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Source: Canadian Journal of Plant Science, 102(3) : 515-528

Published By: Canadian Science Publishing

URL: https://doi.org/10.1139/CJPS-2021-0182

Canadian Science Publishing

ARTICLE

Intercropping organic field peas with barley, oats, and mustard improves weed control but has variable effects on grain yield and net returns

Will Bailey-Elkin, Michelle Carkner, and Martin H. Entz

Abstract: Interest in intercropping semi-leafless field peas (*Pisum sativum* L.) is increasing as a means of weed control in organic production. We evaluated field pea (cv. CDC Amarillo) grown alone or intercropped with three seeding rates of either barley (*Hordeum vulgare* L.), mustard (*Brassica juncea* L.), or oat (*Avena sativa* L.). A full seeding rate of field pea was used in each instance, resulting in an additive intercropping design. Each crop combination was conducted in a separate experiment, three times over two years (2019 and 2020) in Carman, MB. Measurements included crop and weed biomass production, grain yield and quality, and net return. Intercrops reduced weed biomass at maturity from 17% to 44% with barley and oat being more suppressive than mustard. Intercrops also reduced field pea yield from 6% to 26%, but increased field pea seed mass. Barley at the high seeding rate provided the most weed suppression per unit of field pea yield loss (2.62 kg of weed suppression per kg of field pea yield loss) compared with oat (1.29) and mustard (0.87). Barley and mustard intercrops decreased net return compared with monoculture field pea. Under low weed pressure (1150 kg·ha^{-1} weed biomass at maturity) and earlier seeding, oat intercrops reduced net return. However, under weedy conditions (2649 kg·ha^{-1}) and later seeding, field pea-oat intercrops significantly increased net return. In conclusion, while all three intercrop mixtures reduced weed biomass, reductions in field pea yields were observed, and net return benefits were observed only in certain circumstances.

Key words: pea intercropping, organic pea production, integrated weed management.

Résumé : L'agriculture biologique s'intéresse de plus en plus à la culture intercalaire du pois de plein champ semi-aphylle (*Pisum sativum* L.) pour lutter contre les mauvaises herbes. Les auteurs ont évalué la monoculture du pois (cv. CDC Amarillo) ou sa culture intercalaire avec de l'orge (*Hordeum vulgare* L.), de la moutarde (*Brassica juncea* L.) ou de l'avoine (*Avena sativa* L.) à trois densités de semis. Le pois a été semé à sa densité maximale dans les trois cas, de manière à obtenir un effet additif. Chaque combinaison agricole a fait l'objet d'une expérience distincte, à trois reprises en deux ans (2019 et 2020), à Carman (Manitoba). Les auteurs ont mesuré la biomasse de la culture et des adventices, le rendement grainier, la qualité des graines et le revenu net. La culture intercalaire réduit la biomasse de mauvaises herbes à maturité de 17 à 44 %, avec une plus grande suppression pour l'orge et l'avoine que pour la moutarde. La culture intercalaire diminue aussi le rendement du pois de 6 à 26 %, mais augmente la masse des graines. À la densité des semis la plus élevée, l'orge enregistre une meilleure suppression des mauvaises herbes pour chaque unité de rendement du pois perdue (2,62 kg d'adventices supprimées par kilo de rendement en moins du pois) que l'avoine (1,29) et la moutarde (0,87). Les cultures intercalaires d'orge et de moutarde enregistrent un revenu net inférieur à celui de la monoculture du pois. Quand les adventices sont peu nombreuses (biomasse de 1 150 kg par hectare à maturité) et qu'on sème plus tôt, la culture intercalaire d'avoine diminue le revenu net. Cependant, avec des adventices plus abondantes (2 649 kg par hectare) et des semis plus tardifs, la culture intercalaire du pois et de l'avoine accroît sensiblement le revenu net. En conclusion, bien que les trois combinaisons de culture intercalaire réduisent la biomasse de mauvaises herbes, on note une baisse du rendement du pois de plein champ et le revenu net n'augmente que dans certaines circonstances. [Traduit par la Rédaction]

Mots-clés : culture intercalaire du pois, culture biologique du pois, lutte intégrée contre les mauvaises herbes.

Received 4 August 2021. Accepted 22 October 2021.

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Introduction

From 2015 to 2018 there has been a 40% increase in organic field pea (*Pisum sativum* L.) production in Canada, reaching over 52 600 hectares (Canadian Organic Trade Association 2018). Predictions are that demand for organic field peas will increase in the coming decades (Manitoba Pulse & Soybean Growers 2019). Adding field peas to an organic rotation can increase crop diversity, disrupt the lifecycles of disease and weed communities (Anderson 2005; Ma 2016), and enrich the soil with nitrogen (N) through atmospheric N fixation (Beckie and Brandt 1997).

Benefits of intercropping often include weed and disease suppression, reduced lodging, efficient resource use, and soil erosion protection (Wall et al. 1991; Pridham 2006; Corre-Hellou et al. 2011; Podgórska-Lesiak and Sobkowicz 2013). In addition, intercropping can lead to increased per hectare yields and gross returns, as well as reduced risk of total crop failure (Anil et al. 1998; Martin-Guay et al. 2018). In low-N soils, intercropping can increase N_2 fixation in the legume component (Hauggaard-Nielsen et al. 2009; Chapagain and Riseman 2014).

Intercropping has emerged as a unique way to manage risks associated with organic production. Legumes such as field peas are known to experience unstable yields and lack the ability to tolerate variable environmental conditions such as high temperatures at flowering (Watson et al. 2017; Jiang et al. 2019). Intercropping peas with companion crops allow the benefits of intercropping to be captured (ie., weed and disease suppression, over-yielding, and less lodging) (Langat 1992; Pridham and Entz 2008; Corre-Hellou et al. 2011). Langat (1992) observed greater field pea seed mass when grown in intercrops.

