – 50 bu/ac

Screenings: 12 bu/ac

6) In a poor growing year what would be your expected yield for your peas and non-pea crop?

Cleaned:

Peas – 5 bu/ac Oats – 25 bu/ac

7) In an excellent growing year what would be your expected yield for your peas and non-pea crop?

Cleaned:

Peas – 30 bu/ac Oats – 70 bu/ac

8) In the past two years what price have you received for your peas and non-pea crop?

Have not marketed any peas.

6.50 – 7.00 /bu for oats.

9) During excellent market conditions what would you expect to sell your peas and non-pea crop for?

Peas – $16.50/bu

Oats - $6.50/bu - $8.00 /bu

10) During weak market conditions what would you expect to sell your peas and non-pea crop for?

Likely would not sell either crop. Being forced to sell on a low year:

Peas - $13.00/bu

Oats - $5.50/bu

11) Why do you choose to use a pea-intercrop in your rotation?

We have not grown peas in monoculture for perceived weed competitiveness issues, harvest losses from low lying pods and potential disease loss. (Ranked in order of concern)

Intercropped with a cereal we decided that these risks could be mitigated and was worth trying. The peas are desired to produce N during the growing season at higher efficiency with the cereal. Peas are a high value crop.

12) What is your standard multi-year crop rotation, and where does your pea-intercrop fall in your rotation?

As a grain crop:

Heritage HRS Wheat, Pea Oat Intercrop, Multispecies Grazed Green Manure

As a forage:

Grain, Pea/Oat Greenfeed, Fall Rye(Spring grazed) Warm season grazed green manure

13) Does the use of a pea-intercrop eliminate a green manure crop from your rotation?

No.

14) If you use a green manure crop as a source of fertility, how often is a green manure crop used in your rotation and what is the total per/acre cost of the green manure crop?

1 in 3 years on annually cropped land.

$ /ac - not sure

15) If you apply compost to your fields, how often is compost applied and what is the total per/acre cost of compost and compost application?

A future goal is to apply compost at 2 tons per acre.

16) If you apply manure to your fields, how often is manure applied and what is the total per/acre cost of manure and manure application?

Partially composted manure and straw from own cattle pens is applied when available. Any field does not receive consistent manure applications. Pens are cleaned with own equipment and spread with no charge for spreader. Don't have defined values for labour and machinery operating costs.

If you grow monocrop peas, as well as pea-intercrops, please answer the following questions:

1) What type of pea do you mainly grow in your pea-monocrop?

We have only grown yellow peas with oats as an intercrop. Variety choices were based on availability in our region as our original picks were not available. Had to slide down our list from Choice #1 to what would grow in our region, on our soil, and within 3-4 hrs driving distance to pick up seed.

2) What is the most common seeding rate that you use for your pea-monocrop?

n/a

3) For that seeding rate, what are average yields for your pea-monocrop?

n/a

4) In a poor growing year, what would be your expected yield for your pea-

n/a

5) In an excellent growing year, what would be your expected yield for your pea-

n/a

6) Where does your pea-monocrop fall in your rotation?

As mentioned, mostly grown as an intercrop to date.

8.7.5 Farm 5 – Alberta

Pea-Intercropping Questions:

Please answer the following questions if you practice pea-intercropping on your farm:

1) What is your per bushel cost to separate your harvested pea-intercrop mixtures?

I consider rough separation costs with my on-farm equipment to be $0.20 / bushel, which includes labour. If both crops I grow are only feed grade, then this is the only cost I incur for separating the intercrop. However, if either or both crops make human consumption grade, I incur the separating cost as noted above, then also the cleaning cost to meet human consumption grade that I assume is $1.00 / bushel for seed cleaning costs and trucking.

2) What type of pea do you mainly grow in your pea-intercrop?

We most consistently grow a sugar pea that sells into the sprouting seed market. It pays a significant premium over green or yellow peas for me, but the standards are very strict for germination and visual appeal. Thus, intercropping helps us maintain the grade in the event that the crop gets rained on when in the swath. Growing peas with another crop helps minimize earth tag.

3) What non-pea crop do you mainly grow in your pea-intercrop?

