Legume-oilseed intercropping in mechanised broadacre agriculture – a review

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ABSTRACT

Intercropping aims to exploit complementary and facilitative interactions between species to improve capture and efficiency in the use of resources, and yield and profit per unit land and time. This review uses the ecological theory of intercropping to investigate the agronomic benefits and drawbacks of legume-oilseed intercropping and its place in mechanised broadacre agriculture. Complementary, competitive and facilitative interactions between species are analysed with a focus on nutrients and water in a range of legume oilseed pairings including pea-canola, soybean-sunflower, and chickpea-flax. Of the 41 studies investigated, 35 report yield, nutrient-use efficiency, or economic benefits of legume-oilseed intercropping. Legume-oilseed intercrops appear to negate many of the agronomic and technical issues associated with the more traditional cereal-legume pairings, and offer novel benefits such as the break-crop advantage to cereal dominant systems, and allelopathic pest repellence. While many of the traditional constraints to manage intercrops in broadacre mechanised systems appear to be tractable, this review also identifies priorities for further research and development of legume-oilseed intercrops. We conclude that legume-oilseed species pairings may have potential as commercially viable, large scale intercrops, as an effective means to improve productivity in broadacre mechanised agricultural systems.

1. INTRODUCTION

Intercropping is a system of farming whereby multiple crop species are cultivated simultaneously for a significant period of time during a growing season, with the aim of improving productivity through increased capture and efficiency in the use of resources (Betencourt et al., 2012; Iderawumi et al., 2012; Naudin et al., 2014; Temesgen et al., 2015). There are many of types of intercropping (Table 1), differing in layout and the ecosystem services that they provide (Verret et al., 2020). Compared with monocultures, intercropping often increases land and resource-use efficiency (Chapagain and Riseman, 2014; Temesgen et al., 2015), reduces reliance on external inputs (Hauggaard-Nielsen et al., 2008, 2009a, 2009b; Naudin et al., 2010), improves crop growth (Fletcher et al., 2016), and stabilises yield (Hauggaard-Nielsen et al., 2009b). While intercropping has been widely implemented in small-scale subsistence farms (Dedio, 1994; Banik et al., 2000, Western Applied Research Corporation WARC, 2016), logistical and practical issues have prevented its mass adoption in mechanised, large-scale cropping systems.

Differences in the phenology of the crop components, as well as differences in their fertiliser, pesticide, or herbicide requirements has constrained the adoption of intercropping in broadacre mechanised systems (Lithourgidis et al., 2011; Ehrmann and Ritz, 2014). However, recent research has shown that legume-oilseed pairings may have potential as commercially viable, largescale intercrop mixtures (Irrigation Crop Diversification Corporation (ICDC), 2017), especially given the recent improvements in farm machinery and varieties (Chalmers, 2017). Further, in the last 50 years, global demand for oilseeds and legumes has dramatically increased (Zentner et al., 2002), with 90% of global cropland now comprised of cereals, legumes and oilseeds (Maaz et al., 2018). Legume-oilseed intercropping takes advantage of this market expansion.

Owing to renewed commercial potential, there has been increased interest in legume-oilseed intercrops in the last decade (Szumigalski and Van Acker, 2006; VanKoughnet, 2015, 2016; Chalmers, 2017; Westman Agricultural Diversification Organization (WADO, 2018a, 2018b,

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Table 1
Different types of intercrop and their purpose.