Semi-leafless field peas are especially susceptible to weed competition due to late canopy closure (Spies et al. 2010). This was demonstrated in Alberta where 67% of the surveyed field pea fields suffered significant yield losses due to weeds, with field peas suffering more than barley or canola (*Brassica napus* L.) (Harker 2001). Because barley and oats are competitive with early season weeds due to rapid canopy development (Satorre and Snaydon 1992; Beres et al. 2010; Bouhaouel et al. 2015) and production of allelopathic compounds (Bouhaouel et al. 2015), these crops are recommended as companion crops for field peas (Wallace and Canadian Organic Growers 2001). Corre-Hellou et al. (2011) found that field pea-barley intercrops established in an additive design reduced (P < 0.05) weed biomass from 985 to 279 kg·ha^{-1}, compared with a field pea monoculture. *Brassicas* such as mustard are less competitive than barley or oats, but their rapid growth and high level of biomass production can suppress weeds (Blackshaw et al. 2002; Beckie et al. 2008). In a review of the literature 30 years ago, Liebman and Dyck (1993) found that weed biomass was reduced in 90% of cases when a main crop was intercropped with a "smother crop"; more recent examples are given in Blackshaw et al. (2002).

Field pea intercrops with wheat (*Triticum aestivum* L.), oats, barley, and mustard has been previously studied (Pridham and Entz 2008; Bedoussac and Justes 2010; Arlauskiene et al. 2014). However, past studies have mainly used peas as a companion crop (Bedoussac and Justes 2010; Monti et al. 2016), often to add N to the cropping system (Patra et al. 1986; Izaurralde et al. 1992). Such "replacement designs" have included two crop species planted in ratios of 50:50, 66:33, or 70:25, equating to a total plant density of 100% (Nelson et al. 2012) or in innovative spatial arrangements (Chapagain and Riseman 2014). Due to the low seeding rates used, and the lack of field pea competitiveness with weeds, 50:50 ratio mixtures of field pea intercrops can result in suboptimal field pea yields and poor weed control (Pridham and Entz 2008; Nelson et al. 2012; Pelzer et al. 2016).The present study considered an additive mixture, where a high density of field peas was intercropped with various seeding rates of companion crops. One important objective in the research was whether the additive mixtures (with field pea as main crop) would provide weed suppression without compromising field pea grain or economic yield. Working with finger millet (*Eleusine coracana* (L.) Gaertn.) – haricot (*Phaseolus vulgaris* L.) in an additive intercrop design, Bitew et al. (2020) observed a 2% to 5% finger millet yield penalty. On the other hand, Saucke and Ackermann (2006) observed no yield penalty in additive field pea-false flax (*Camelina sativa* (L.) Crantz) intercrops.

We were also interested in knowing how different seeding rates would affect the balance between weed suppression and field pea seed yield. Increasing the seeding rate of barley and oats is known to increase grain yield and the competitiveness with other plants (Blackshaw et al. 2002; Mason et al. 2007; Beres et al. 2010). However, in grain intercropping, as one crop species density is increased over another with similar environmental niche requirements, the level of interspecific competition increases, resulting in reduced biomass and grain yields of the crop species that is being outcompeted (Vandermeer 1992; Pelzer et al. 2016). Hence, our second objective was to compare field pea yield and weed suppression at standard field pea plant populations, but increasing populations of the companion crops, barley, oat and mustard. We hypothesized that field pea intercrops would reduce weed biomass and field pea grain yields in comparison to the pea monocrop control and wanted to investigate the extent of these effects. In addition, we hypothesized that the additional harvest of the non-field pea grain in the field pea intercrops may compensate for any reductions in field pea grain yield, leading to greater net returns than the pea monocrop control. By investigating different field pea intercrop companion crops and seeding rates this study aimed to further understand their effect on weed suppression, crop and weed biomass productivity, grain yield and grain quality, and profitability.

Materials and Methods

In 2019 and 2020 three separate semi-leafless yellow field pea intercrop experiments (yellow field pea–barley, yellow field pea–oat, and yellow field pea–mustard) were completed at the Ian N. Morrison Research Farm in Carman, MB, Canada (49°29′56″N, 98°1′29″W). Two site-years were conducted in 2020; conditions were varied by staggering the seeding dates. In 2019 the experiments were seeded on 10 May (Carman 2019). In 2020 the same experiments were seeded on 7 May (Carman 2020*a*) and 21 May (Carman 2020*b*). Each experiment was a randomized complete block design replicated four times, with 2 by 10 m plots. At each site-year the three separate field pea intercrop experiments (field pea–barley, field pea–oat, and field pea–mustard) were planted side-by-side in field sections separated by a 2-m border. Each site year had natural weed populations that were uniform across the experiment.

The 2019 experiments were preceded by an oat grain crop; 2020*a* experiments were preceded by a rye grain crop, and 2020*b* experiments were preceded by a wheat grain crop. A small number of volunteer oats from previous years were hand weeded before heading. All areas were managed organically since 2004. Fields were tilled two times (6 cm deep) immediately before seeding. Field peas and their associated companion crops were seeded together in the same rows at the same depth of 2–5 cm using a cone seeder with double disc openers, with 15 cm row spacing (Fabro Enterprises Ltd., Swift Current, SK, Canada). Entire plots were harvested using a Wintersteiger plot combine (Wintersteiger Ag., Ried im Innkreis, Austria).

Field peas were planted in both monoculture and additive intercrop plant stands. Field peas exhibited 98% germination in 2019 and 2020 and seeding rates were adjusted for germination test results and a 10% mortality rate. Field peas (cv. CDC Amarillo) were sown at the appropriate rate to achieve a target plant density of 120 plants·m^{-2}. Field peas were inoculated with a liquid-based rhizobium (*Rhizobium leguminosarum* (Frank) Ramírez-Bahena) inoculant at 35 mL per 11 kg of seed (Nodulator XL, BASF, Ludwigshafen, Germany). Mustard exhibited 96% germination in 2019 and 98% germination in 2020. Barley and oats exhibited 98% germination in 2019 and 95% germination in 2020. Mustard, barley, and oat seeding rates were adjusted for germination test results and a 10% mortality rate. The non-field pea companion crop species were seeded to low (approximately 10%), medium (approximately 25%), or high percentages (approximately 50%) of their recommended monoculture target plant densities: low barley, 40 plants·m^{-2}, medium barley, 75 plants·m^{-2}, high barley, 150 plants·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 seeded at twice the target plant densities. This resulted in a doubling of barley and oat plant density in the Carman 2019 experiments compared with the other two site-years (Carman 2020*a* and 2020*b*).