We like canola with our peas, as they are branchy and fluff up the swath, holding the peas off the ground. However, as an organic farmer, we are required to not grow any GMO crops, and thus can only use polish canola as our intercrop. This presents a challenge on land where we have wild mustard pressure as it is inseparable from polish canola. So, if we suspect this weed problem, we choose to grow the peas with either barley or oats.

4) What is the most common seeding rate that you use for your pea-intercrop?

As this is a small seeded pea variety, we target 2.75 bushel / acre if germination is 95+%. If it is a larger seeded variety, we will seed as much as 4 bushel / acre.

5) For that seeding rate, what are average yields for your peas and non-pea crop?

For the sugar peas, this is an older variety that usually would yield only 25 bushel / acre when planted on it's own. Our average yield is 17 bushel / acre when grown with polish canola, and a polish canola yield of 6 bushel / acre.

When seeded with oats or barley, we will see pea yields average 12 bushel per acre, and cereal either 50 bushel of barley or 65 bushel of oats. This is when peas are seeded at the full rate listed above, and oats / barley at ½ rate.

If we are growing a larger green or yellow pea, consider the average pea yields to be 150% of what I quoted here.

6) In a poor growing year what would be your expected yield for your peas and non-pea crop?

2020 was our poorest ever, and we achieved 9 bushel / acre sugar peas and we sold the canola along with the weed seeds as screenings, which was another 5 bushel / acre.

7) In an excellent growing year what would be your expected yield for your peas and non-pea crop?

Our best intercrops have been sugar peas @ 22 bu / acre and canola at 15 bshel / acre, or peas at 18 bushel / acre and barley at 70 bushel / acre.

8) In the past two years what price have you received for your peas and non-pea crop?

Hmmm, I would rather not share this information as the peas we are growing a very niche, and we have a dedicated understanding with our customer where I feel it would be inappropriate to divulge my pricing. However, I can say that only one time have we not received human consumption grade on our peas in the past 15 years., and so for the past two years, you could assume market price of regular peas for the yields quoted. I can see I'm not helping you here.

9) During excellent market conditions what would you expect to sell your peas and non-pea crop for?

Regular Commodity peas(Green or Yellow) at $18.00 / bushel, Canola at $25.00 / bushel, Oats at 8.00 / bushel, and Barley Malt @ 12.00 / bushel and Barley Feed at 9.00 / bushel. I would note, that I have never seen all these prices for all commodities in the same year, however. All organic pricing.

10) During weak market conditions what would you expect to sell your peas and non-pea crop for?

Hmmm… also going to be difficult for you here…… as in poor market conditions, I typically would not sell. I would buy more bins and hold on until the price rebounds. I would use more peas in my green manure mixture. Still, I have seen organic peas as low as $8.00 / bushel, and oats as low as $3.50, Canola as low as $12, and barley as low as $4.00 for feed. All organic pricing.

11) Why do you choose to use a pea-intercrop in your rotation?

Peas are a valuable niche crop for us, so we get compensated well for them. However, we will also grow faba beans instead of peas if our customer is not needing more peas in any given year, so from an agronomic stand point, it is so that we can get nitrogen fixation while growing the crop. Ideally, we crop for 2/3 years, with the third being a green manure crop. I like to see a nitrogen fixing crop grown at least two out of three years including what is in the green manure.

12) What is your standard multi-year crop rotation, and where does your pea-intercrop fall in your rotation?

I don't have a standard, I have a bag full of considerations that help me land on a choice. However, here is an example.: 1) Green manure poly crop mixture, with approx. 50% nitrogen fixing. Up to 12 species. 2) Cereal that needs N2 for protein, so usually spring wheat, and it may have flax intercropped with it, or sweet clover sown into it after it is standing. However, if there is wild oat weed pressure in the field, I will choose fall rye or winter wheat sown in the fall after the green manure crop in year 1. 3) pea / canola intercrop, unless the previous year had sweet clover sown into it, then I may let the sweet clover come for forage seed. Then it goes back to green manure for another 3 year cycle, but I consider what was done in the first 3 year cycle and do something different in the second three year cycle.