Intercrop type	Layout	Legume-oilseed example	Purpose (ecological/agronomic services provided)	Crop component one	Crop component two
Mixed rows	Two cash crops seeded together in the same row	Chalmers, 2014a	Nutrient efficiency, overyielding, structural support of the pulse, temporal and spatial complementarity, disease and weed suppression	Harvested for grain	Harvested for grain
Alternate rows	Two cash crops seeded together in alternate rows. Row ratio can vary, i.e. 1:1, 1:3 etc.	Chalmers, 2014a	Nutrient efficiency, overyielding, temporal and spatial complementarity, disease and weed suppression	Harvested for grain	Harvested for grain
Strip intercropping	Arrangement of species in separate strips	Robinson, 1984	Nutrient efficiency, overyielding, ease of sowing, management and harvest	Harvested for grain	Harvested for grain
Relay intercropping	Sowing delay of one crop component AND/OR early harvest of one crop component	Andrade et al., 2012	Nutrient efficiency, resources use complementarity, asynchronous sowing and harvesting	Harvested earlier for grain	Harvested later for grain
Living mulch	One species broadcast as soil cover, main crop component sown in rows for harvesting	Lorin et al., 2015	Nutrient efficiency, soil health improvements, weed and disease suppression	Main crop – harvested for grain	Companion crop - chemically destroyed end of season or killed by frost mid-season
Cover crop	Two species seeds broadcast sown	Jiménez-Calderón et al., 2018	Included as a break crop as part of a cereal cash crop rotation - reduce evaporation, maintain/increase soil fertility	Harvested for forage or chemically destroyed	Harvested for forage or chemically destroyed

Adapted from Gaba et al. (2015), Verret et al. (2020).

2018c). The aim of this review is to synthesise current knowledge and identify new opportunities to enhance legume-oilseed intercrops. The review first i) outlines the ecological theory underpinning intercropping in general, and ii) details how these mechanisms operate in legume-oilseed intercrops, iii) discusses the agronomic and logistical benefits and drawbacks of legume-oilseed intercropping, and iv) provides directions for future research.

2. METHODS

The legume-oilseed intercropping studies analysed in this review were sourced using two methods; i) a search of 31 Agricultural Science databases, and ii) a web search. In both searches, the search terms 'oilseed', 'brassica*', 'sunflower', 'soybean', 'legume', 'intercrop*', and 'mixture' were entered in various combinations. All papers returned by this initial search were read and sorted into two groups: large-scale, mechanised cropping system, and small-scale subsistence cropping system. Studies falling into the latter category were discarded. This method returned 23 peer-reviewed papers from the scientific databases and 18 studies conducted by government or industry research groups from websites (Table 2). Of the 41 studies, 19 were conducted in Canada, 5 in Argentina, 4 in each of USA and Australia, 3 in France, 2 in Denmark, and one in each of Poland, China, Germany, and Switzerland. The studies cover a wide range of legume-oilseed species mixtures (n = 33), the most common of which is pea-canola (n = 18), followed by soybean-sunflower (n = 6), and chickpea-flax (n = 3).

We used the Land Equivalent Ratio (LER) as the key metric to gauge intercrop yield advantage (Bedoussac et al., 2015); it measures the relative land area a crop requires as a monoculture to produce the same yield it achieves in an intercrop (Fletcher et al., 2016). An LER greater than one indicates a yield advantage of the intercrop. Where a study did not provide LER, the intercrop yield advantage was gauged by comparing the yield of one intercrop component to its respective monocrop yield, and then running a significance test (ANOVA, t-test). However, this method does not take into account the reduced density and area per species when moving from monocrop to intercrop, and so was only used as a measure of yield if the study did not provide the LER.

2.1. ECOLOGICAL THEORY

In natural ecosystems, increased species richness increases the range of interactions between plant species and their abiotic environment, and between plant species themselves (Malézieux et al., 2009), and is associated with increased productivity (Skelton and Barrett, 2005; Powlson et al., 2011; Tilman and Snell-Rood, 2016). Interactions in multispecies stands can be classified as: i) complementary, ii) competitive, or iii) facilitative (Naudin et al., 2010). Intercropping, despite only increasing species diversity from one to two species, aims to exploit these three types of interactions and apply them within the agricultural context to benefit yield and crop system stability (Malézieux et al., 2009; Zarea et al., 2011).

Complementarity occurs when resource acquisition across the species varies in time, space, or the chemical form that is assimilated, increasing capture and efficiency in the use of resources (Fridley, 2001; Hinsinger et al., 2011; Betencourt et al., 2012). Complementarity is made possible by the differences in plant morphology and phenology, environmental range, and resource needs that make up a species' niche (Lehman and Tilman, 2000). Within a plant community, increasing species richness broadens the range of chemical and environmental conditions that can be utilised through niche differentiation, explaining why greater plant diversity enhances ecosystem productivity and efficiency (Skelton and Barrett, 2005; Tilman and Snell-Rood, 2016).