Table 1. Soil nutrient status and pH of three site-years for three pea intercrop experiments (pea–barley, pea–mustard, and pea–oat) in 2019 and 2020, located in Carman MB, Canada.

Site-year	N[a]	P[b]	K	S	pH[c]
	ppm				
Carman 2019 (0–60 cm)	26	10	205	25	6.0
Carman 2020*a* (0–30 cm)	12.5	10	246	13	5.9
Carman 2020*b* (0–30 cm)	13	11	368	8	6.1

Note: 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. Analysis completed by Agvise Laboratories Ltd.

[a]N = ppm in nitrate.

[b]P measured using Olsen phosphorous analysis method.

[c]pH measurements were taken at the 0–15 cm soil depth for all site-years.

Climatic data was obtained from the Manitoba Ag-Weather Program and Environment Canada, Manitoba Station. 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), with a medium organic matter content (Mills and Haluschuk 1993; Manitoba Agriculture and Resource Development 2020). 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. All site-years had residual soil N levels below the recommended 30 ppm; 26 ppm in Carman 2019 (0–60 cm depth), and 12.5 to 13 for Carman 2020 (0–30 cm depth) sites (Table 1). Across all site-years phosphorous (P) levels were moderate (10–11 ppm range), while potassium levels were above 200 ppm (205 to 368 ppm range) (Table 1).

Crop density was measured by counting two randomly selected one-metre sections of two crop rows in each plot, after full crop emergence. Maturity biomass samples were taken from two 0.25 m^{-2} quadrats, in each plot, when crops had reached physiological maturity. Biomass samples were separated into field pea, non-field pea companion crop and weed biomass components. Separated samples were dried in an oven at 65 °C for 48 h and weights were taken. Thousand kernel weights (TKW) were measured using a seed counter and scale. Field pea protein percentage on a dry matter basis was measured using a Perten Inframatic 9500 near-infrared

Table 2. Grain prices and production costs used for economic analysis of three pea intercrop experiments (pea–barley, pea–oat, and pea–mustard) in 2019 and 2020, in Carman MB, Canada.

Seed costs	
Pea + inoculant[a]	\$0.61 kg^{-1}
Barley[a]	\$0.51 kg^{-1}
Oat[a]	\$0.59 kg^{-1}
Mustard[b]	\$9.64 kg^{-1}
Other costs	
Seed separation cost[c]	\$0.02 kg^{-1}
Operating costs minus seed cost, separation cost, and crop insurance[d]	\$511.89 ha^{-1}
Fixed costs[d]	\$337.48 ha^{-1}
Labour[d]	\$177.84 ha^{-1}
Grain market prices	
Peas[e]	\$0.53 kg^{-1}
Barley[e]	\$0.36 kg^{-1}
Oat[e]	\$0.49 kg^{-1}
Mustard[e]	\$1.78 kg^{-1}

[a]Estimated seed cost adapted from (Province of Manitoba 2020).
[b]Estimated seed cost adapted from (Government of Saskatchewan 2020).
[c]Average separation cost obtained from pea intercropping survey (Bailey-Elkin 2021).
[d]Production costs adapted from (Province of Manitoba 2020).
[e]Organic grain market prices adapted from (OrganicBiz 2020).

grain analyzer (PerkinElmer, Massachusetts, USA). Field pea intercrop grain yields were separated using a dockage sorter and spiral gravity separator.

Net returns were calculated by using organic production costs that were determined by reviewing a pea intercropping survey (Bailey-Elkin 2021), 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 field pea intercropping compared with the field pea monoculture was the cost of non-field pea seed, the grain separation cost, and crop insurance (Table 2). Net returns were defined as the gross revenue minus total costs (fixed costs + operating costs + labour).

Statistical analysis

Using PROC Mixed procedure in SAS version 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, biomass at maturity, grain yield, and net returns. Site-year was a combination of site and/or year, resulting in three separate site-years (Carman 2019, Carman 2020*a*, and Carman 2020*b*). Site-years were combined for the analysis and when site-year × treatment interactions were detected, data were analyzed separately. No significant site-year by treatment interaction was observed for plant population density, even though a higher seeding rate for companion crops was used in 2019. This supported a combined site-years analysis. Treatments, site-years, and site-year × 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 transformations were used. 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 × 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.

Results and Discussion

Climate

The 2019 and 2020 growing season mean temperatures were the same (13.9 °C) at 98% of the long-term mean temperature (Table 3). Growing season precipitation in 2019 and 2020 was 64% and 61% of the long-term precipitation, respectively (Table 3), resulting in drier than average conditions.

Weed populations

The Carman 2020*a* site-year weed community was dominated by common lamb's quarter (*Chenopodium album* L.), smart weed (*Polygonum pensylvanicum* L.), wild buckwheat [*Fallopia convolvulus* (L.) Á. Löve], and Canada thistle (*Cirsium arvense* L.). Carman 2019 and Carman 2020*b* were dominated by green foxtail (*Setaria viridis* L.). Weed biomass at maturity was similar between Carman 2019 and 2020*a* (1216 and 1176 $kg{\cdot}ha^{-1}$, respectively) but higher at Carman 2020*b* (2412 $kg{\cdot}ha^{-1}$). These biomass levels may be considered above-average when compared with 41 organic green manure fields across southern Manitoba and eastern Saskatchewan (average weed biomass 675 $kg{\cdot}ha^{-1}$, range 0 to 3266 $kg{\cdot}ha^{-1}$) (Thiessen Martens et al. 2019), or organic field experiments in Alberta (weed biomass 25 to 868 $kg{\cdot}ha^{-1}$) (Nelson et al. 2012).