13) Does the use of a pea-intercrop eliminate a green manure crop from your rotation?

I wish it did, however, I currently need the 1/3 year green manure rotation for weed control. Still, it is a goal I shoot for.

14) If you use a green manure crop as a source of fertility, how often is a green manure crop used in your rotation and what is the total per/acre cost of the green manure crop?

We do 1/3 years as a green manure. I used to consider a total cost of $150 / acre for green manure costs (Seed, machinery, fuel, labour), however, that is now being offset as we are using a herd of cattle to custom graze the green manure crop and if weed pressure is light enough, we seed directly into the soil without working it. If this is the case, we feel our green manure cost / acre is as low as $50 / acre.

15) If you apply compost to your fields, how often is compost applied and what is the total per/acre cost of compost and compost application?

We have just spread the first batch of compost on 60 acres this year, total cost of sourcing inputs, turning, and spreading the compost was $270 / acre. We anticipate doing this 1/5 years.

16) If you apply manure to your fields, how often is manure applied and what is the total per/acre cost of manure and manure application?

Manure spreading is done by bale grazing the cows. We assume 80% of the hay brought in stays on our fields as nutrient import. We charge a yardage rate to feed the cows, but price it low to make it attractive to the cattle owner. The yardage rate covers our labour and infrastructure costs, and the nutrient import benefit is estimated at $75.00 / acre at the rate we are covering the feeding area over the past 3 years. I know, this will be an outlier in your data as well. Sorry.

If you grow monocrop peas, as well as pea-intercrops, please answer the following questions:

1) What type of pea do you mainly grow in your pea-monocrop?

Either yellow peas as a general commodity grown on speculation, or a brown marafat pea that was specific to one customer.

2) What is the most common seeding rate that you use for your pea-monocrop?

Depending on pea size, we seed at 3-4 bushel / acre.

3) For that seeding rate, what are average yields for your pea-monocrop?

30 bushel / acre

4) In a poor growing year, what would be your expected yield for your pea-

20 bushel / acre

5) In an excellent growing year, what would be your expected yield for your pea-

Large pea mono crop excellent yield for us was 45 bushel per acre. (for variety, see last question.

6) Where does your pea-monocrop fall in your rotation?

When we grow for a specific customer who does not want an intercrop. This has not been for a few years, but we used to grow a brown marafat peas for a pea-butter manufacturing company (allergen free alternative to peanut butter).

8.7.6 Farm 6 – Alberta

Pea-Intercropping Questions:

Please answer the following questions if you practice pea-intercropping on your farm:

1) What is your per bushel cost to separate your harvested pea-intercrop mixtures?

Separation is $0.50/bu

2) What type of pea do you mainly grow in your pea-intercrop?

We tried Chrome peas this year

3) What non-pea crop do you mainly grow in your pea-intercrop?

Pea + canola. We tried Nexera canola, will not do again.

Peas – 2 bu (120 lbs) Canola – 3 lbs

5) For that seeding rate, what are average yields for your peas and non-pea crop?

37 bu (50/50) 18.5 peas and 18.5 canola

6) In a poor growing year what would be your expected yield for your peas and non-pea crop?

25 bu 12.5 pea and 12.5 canola

7) In an excellent growing year what would be your expected yield for your peas and non-pea

40 bu peas and 40 bu canola

8) In the past two years what price have you received for your peas and non-pea crop?

$7.50/bu peas $13/bu canola

9) During excellent market conditions what would you expect to sell your peas and non-pea crop for?

$8/bu peas $13/bu canola

10) During weak market conditions what would you expect to sell your peas and non-pea crop for?

$7/bu peas $10/bu canola

11) Why do you choose to use a pea-intercrop in your rotation?

No inputs being used in production system

12) What is your standard multi-year crop rotation, and where does your pea-intercrop fall in your rotation?

Wheat CWRS; pea, canola; barley; oats/alfalfa; alfalfa; alfalfa; alfalfa; fall rye; barley, oats, pea, hairy vetch; wheat CWRS

13) Does the use of a pea-intercrop eliminate a green manure crop from your rotation?