Competition occurs when two individuals in a stand interact in such a way that at least one exerts a negative effect on the other (Vandermeer, 1989; Malézieux et al., 2009). Inter-plant competition acts directly on an individual's growth and morphology, i.e. reduced growth in crops due to

Table 2

Legume-oilseed intercropping studies included in this review. The studies are ordered by species mixtures as follows; pea-canola, soybean-sunflower, chickpea-flax, pea-, soybean-, -canola, -sunflower, -flax.

Source	Country	Legume component/s	Oilseed component/s	Soil properties	Cropping system conditions	Focus	Intercrop benefit*	Key success metric**
Andersen et al., 2004	Denmark	Pea (*Pisum sativum*)	Canola (*Brassica napus*)[a]	sandy loam, pH 6.7	Rain fed; in-season rainfall (April-Aug): 200 mm	Nitrogen dynamics	YES	LER at diff N fert rates 0.5 g N m^{-2}: 1.32 4.0 g N m^{-2}: 1.16
Andersen et al., 2007	Denmark	Pea (*Pisum sativum*)	Canola (*Brassica napus*)[a]	sandy loam, pH 6.7	Rain fed; in-season rainfall (April-Aug): 200 mm	Interspecies competition	YES	Partial LER in triple intercrop with barley Pea: 0.28 Canola: 0.26
Bennet, 2009	Australia	Pea (*Pisum sativum*)	Canola (*Brassica napus*)	Sandy loam	Rain fed; annual average: 325 mm	Agronomic	YES	Gross income ($ ha^{-1}) Pea-canola 100kg-3 kg ha^{-1} sowing rate: $543 Sole crop pea: $436
IHARF, 2013	Canada	Pea (*Pisum sativum*)	Canola (*Brassica napus*)	Sasketchwan site - heavy clay Manitoba site - Langvale sandy loam	Rain fed; rainfall over growing season (May-Aug): Sask. 2011: 290 mm Sask. 2012: 285 mm Manitoba 2011: 320 mm	Agronomic	YES	Sask. 2011: LER 1.1 Sask. 2012: LER$_{alt}^{\psi}$ 1.1, LER$_{mix}$ 1.2 Manitoba 2011: LER$_{alt}$ 1.5, LER$_{mix}$ 1.6
Malhi, 2012	Canada	Pea (*Pisum sativum*)	Canola (*Brassica napus*)[a]	Gray Luvisol loam, pH 6.6	Rain fed; in-season rainfall (May-Aug): 2009: 225 mm 2010: 300.2 mm 2011: 198mm	Agronomic	YES	LER for seed yield (kg ha^{-1}) 0 kg N ha^{-1}: IC$_{alt}$ 1.45; IC$_{mix}$ 1.56 40 kg N ha^{-1}: IC$_{alt}$ 1.31 (N to canola only); IC$_{mix}$ 1.40
Roberts et al., 2019	Australia	Pea (*Pisum sativum*) Lentil (*Lens culinaris*) Vetch (*Vicia sativa*)	Canola (*Brassica napus*)	Red sandy loam	Rain fed; in-season rainfall (April-Oct): 2016: 208 mm 2017: 103mm	Agronomic	YES	LER pea-canola 2016: 1.3 pea-canola 2017: 1.1 lentil-canola 2017: 1.8
Soetedjo et al., 1998	Australia	Pea (*Pisum sativum*)	Canola (*Brassica napus*)	No soil data given	Rain fed; in-season rainfall (May-Oct): 442.4mm	Agronomic and water dynamics	YES	LER Early sown: 1.82 Late sown: 1.15
Soetedjo et al., 2003	Australia	Pea (*Pisum sativum*)	Canola (*Brassica napus*)	Sandy loam, pH 5.7	Rain fed; in-season rainfall: 1996: 442 mm 1997: 327mm 1998: 345 mm	Agronomic	YES	LER Exp 1 (cultivar): 1.53 Exp 2 (sowing time): Early sown: 1.41 Late sown: 1.32 Exp 3 (pea density): 40 kg ha^{-1}: 1.61 80 kg ha^{-1}: 1.73 120 kg ha^{-1}: 1.39
Szumigalski and Van Acker, 2006	Canada	Pea (*Pisum sativum*)	Canola (*Brassica napus*)[c]	Site 1 - Typic Haplocryoll Site 2 - Borafilic Haploboroll	Rain fed; in-season rainfall (May-Aug): 2001 site 1: 309 mm 2002 site 1: 361 mm 2003 site 1: 288mm 2001 site 2: 357mm 2002 site 2: 419 mm 2003 site 2: 247 mm	Nitrogen dynamics	YES	NLER grain yield (herbicide applied) 2001 site 1: 1.23 2002 site 1: 1.24 2003 site 1: 1.25 2001 site 2 1.22 2002 site 2: 1.20 2003 site 2: 1.14
VanKoughnet, 2015	Canada	Pea (*Pisum sativum*)	Canola (*Brassica napus*)	No soil data given	Rain fed; "soil moisture conditions were ideal"	Agronomic	YES	LER at diff N fert rates 20 lbs N/ac: 1.04 50 lbs N/ac: 1.09 80 lbs N/ac: 1.10
VanKoughnet, 2016	Canada	Pea (*Pisum sativum*)		No soil data given		Agronomic	YES	LER at diff N fert rates 0 lbs N/ac: 1.16