Plant population density

Baird et al. (2009) reported an optimal target plant density for organic field peas of 120 $plants{\cdot}m^{-2}$. In the present study, field pea monoculture ranged from 73% to 89% of this target plant density for barley

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

Location	April		May		June		July		August		Growing Season[a]	
	T[b]	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*
Carman 2019	4.8	17	9.6	37	17.3	37	19.6	57	18.1	61	13.9	209
Carman 2020	1.6	24	10.7	26	18.3	70	20.2	54	18.7	24	13.9	198
Carman LTA[c]	4.5	44	11.6	60	17.2	78	19.4	76	18.5	67	14.2	325

[a]Total precipitation and average temperature over the growing season (April to end of August).
[b]Temperature (*T*); precipitation (*P*).
[c]Long term average (1981–2010) for Carman, MB (Environment Canada).

Table 4. Mean crop establishment of three pea intercrop (IC) experiments (pea–barley, pea–oat, and pea–mustard), averaged across three site-years in 2019 and 2020, in Carman MB, Canada.

Mean crop establishment	Plants m^{-2}					
	Pea–Barley		Pea–Oat		Pea–Mustard	
	Pea density	Barley density	Pea density	Oat density	Pea density	Mustard density
Site-year						
Carman 2019	105a	119a	116a	177a	122a	47ab
Carman 2020*a*	87b	56b	91b	60c	92b	38b
Carman 2020*b*	91ab	74b	92b	78b	85b	54a
Treatment						
Pea monocrop	101a	—	103a	—	111a	—
IC low seed rate	86a	47c	99a	57c	94b	25c
IC medium seed rate	99a	75b	92a	94b	95ab	43b
IC high seed rate	92a	139a	104a	163a	98ab	74a
Site-year effect	0.0230	0.0151	0.0006	<0.0001	<0.0001	0.0215
Treatment effect	0.0757	<0.0001	0.1584	<0.0001	0.0372	<0.0001
Site-year × treatment Interaction	0.7111	0.5223	0.5816	0.0638	0.1198	0.2582

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

experiments, 76% to 97% for oat experiments and 71% to 102% for mustard experiments (Table 4). It is interesting to note that field pea plant density was greater in 2019 than 2020. Lower field pea plant emergence in 2020 may have been due to wet conditions during tillage in 2020, resulting in a course seedbed due to soil clods on the soil surface. Surprisingly, field pea plant density was mostly unaffected ($P > 0.05$) by companion seeding rate, even though seeding rate increased the population density of the companion crops (Table 4). Similar results were observed for false flax intercropped with field pea (Saucke and Ackermann 2006). Therefore, any niche overlap for resources was not strong enough to reduce pea establishment. The lack of any significant intercrop treatment by site-year interaction for either field pea or companion crop plant density (Table 4) indicated that effects of companion crop seeding rates were consistent across the different environments, and that the higher seeding rate used in 2019 did not produce a different trend in field pea plant population results compared with the 2020 experiments.

Maturity crop and weed biomass

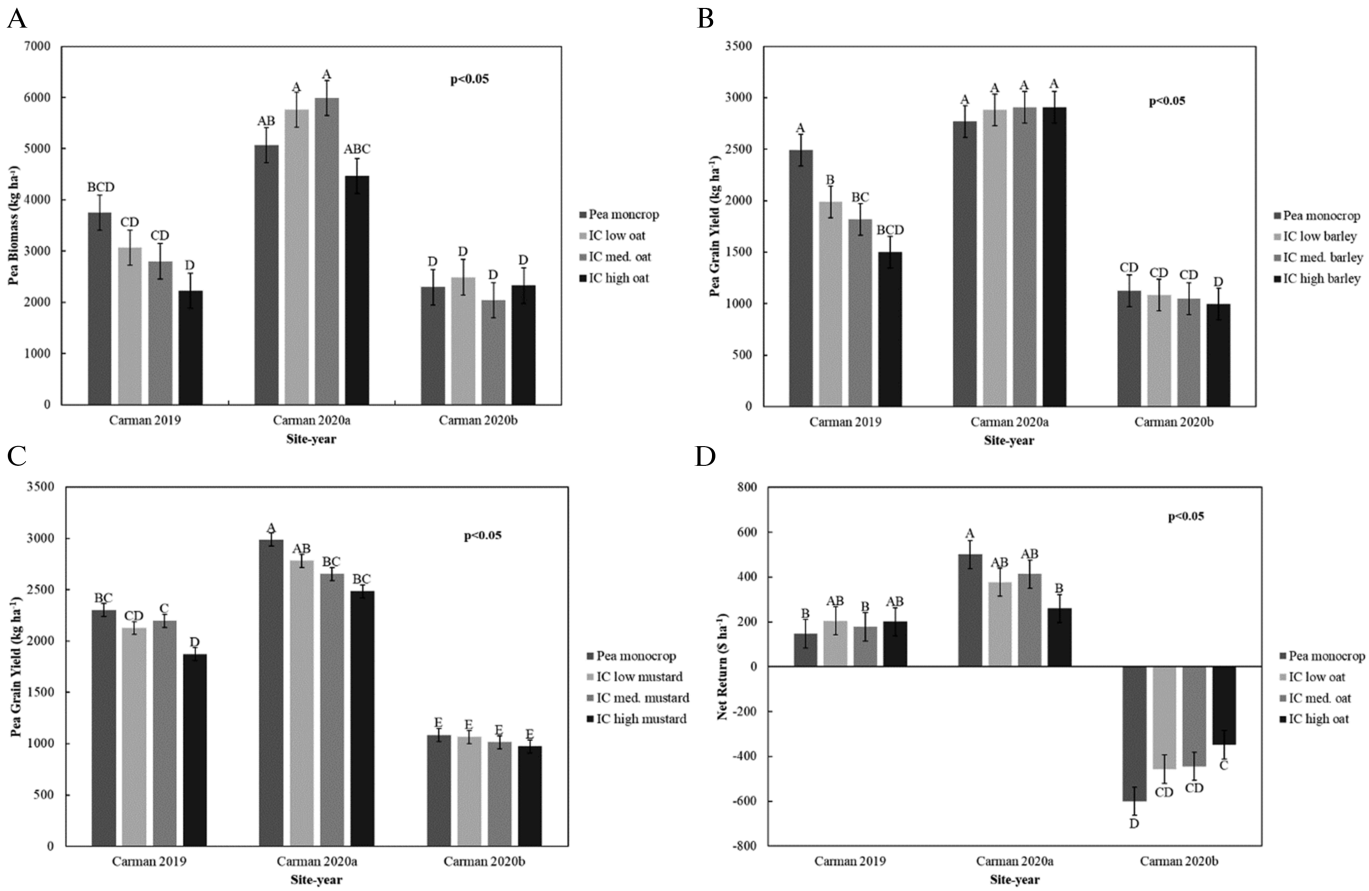
Field pea biomass at maturity ranged from 3007 to 4198 kg·ha^{-1} (Table 5); similar to biomass values reported for organic (Baird et al. 2009) and conventional (Borstlap and Entz 1994) field pea production. The early seeded site-year (Carman 2020*a*) produced significantly more pea biomass for all crops than the later seeded Carman 2020*b* or Carman 2019. Early seeding is known to favour biomass accumulation in cool season crops such as peas and barley (Juskiw and Helm 2003; Chen et al. 2006). Low soil N status at Carman 2020*a* (Table 1) may also have been a contributing factor. Field pea N use efficiency was shown to be higher in intercrops than monocultures (Hauggaard-Nielsen et al. 2009; Bedoussac and Justes 2010).