No

14) If you use a green manure crop as a source of fertility, how often is a green manure crop used in your rotation and what is the total per/acre cost of the green manure crop?

The barley, oat, pea, vetch is winter killed, and seeded in with the wheat the following year. It’s our own seed except vetch.

15) If you apply compost to your fields, how often is compost applied and what is the total per/acre cost of compost and compost application?

No

16) If you apply manure to your fields, how often is manure applied and what is the total per/acre cost of manure and manure application?

No

If you grow monocrop peas, as well as pea-intercrops, please answer the following questions:

1) What type of pea do you mainly grow in your pea-monocrop?

We don’t

2) What is the most common seeding rate that you use for your pea-monocrop?

N/A

3) For that seeding rate, what are average yields for your pea-monocrop?

N/A

4) In a poor growing year, what would be your expected yield for your pea-

N/A

5) In an excellent growing year, what would be your expected yield for your pea-

N/A

6) Where does your pea-monocrop fall in your rotation?

N/A

8.7.7 Farm 7 – Alberta

Pea-Intercropping Questions:

Please answer the following questions if you practice pea-intercropping on your farm:

1) What is your per bushel cost to separate your harvested pea-intercrop mixtures?

$0.64/bu

2) What type of pea do you mainly grow in your pea-intercrop?

Yellow

3) What non-pea crop do you mainly grow in your pea-intercrop?

Barley and oats

4) What is the most common seeding rate that you use for your pea-intercrop?

2 bu barley, 2 bu peas

5) For that seeding rate, what are average yields for your peas and non-pea crop?

55 bu/ac barley

20 bu/ac peas

6) In a poor growing year what would be your expected yield for your peas and non-pea crop?

40 bu/ac barley

60 bu/ac oats

10 bu/ac peas

7) In an excellent growing year what would be your expected yield for your peas and non-pea

75 bu/ac barley; 30 bu/ac peas

110 bu/ac oats; 25 bu/ac peas

8) In the past two years what price have you received for your peas and non-pea crop?

Had to take conventional feed price on oats due to pea chips on clean over A 12 round screen

9) During excellent market conditions what would you expect to sell your peas and non-pea crop for?

$7.50/bu barley

$6/bu oats

$16/bu peas

10) During weak market conditions what would you expect to sell your peas and non-pea crop for?

$7.50/bu barley

$6/bu oats

$12-14/bu peas

11) Why do you choose to use a pea-intercrop in your rotation?

My soil needs nitrogen!

12) What is your standard multi-year crop rotation, and where does your pea-intercrop fall in your rotation?

Fall rye underseeded clover, 2 cut – plow down clover – oats – barley or oats underseeded to clover

13) Does the use of a pea-intercrop eliminate a green manure crop from your rotation?

No

14) If you use a green manure crop as a source of fertility, how often is a green manure crop used in your rotation and what is the total per/acre cost of the green manure crop?

I would like every third year to have a plow down if I get too many thistle, then alfalfa needs to be rotated in.

Approximately $200/acre.

15) If you apply compost to your fields, how often is compost applied and what is the total per/acre cost of compost and compost application?

I have manure and the cost to apply is $35 per acre.

16) If you apply manure to your fields, how often is manure applied and what is the total per/acre cost of manure and manure application?

1 per 3 years – 10 ton/acre

If you grow monocrop peas, as well as pea-intercrops, please answer the following questions:

1) What type of pea do you mainly grow in your pea-monocrop?

N/A

2) What is the most common seeding rate that you use for your pea-monocrop?

3) For that seeding rate, what are average yields for your pea-monocrop?

4) In a poor growing year, what would be your expected yield for your pea-monocrop?

5) In an excellent growing year, what would be your expected yield for your pea-monocrop?

6) Where does your pea-monocrop fall in your rotation?

8.7.8 Farm 8 – Saskatchewan

Pea-Intercropping Questions:

Please answer the following questions if you practice pea-intercropping on your farm:

1) What is your per bushel cost to separate your harvested pea-intercrop mixtures?