Table 2 (*continued*)

Source	Country	Legume component/s	Oilseed component/s	Soil properties	Cropping system conditions	Focus	Intercrop benefit*	Key success metric**
Chalmers, 2014a	Canada	Pea (*Pisum sativum*)	Canola (*Brassica napus*) Canola (*Brassica napus*)	Sandy loam, pH 8.1	Rain fed; no rainfall data given Rain fed; no rainfall data given	Agronomic and nitrogen dynamics	YES	30 lbs N/ac: 1.12 60 lbs N/ac: 1.09 LER at diff N fert rates 45 lbs N/ac mixed row: 1.28 single row: 1.03 double row: 1.17 triple row: 1.11 90 lbs N/ac mixed row: 1.29 single row: 1.14 double row: 1.18 triple row: 1.08
Chalmers, 2017	Canada	Pea (*Pisum sativum*)	Canola (*Brassica napus*)	Waskada Loam, pH 7.55	Rain fed; no rainfall data given	Nitrogen & phosphorus dynamics	Fertiliser dependent	LER at diff N-P fert rates 0P0 N: 0.80 30P0 N: 0.96 60P0 N: 1.03 0P45N: 0.94 30P45N: 1.03 60P45N: 1.05 0P90 N: 0.94 30P90 N: 1.08 60P90 N: 1.11
WADO, 2018c	Canada	Pea (*Pisum sativum*)[g]	Canola (*Brassica napus*)	Waskada Loam	Rain fed; no rainfall data given	Agronomic	YES	LER 1.0
Nybo and Sluth, 2015	Canada	Pea (*Pisum sativum*)	Canola (*Brassica napus*)[a,c,d]	Swinton silty loam	Rain fed; in-season rainfall (Jan-Oct): 429mm	Agronomic	NO	Yield IC: 1400 kg/ha SC pea: 2400 kg ha^{-1} SC canola: 1900 kg ha^{-1} p > 0.05
Andrade et al., 2012	Argentina	Soybean (*Glycine max*)	Sunflower (*Helianthus annuus*)	Typic Argiudol, pH 6.1	Rain fed; in-season rainfall (Sept-April): 330 mm additional irrigation Exp 1: 136 mm Exp 2: 333mm Exp 3: 0 mm	Water availability and sowing management	YES	Average relative total grain yield (ryt) Exp 1 I00 (sown together): 1.30 Exp 1 I30 (soybean 30-day sowing delay): 1.25 Exp 2 I00: 1.14 Exp 2 I30: 1.07 Exp 3 I00: 1.15 Exp 3 I30: 1.06
Coll et al., 2012	Argentina	Soybean (*Glycine max*)	Sunflower (*Helianthus annuus*)	Silty loam	Rain fed; monthly average annual rainfall: 2005-06: 75 mm 2006-07: 95 mm additional irrigation: Jan 06: 12 mm Nov 06: 12 mm Jan 07: 78mm Feb 07: 26 mm	Water- and radiation- use efficiency	YES	LER 2005-06: 1.24 2006-07: 0.97
Dedio, 1994	Canada	Soybean (*Glycine max*)	Sunflower (*Helianthus annuus*)	No soil data given	No rainfall data given	Agronomic	YES	Average LER over two years 46 cm row spacing: 1.40 61 cm row spacing: 1.14 76 cm row spacing: 1.09
Echarte et al., 2011	Argentina	Soybean (*Glycine max*)	Sunflower (*Helianthus annuus*)[b]	Typic Argiudol	Rain fed; monthly average in-season rainfall (Sept-April): 2005-06: 78mm	Agronomic	YES	LER 2005-06 3 sunflower plant m^{-2}: 1.3 6 sunflower plant m^{-2}: 1.2 9 sunflower plant m^{-2}: 1.1