Table 5. Mean maturity biomass of three pea intercrop (IC) experiments (pea–barley, pea–oat, and pea–mustard), averaged across three site-years in 2019 and 2020, Carman MB, Canada.

Mean maturity biomass (kg·ha^{-1})	Pea–Barley				Pea–Oat				Pea–Mustard			
	Pea	CC	TC	Weed	Pea	CC	TC	Weed	Pea	CC	TC	Weed
Site-year												
Carman 2019	2959b[a]	1520a	4268b	1197b	2962b	2164a	4727a	1150b	3528b	758a	4201b	1302b
Carman 2020*a*	5658a	304b	5924a	1069b	5320a	458c	5731a	1232b	5138a	341b	5440a	1228b
Carman 2020*b*	2504b	574b	3010b	2286a	2287b	973b	3098b	2649a	2260c	361ab	2568c	2310a
Treatment												
Pea monocrop	4198a	-	4198a	1952a	3704ab	—	3704b	2085a	4156a	—	4156a	1804a
IC low seed rate	3983ab	373b	4545a	1544ab	3772a	715b	4796a	1753ab	3740ab	277b	4119a	1680ab
IC medium seed rate	3481ab	679a	4434a	1261bc	3609ab	886b	4685a	1549b	3542ab	479a	4052a	1472b
IC high seed rate	3165b	1009a	4426a	1092c	3007b	1489a	4889a	1322c	3130b	682a	3951a	1498b
Site-year effect	<0.0001	0.0029	0.0011	0.0023	<0.0001	0.0008	0.0002	<0.0001	0.0003	0.0335	0.0003	<0.0001
Treatment effect	0.0184	0.0002	0.7658	<0.0001	0.0226	0.0003	0.0003	0.0002	0.0277	<0.0001	0.9315	0.0091
Site-year × treatment interaction	0.6055	0.0753	0.7944	0.0968	0.0314	0.3606	0.0731	0.1260	0.6810	0.0236	0.9766	0.0358

Note: Means with different letters in the same column are significantly different (Tukey's HSD, $P < 0.05$). Abbreviations: CC, companion crop biomass; TC, total crop biomass.

Fig. 1. Pea biomass at physiological maturity (A) and net returns (D) of pea-oat intercrop experiment. Pea grain yields of pea-barley (B) and pea-mustard (C) intercrop experiments. 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, $P < 0.05$).



Previous research has shown that intercrops often (Langat 1992), though not always (Gliessman 1990) decrease growth of the main crop. In the present study, only the highest seeding rates of barley and mustard significantly reduced field pea biomass compared with the monoculture or the lower companion crop seeding rates (Table 5). No significant interactions between site-year and barley or mustard seeding rate were observed indicating similar trends of these intercrops on field pea biomass across the range of growing conditions. However, a significant site-year by intercrop seeding rate interaction was observed for oat. At Carman 2019, oat intercropping resulted in lower field pea biomass levels than monoculture (Fig. 1A) while at Carman 2020*a* and 2020*b*, field pea biomass was not significantly affected by oat at any seeding rate. Grimmer and Masiunas (2005) found that the presence of oat in a pea–oat cover crop study inhibited pea germination, due to the presence of allelopathic chemicals from oat. Although there was no effect of intercropping on field pea plant density in our study, the reduction in field pea biomass in 2019 only, may have been due to the overseeding of oat, resulting in a greater presence of allelopathic chemicals, thereby reducing field pea biomass.

Intercrops contributed 8%, 15%, and 23% to the total crop biomass for the low, medium, and high seeding rates for barley, 14%, 19%, and 30% for oat, and 7%, 11%, and 17% for mustard, respectively (Table 5). For all three companion crops, the highest seeding rates resulted in statistically greater companion crop biomass at maturity than the lowest seeding rate (Table 5). However, total crop biomass (field pea and companion crop) was increased only with oats, where intercropping increased total crop biomass compared with the field pea monocrop (Table 5). For barley and mustard, total crop biomass was similar to the field pea monoculture. Therefore, within a static field pea population regime, increasing the seeding rate of the non-field pea crop resulted in more total crop biomass at harvest only for oat. Others have also observed that an additive field pea intercropping system increases above ground net primary productivity over field pea monocrops (Corre-Hellou et al. 2011) and the overyielding with oat here helps explain why oat-field pea intercrops are a popular choice for annual green manures in organic production (Thiessen Martens et al. 2019).