The initial separation of the green peas and yellow was done with a Kwik Kleen with 10/64 slots. This is a low cost machine to operate and would be less than 10 cents per bushel as an estimate.

2) What type of pea do you mainly grow in your pea-intercrop?

Green peas in 2020. That is the first pea intercrop in a few years.

We have also grown yellow peas and red lentils but did not have very good yields with this combination.

3) What non-pea crop do you mainly grow in your pea-intercrop?

In 2020 it was yellow mustard.

Red lentils in a previous year.

4) What is the most common seeding rate that you use for your pea-intercrop?

200 lbs of green peas per acre and 5 lbs per acre yellow mustard. 120 yellow forage peas and 60 lbs of red lentils.

5) For that seeding rate, what are average yields for your peas and non-pea crop?

My initial estimate in 2020 is 15 bu per acre of pea, 2 bushels of mustard and 3.5 bushels of volunteer spring wheat.

6) In a poor growing year what would be your expected yield for your peas and non-pea crop?

50% of the above yields.

7) In an excellent growing year what would be your expected yield for your peas and non-pea

25 bu of green peas, 5 bushels of yellow mustard.

8) In the past two years what price have you received for your peas and non-pea crop?

This years peas were contracted at $19 per bushel. Bt quality is not great because of bleaching so I don’t have a sales price yet. We could estimate $12. The mustard is worth $30 per bushel. Normally organic mustard is worth around $50 per bushel. The wheat is worth about $16 per bushel.

9) During excellent market conditions what would you expect to sell your peas and non-pea crop for?

$20 for peas, $50 for the mustard, $19 per bu for the wheat. If good quality.

10) During weak market conditions what would you expect to sell your peas and non-pea crop for?

$10, $40, $12 respectively.

11) Why do you choose to use a pea-intercrop in your rotation?

I have not used a pea intercrop very often. It may work well in some years. But green peas are quality sensitive and yellow mustard has later maturity than green peas which makes bleaching of green peas a higher risk.

12) What is your standard multi-year crop rotation, and where does your pea-intercrop fall in your rotation?

Green manure fallow, wheat, or oats or flax or hemp with alfalfa or clover. In some cases we second crop flax after wheat or hemp. Peas also are an option. We have about 60% crop and 40% green manure fallow each year.

13) Does the use of a pea-intercrop eliminate a green manure crop from your rotation?

Yes

14) If you use a green manure crop as a source of fertility, how often is a green manure crop used in your rotation and what is the total per/acre cost of the green manure crop?

Every second year on some fields. In some cases after 2 or 3 crops depending on rotation and weed pressure.

An estimate cost of using clover or alfalfa as green manure is $15-20 per acre for seed costs. The full cost of a green manure would easily be an estimate $100 per acre or more for fuel, machinery and labour.

15) If you apply compost to your fields, how often is compost applied and what is the total per/acre cost of compost and compost application?

We don't use compost.

16) If you apply manure to your fields, how often is manure applied and what is the total per/acre cost of manure and manure application?

We have applied some heat treated chicken manure pellets at a cost of about $35 per acre on hemp fields.

If you grow monocrop peas, as well as pea-intercrops, please answer the following questions:

1) What type of pea do you mainly grow in your pea-monocrop?

N/A. We have stopped growing monocrop peas because of rot disease and poor performance due to suspected fertility issues. The intercrop is possible solution to help reduce diseases. If the peas don't perform well then the hope is the intercrop produces better yields.

2) What is the most common seeding rate that you use for your pea-monocrop?

3) For that seeding rate, what are average yields for your pea-monocrop?

4) In a poor growing year, what would be your expected yield for your pea-monocrop?

5) In an excellent growing year, what would be your expected yield for your pea-monocrop?

6) Where does your pea-monocrop fall in your rotation?

8.7.9 Farm 9 – Manitoba

Pea-Intercropping Questions:

Please answer the following questions if you practice pea-intercropping on your farm:

1) What is your per bushel cost to separate your harvested pea-intercrop mixtures?

$1.5/bu - would be cheaper with greater volume or a more perminant setup.. lots of time spent setting up and cleaning up relative to time spent cleaning.

2) What type of pea do you mainly grow in your pea-intercrop?