(*continued on next page*)

Table 2 (*continued*)

Source	Country	Legume component/s	Oilseed component/s	Soil properties	Cropping system conditions	Focus	Intercrop benefit*	Key success metric**
					2006-07:108mm additional irrigation: Jan-Feb 06: 30 mm Nov-Dec 06: 12 mm Jan-Feb 07: 104mm			LER 2006-07 2 sunflower plant m^{-2}: 0.9 3 sunflower plant m^{-2}: 1.0 6 sunflower plant m^{-2}: 0.9
IHARF, 2015	Canada	Chickpea (*Cicer arietinum*)	Flax (*Linum usitatissimum*)	Heavy Clay	Rain fed; in-season rainfall (May-Aug): 385 mm	Agronomic	YES	Yield (kg ha^{-1}): flax was boosted by intercrop + N fert, chickpea sig boosted by intercrop no fert. Neither benefited from alternate rows
SERF, 2015	Canada	Chickpea (*Cicer arietinum*)	Flax (*Linum usitatissimum*)	No soil data given	Rain fed; no rainfall data given	Agronomic	YES	2014-2015 average LER no N flax-Kabuli IC: 1.3 no N flax-Desi IC: 1.4 N flax-Kabuli IC: 1.1 N flax-Desi IC: 1.3
WARC, 2016	Canada	Chickpea (*Cicer arietinum*)	Flax (*Linum usitatissimum*)	No soil given	Rain fed; in-season rainfall (May-Sept): 2014: 265.2 mm 2015: 194.0 mm	Agronomic	YES	Intercropping significantly increased both chickpea and flax yield (kg ha^{-1}). Flax: $p < 0.01$ Chickpea: $p < 0.0001$
Fernandez et al., 2014	USA	Pea (*Pisum sativum*) Lentil (*Lens culinaris*)	Oilseed radish (*Raphanus sativus*)[c,d,f,h]	Site 1 – loamy sand, pH 6.9 Site 2 – fine loam, pH 6.1 Site 3 – silty loam, pH 6.7	Rain fed; in-season rainfall 2009 Site 1 - 224mm Site 2 – 204mm Site 3 – 169mm 2010 Site 1 – 274mm Site 2 – 340 mm Site 3 – 384mm	Agronomic	NO	Net income ($ ha^{-1}): SC pea: $2292 Pea-mustard: $2177 Pea-radish: $2463 SC lentil: $285 Lentil-mustard: $100 Lentil-radish: $888
ICDC, 2017	Canada	Pea (*Pisum sativum*)	Yellow mustard (*Brassica juncea*)	No soil data given	Rainfed; no rainfall data given	Agronomic	NO	In the intercrop, mustard significantly outcompeted pea Yield (kg ha^{-1}) SC pea: 25.8 SC mustard: 56.7 IC pea: 2.2 IC mustard: 55.5
Klimek-Kopyra et al., 2015	Poland	Pea (*Pisum sativum*) Common vetch (*Vicia sativa*)	Flax (*Linum usitatissimum*)	Site 1 - Luvic Phaeozem (fine grained, clay dominant); Site 2 - Eutric Cambisol (fine grained, silt dominant)	Rain fed; average annual rainfall (2006-2008): Site 1: 294mm Site 2: 289 mm. Severe drought Site 1: July 2006, April 2007, June 2008 Site 2: July 2006, June 2008. Drought: Site 1: May, June & July 2008 Site 2: April 2007, May & July 2008	Root dynamics	Soil dependent	Mean (2006-2008) root DW (g cm^{-3}) Site 1: IC pea < MC pea $p < 0.01$ IC flax < IC flax $p < 0.01$ Site 2: IC pea > MC pea $p < 0.01$ IC flax > MC flax $p < 0.01$
Paulsen et al., 2006	Germany	Pea (*Pisum sativum*)	Flax (*Linum usitatissimum*) False flax	Clay	Rain fed; annual rainfall: Site 1 2004: 660 mm	Weed suppression	Species mixture dependent	Soil covered by weed SC pea: 12% IC pea-false flax: 4% ($p > 0.05$)