A universal observation was that intercropping reduced weed biomass at harvest (Table 5), supporting earlier studies (Blackshaw et al. 2002; Liebman and Dyck 1993). Weed biomass was reduced ($P < 0.05$) by 35% and 44% for the medium and high barley seeding rates compared with the field pea monoculture, respectively (Table 5). For oat, the medium seeding rate significantly reduced weed biomass by 36% compared with the field pea monoculture, and the high oat seeding rate significantly reduced weed biomass by 37%, 25%, and 15%, compared with the field pea monoculture, and low and medium oat seeding rates, respectively. Mustard resulted in the least weed suppression; 17% less weed biomass at the higher mustard seeding rate compared with the field pea monocrop (Table 5). Except for mustard, our levels of weed suppression were similar to the field pea intercropping study of Fernandez et al. (2015) in Minnesota: oilseed radish (39%), winter rye (41%), oat (42%), and wheat (48%). The differences in aboveground leaf architecture between pea and barley can increase light interception, leading to increased overall nutrient use, reducing the available resources for weeds (Corre-Hellou et al. 2006; Bedoussac and Justes 2010). In the present study, barley and oats emerged sooner than field pea which may have resulted in an earlier canopy closure when compared with the field pea monoculture, giving the intercrop a size advantage over weeds. Barley and oats are competitive against weeds due to rapid biomass production and allelopathic compounds found in their plant residue (Satorre and Snaydon 1992; Grimmer and Masiunas 2005; Bouhaouel et al. 2015).

No significant interaction was observed for either barley or oat weed biomass (Table 5), even though Carman 2020*b* contained 48% and 53% more weed biomass than the other sites-years. The weed community in Carman 2020*b* was dominated by green foxtail. As a C_4 plant, green foxtail can have a competitive advantage over C_3 species such as pea, oat, barley and mustard, especially under low soil moisture and high temperature conditions (Peterson and Nalewaja 1992; Taylor et al. 2014). However, even under these conditions, the cereal companion crops provided significant weed suppression.

While others have documented mustard's competitiveness against weeds (Blackshaw et al. 2002; Beckie et al. 2008), in the present study, relatively poor weed suppression by mustard, compared with cereals was observed. This may be because flea beetle damage to the mustard crop reduced plant growth to the point where mustard's weed competitiveness declined. Pridham and Entz (2008) found that mustard in an organic wheat–mustard intercrop did not increase net primary productivity owing to flea beetles defoliating the mustard plants.

Grain yield

Relatively low field pea grain yields (1650 to 2238 kg·ha^{-1}) reflect the water limited conditions of our study. A 2019 survey (Bailey-Elkin 2021) showed organic pea yields grown in intercrops ranged from 1008 to 4033 kg·ha^{-1}, while unweeded yellow field pea yields over six site-years in Minnesota ranged from 2229 to 3607 kg·ha^{-1} (Fernandez et al. 2015).

In addition to below-average precipitation, the low water holding capacity of sandy soils at Carman (Mills and Haluschuk 1993) likely exacerbated the stress. Under these water-limited growing conditions, intercropping consistently resulted in a field pea yield decline (Table 6). For barley, the highest seeding rate reduced field pea yield by 15% ($P < 0.05$) compared with the field pea monoculture (Table 6). For oats, the low, medium, and high seeding rates reduced ($P < 0.05$) field pea yield by 12%, 17%, and 26%, compared with the field pea monoculture, respectively (Table 6). Furthermore, yield was significantly reduced by the high oat seeding rate compared with the low and medium rates. For mustard, the low, medium, and high seeding rates significantly reduced field pea yield by 6%, 8%, and 16%, compared with the field pea monoculture, respectively (Table 6).

Working under similar water-limited conditions, Carr et al. (1995) found that intercropping lentil (*Lens culinaris*) and field pea with other crops was not successful. Under water-limited conditions, below-ground competition for water may increase as the different crop species begin to share similar areas of the soil profile (similar resource pool), resulting in greater niche overlap (Bramley et al. 2007), limiting some intercropping benefits. Interestingly, Fernandez et al. (2015) found that competition between intercrops (and weeds) and field pea were reduced even when soil moisture levels were adequate. On the other hand, other researchers have observed positive benefits to grain intercropping (Saucke and Ackermann 2006). Hauggaard-Nielsen et al. (2001) and Sekiya and Yano (2004) reported that under adequate soil moisture, different root growth habits among crop species can lead to water being used from different areas of the soil profile, thereby resulting in less competition between crop species.

In grain intercropping, as one crop species density is increased over another with similar environmental niche requirements, the level of interspecific competition increases, resulting in reduced biomass and grain yields of the crop species that is being outcompeted (Vandermeer 1992; Pelzer et al. 2016). Therefore, when designing intercropping systems, the unique environmental niche of each crop partner must be considered. Field peas have a shallow root system with the majority of the root biomass within approximately 0.6 m of the soil surface (Cutforth et al. 2013). 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 2016*a*). In comparison, oats and barley have deep fibrous

Table 6. Mean grain yields, pea protein, and pea thousand kernel weight (TKW) of three pea intercrop (IC) experiments (pea–barley, pea–oat, and pea–mustard), averaged across three site-years in 2019 and 2020, in Carman MB, Canada.