Yellow - have been using carver lately

3) What non-pea crop do you mainly grow in your pea-intercrop?

Mustard initially, but have had better luck with Oats lately. I will use oats for my following answers

4) What is the most common seeding rate that you use for your pea-intercrop?

3.5bu peas (+/- 8 pl/ft2)

5) For that seeding rate, what are average yields for your peas and non-pea crop?

really depends on what intercrop, and seeding rate of the companion. I am not sure I have enough history/datapoints to come up with an average.

6) In a poor growing year what would be your expected yield for your peas and non-pea crop?

I don't think I can define poor... most change seems to be dependant on moisture. More moisture --> more oats and less peas. Less moisture is the opposite.

7) In an excellent growing year what would be your expected yield for your peas and non-pea

2019 was a relatively good year - could have used more moisture I think, but I had some strip trials with different oat seeding rates. 1.5bu/ac oats was the economic winner with 37 bu of peas, and 48 bushels of oats (867/ac gross).

8) In the past two years what price have you received for your peas and non-pea crop?

Peas from 12-15.50, oats have been 6.50/bu

9) During excellent market conditions what would you expect to sell your peas and non-pea crop for?

Peas 16/bu oats up to 7$

10) During weak market conditions what would you expect to sell your peas and non-pea crop for?

Peas 14/bu oats 6

11) Why do you choose to use a pea-intercrop in your rotation?

Helps to increase value, resiliency, economic predictability in years where I expect available nitrogen levels to be dwindling. I don't have any use for crop insurance, and this helps me to manage risk of moisture extremes.

12) What is your standard multi-year crop rotation, and where does your pea-intercrop fall in your rotation?

I don't think I have one. 3 years of grazed alfalfa, 2 years of crop, one year grazed Green Manure, 2 years of annual crop. Pea intercrop likely happens once per cycle, but position depends upon weed pressure, nitrogen availability, etc... Last year was in year 8, but this coming year, I am planning to seed 150 acres into some alfalfa that was terminated very late, to take advantage of well aerated soils, likely low moisture levels enabling early seeding, and low N availability early in season.

13) Does the use of a pea-intercrop eliminate a green manure crop from your rotation?

No, it is treated more like an annual crop with low N needs

14) If you use a green manure crop as a source of fertility, how often is a green manure crop used in your rotation and what is the total per/acre cost of the green manure crop?

see q 12. Cost to establish GM is about 40$/ac, spread over longer in perennial years

15) If you apply compost to your fields, how often is compost applied and what is the total per/acre cost of compost and compost application?

Compost is applied every 4-5 years Cost is 50$/ac

16) If you apply manure to your fields, how often is manure applied and what is the total per/acre cost of manure and manure application?

No un composted manure applied (except in grazing scenario

If you grow monocrop peas, as well as pea-intercrops, please answer the following questions:

1) What type of pea do you mainly grow in your pea-monocrop?

Carver

2) What is the most common seeding rate that you use for your pea-monocrop?

3.5 bu/ca

3) For that seeding rate, what are average yields for your pea-monocrop?

46 bu/ac

4) In a poor growing year, what would be your expected yield for your pea-monocrop?

10 bu (would be terminated)

5) In an excellent growing year, what would be your expected yield for your pea-monocrop?

Maybe up to 50 bu/ac?

6) Where does your pea-monocrop fall in your rotation?

N/A

8.8 Additional operating costs used in economic analysis

Operating Costs	$ per hectare
Fertility	$293.86
Compost	$30.21
Fuel	$48.86
Machinery Operating	$24.70
Machinery Lease	0
Rental and Custom	0
Crop Insurance	$27.74 or $9.68֍
Hail Insurance	$32.6
Other Costs	$19.14
Certification Costs	$8.23
Land Taxes	$37.05
Drying Costs	0
Interest on operating	$17.24

֍Crop insurance for pea monoculture was $27.74 ha^{-1} and the crop insurance for all intercrop treatments was $9.68 ha^{-1}

*A separation cost (rotary screen) of $0.50 bu was included in intercrop treatments and calculated individually for the different seed mixtures