	Pea–Barley				Pea–Oat				Pea–Mustard			
	Grain yield[a]		TKW[b]	Protein[c]	Grain yield		TKW	Protein	Grain yield		TKW	Protein
Site-year	Pea	Barley			Pea	Oat			Pea	Mustard		
Carman 2019	1949b[a]	1012a	247.8a	24.0a	1838b	962a	244.6a	23.7a	2124b	74a	236.5a	23.5b
Carman 2020*a*	2867a	30c	229.9b	24.0a	2921a	28c	232.1b	24.2a	2727a	27b	234.8a	24.3a
Carman 2020*b*	1063c	120b	220.2b	23.6a	1034c	398b	220.2c	23.7a	1034c	43b	209.3b	24.2ab
Treatment												
Pea monocrop	2129a	—	230.5b	23.8a	2238a	—	229.2b	23.8a	2125a	—	220.4a	23.9a
IC low seed rate	1984ab	78c	231.0ab	23.8a	1970b	151c	231.6ab	23.7a	1990b	19c	227.9a	23.9a
IC medium seed rate	1924ab	141b	232.0ab	23.8a	1866b	212b	229.6b	23.9a	1954b	55b	227.0a	24.2a
IC high seed rate	1801b	320a	237.0b	24.0a	1650c	328a	238.8a	24.1a	1776c	83a	232.1a	24.1a
Site-year effect	<0.0001	<0.0001	0.0005	0.1074	<0.0001	<0.0001	0.0016	0.1201	<0.0001	0.0010	0.0015	0.0191
Treatment effect	0.0032	<0.0001	0.0350	0.7745	<0.0001	<0.0001	0.0283	0.1105	<0.0001	<0.0001	0.2631	0.2473
Site-year × treatment interaction	0.0002	0.0040	0.1432	0.2226	<0.0001	0.7452	0.6270	0.0854	0.0347	0.1764	0.2104	0.1795

Note: Means with different letters in the same column are significantly different (Tukey's HSD, $P < 0.05$).
[a]Grain yields reported in kg·ha^{-1}.
[b]Pea seed thousand kernel weights.
[c]Pea seed protein percentage on a dry matter basis.

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root structures that can reach depths of 0.84 to 1.95 m and 1.8 to 2.1 m, respectively (Province of Ontario 2016*b*, 2016*c*). While our study included different companion crops in an effort to provide contrasting herbage (eg., grass verses broadleaved) and root (eg., fibrous rooted cereals; taprooted brassica) structures aimed at utilizing different niches (Fernandez et al. 2015), all companion crops reduced field pea yield. The challenge is even greater in organic production where a third plant partner must be considered, weeds. The type of niche occupied by the "weed intercrop partner" in organic cropping systems will be based on the weed community present. Future research should consider detailed resource pool use (Smith et al. 2010) for intercrops of organic field peas with various partner species, including both crops and weeds.

Site-year by intercrop seeding rate interactions were observed in all three experiments (Table 6); the field pea yield reduction with intercrop seeding rate was more serious in 2019 than in 2020*a* or 2020*b* (e.g., barley, Fig. 1B). One explanation for a great negative effect on seeding rates in 2019 was the accidental doubling of the seeding rate that year. The conclusion, certainly for barley, was that at the planned seeding rates, barley did not affect field pea yield; negative effects were only observed at much higher rates. Increasing the seeding rate of barley and oats is known to increase grain yield and the competitiveness with other plants (Blackshaw et al. 2002; Mason et al. 2007; Beres et al. 2010). One reason for greater competitiveness of field pea in Carman 2020*a* was lower soil N (12.5 ppm, 0–30 cm) (Table 1). Carkner and Entz (2017) observed that organic soybeans were most competitive with weeds when soil N status at planting was low. In Carman 2020*b*, where soil N levels were similar to Carman 2020*a*, the high level of green foxtail may have outcompeted field pea. Furthermore, pea yield results in the present study also corresponded to those of Boerboom and 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 and Young (1995) experienced growing conditions that were similar to the low precipitation in June in the Carman 2019 site-year (Table 3), and the high levels of weeds found in the Carman 2020*b* site-year.

For mustard, there were significant reductions in field pea yield in both 2019 and 2020*a*, even though no seeding rate error occurred (Fig. 1C). One explanation may have been the much greater weed competition in Carman 2020*b*; at high plant densities green foxtail is known to be highly competitive (Weaver 2001) and may have masked any negative effects of the mustard. Our results contrast with Langat (1992) who found no negative effect of mustard intercrops on field pea yields. Similar to observations by Pridham and Entz (2008), mustard in the present study was attacked by later season flea beetles. The late season defoliation by insects sometimes resulted in the unfortunate scenario where the companion crop (in this case mustard) exerted a negative effect on the main crop (field peas) but yielded poorly due to seed pod defoliation. By comparison, barley and oat were not affected by any late-season insect or pathogen attacks.

The average field pea protein percentage on a dry matter basis was 23.9 %, and the presence of intercrops did not change field pea grain protein content (Table 6). The average field pea seed mass was 230.6 g, and results showed that field pea seed mass was significantly greater for the highest oat seeding rate compared with the other seeding rates of the field pea monocrop (Table 6). Langat (1992) studied field pea-mustard intercrops and found that the thousand kernel weight of field peas were higher in intercrop treatments, when compared with field pea monocrop treatments. Langat (1992) attributed this response to competition stress within the intercrops resulting in a low number of pods per plant, but greater supply of photosynthates per pod, resulting in greater individual seed mass.

Synthesis of the weed-crop trade-off

Given that intercropping resulted in both reduced weed growth and a reduced field pea grain yield, an important question regards the level of field pea yield loss sustained per unit of weed suppression with the intercrops. In other words, how much pea yield did the weed control cost? Expressed as kg of weed biomass reduction per kg of field pea yield loss at the highest seeding rate for intercrops, mustard averaged 0.87, oat averaged 1.29, and barley averaged 2.62. Therefore, barley provided the highest level of weed suppression at the lowest field pea yield cost.

The seed cost for the high seeding rate barley, mustard, and oat treatments were \$27.31 ha^{-1}, \$75.67 ha^{-1}, and \$32.63 ha^{-1}, respectively (Table 2). These companion crop seed costs can be considered the price of weed management. By comparison, Alba (2019) found that the cost of using a rotary hoe, harrow, or interrow cultivator for weed control in organic field pea production was \$47.20 ha^{-1}, \$30.00 ha^{-1}, and \$34.00 ha^{-1}, respectively.

Economic analysis

Based on the costs of production and a field pea market price of \$0.53 per kg, field pea monoculture grain yield needed to exceed 2208 kg·ha^{-1} for a positive net return. Site-year was the most consistent effect with Carman 2019 and 2020*a* registering positive net returns and Carman 2020*b* showing a negative net return (Table 7).

Significant interactions were observed for net return in field pea-oat and field pea-mustard intercrops (Table 7). For field pea-mustard, the significant interaction was attributed to a greater magnitude of net return decline with increasing mustard seeding rate at Carman

Table 7. Mean net returns of three pea intercrop (IC) experiments (pea–barley, pea–oat, and pea–mustard), averaged across three site-years in 2019 and 2020, in Carman MB, Canada.

	$\$\cdot ha^{-1}$		
	Pea–Barley	Pea–Oat	Pea–Mustard
Site-year			
Carman 2019	154.54a	182.88a	55.23b
Carman 2020*a*	361.75a	387.58a	297.91a
Carman 2020*b*	(555.77)b[a]	(462.15)b	(585.87)c
Treatment			
Pea monocrop	(24.43)a	15.91a	(44.11)a
IC low seed rate	(32.54)a	41.59a	(84.22)ab
IC medium seed rate	(2.58)a	49.30a	(52.80)a
IC high seed rate	(6.92)a	37.61a	(129.19)b
Site-year Effect	<0.0001	<0.0001	<0.0001
Treatment Effect	0.6998	0.7372	0.0053
Site-year*treatment Interaction	0.5488	0.0001	0.0008

Note: Means with different letters in the same column are significantly different (Tukey's HSD, $P < 0.05$).
[a]Parentheses indicate negative values.

2020*a* compared with the other site-years (Data not shown). Therefore, adding mustard to a full seeding rate of field pea decreased net return in all cases, though sometimes the negative effect was less severe than others. The presence of flea beetles appeared to play a significant role in the results since mustard biomass competed with field pea plants but, the mustard plants themselves produced little seed yield (Table 6).

For field pea–oat, the site-year interaction showed that intercropping with the high oat seeding rate improved net return at Carman 2020*b* but significantly reduced net return at Carman 2020*a* (Fig. 1D). By comparison, oat intercropping did not affect net return in 2019. Improved net returns with intercropping at Carman 2020*b* may be attributed to weedier conditions, which oats helped to control. Under less weedy conditions at Carman 2020*a*, on the other hand, the presence of the oat intercrop significantly reduced net return compared with field pea monoculture (Fig. 1D). Oat was the only companion crop to show any improvement in net return and this was only observed at one site-year characterized by late seeding and weedy conditions.

Our results support those of (Fernandez et al. 2015) who also observed few economic benefits of field pea intercrops. When using a field pea market price that was 46% greater than ours, Fernandez et al. (2015) found that field pea–oat intercrops were the least profitable ($1498 ha^{-1}) of five different field pea intercrop mixtures studied, with net returns that were 45% less profitable than the unweeded field pea monoculture control. Fernandez et al. (2015) found no difference in profitability between a field pea–oilseed radish intercrop and unweeded field pea monoculture control. Although field 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}).

Summary and Conclusions

Our study supported previous research (eg., Bedoussac and Justes 2010; Corre-Hellou et al. 2011; Fernandez et al. 2015) where field pea intercropping provided significant weed control benefits, and that intercrops did not significantly interfere with field pea establishment. We measured the trade-off between weed suppression and field pea yield loss and found that barley was the most efficient weed suppressing companion crop.

In most cases, intercropping did not improve short-term economic outcomes as measured by net return to the farmer; results showed both significant increases and decreases in net return with seeding rate depending on growing circumstances. We concluded that field pea monoculture yields needed to exceed 2208 $kg\cdot ha^{-1}$ for a positive net return, and early seeding was important to achieving this yield goal. Only under conditions of later seeding and high weed pressure did field pea–oat intercrops significantly increased net returns over field pea monoculture. Additional research is required to better understand the conditions which might lend themselves to more positive intercropping outcomes, including conducting additive design organic intercropping experiments in wetter growing conditions. Furthermore, this study was limited because the three site-years were in the same location. Future intercrop studies should be implemented across different regions to understand how field pea intercrops function across different growing regions. It is also important to note that our work did not consider the role of intercropping on future weed challenges. The significant reduction in weed biomass recorded here should translate into longer term weed management benefits to organic producers.

No weed management factors other than intercropping were considered in our study. Future studies should test intercrops in the presence of supplemental weed management tools such as increased field pea seeding rate (Baird et al. 2009) and mechanical weed control (Alba 2019). Further, the role of different intercrop and even field pea genotypes should be tested to better understand the role that genetic variation might play in the intercrop plant community.

While intercrops did produce their own grain yields, with barley producing the most, the lower economic value of intercrops compared with field pea limited the economic success of the intercrop in our work. More valuable companion crops should be explored in future research. The experience with insect damage to the mustard intercrops tested here, should alert future researchers to be mindful of pest resistance of future intercrop candidates.

Acknowledgements

We gratefully acknowledge the technical assistance of Katherine Stanley and Wilson Fink. This research was supported by The Manitoba Pulse and Soybean Growers Association and the Manitoba Government. Scholarships to the senior author included: the Lord Selkirk Association of Rupert's Land Agriculture Scholarship, the W.W. Thomson Scholarship, the William Wilson Muir Graduate Fellowship, the University of Manitoba Graduate Fellowship, the Prairie Improvement Network Graduate Fellowship, and the OCIA Research and Education Scholarship.

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