Table 2 (*continued*)

Source	Country	Legume component/s	Oilseed component/s	Soil properties	Cropping system conditions	Focus	Intercrop benefit*	Key success metric**
			(*Camelina sativa*)[c]		2005: 570 mm Site 2 2004: 560 mm 2005: 490 mm			SC false flax: 5.8% IC false flax-pea: 4% ($p < 0.01$)
SERF, 2017	Canada	Yellow pea (*Pisum sativum*) Maple pea (*Pisum sativum spp. arvense*) Green lentil (*Lens culinaris*) Red lentil (*Lens culinaris*)	Yellow mustard (*Sinapis alba*)[e]	Soybean stubble	Rain fed; no rainfall data given	Agronomic	YES	<u>Partial LER for mustard intercropped with:</u> Yellow pea 2.23 Maple pea 2.20 Green lentil large 1.27 Green lentil small 1.36 Red lentil 1.31
WADO, 2018	Canada	Pea (*Pisum sativum*)	Hemp (*Cannabis sativa*)	Waskada Loam	Rain fed; in-season rainfall (May-Aug): 164 mm 65% of normal rainfall	Agronomic	NO	<u>Crop yield</u> MC hemp: 637 kg ha^{-1} IC hemp: 581 kg ha^{-1} $p > 0.05$
Waterer et al., 1994	Canada	Pea (*Pisum sativum*)	Yellow mustard (*Sinapis alba*)	1990 site - Dugas clay 1991 site - Fortier Silty clay	Rain fed; no soil data given	Nitrogen dynamics	YES	<u>1990 & 1991 average LER at diff N fert rates</u> 10 N: 1.19 30 N: 1.17 60 N: 1.22 90 N: 1.07
Wendling et al., 2017	Switzerland	Pea (*Pisum sativum*)	Indian mustard (*Brassica juncea*)[d, g]	Sandy clay	Rain fed; Average annual rainfall: 999mm	Cover crop and nitrogen dynamics	YES	<u>LER at diff N fert rates (kg ha^{-1})</u> 0 N: 1.40 30 N: 1.28
De la Fuente et al., 2014	Argentina	Garden peas (*Pisum arvense*)	Sunflower (*Helianthus annuus*)	Clay-loam	Rain fed; annual rainfall: 2008: 988mm 2009: 678mm	Agronomic/ weed and insect assemblages	YES	<u>Average LER over two years</u> 1.27
Dong et al., 2018	China	Soybean (*Glycine max*)	Canola (*Brassica napus*)[b,e]	Orthic Anthrosol, pH 7.6	Rain fed; in-season rainfall (March-Oct): 161mm	Agronomic	YES	<u>LER 2013</u> 1.95 <u>LER 2014</u> 1.65
Robinson, 1984	USA	Soybean (*Glycine max*) Field bean (*Phaseolus vulgaris*)	Sunflower (*Helianthus annuus*) Yellow mustard (*Brassica hirta*)[b,f]	Fine silty Silty loam Sandy	Rain fed; no rainfall data given	Agronomic	NO	<u>Strip intercrop</u> No sig IC yield increase compared with SC ($p > 0.05$) <u>Row intercrop</u> Sig yield reduction in IC ($p < 0.05$)
WADO, 2018a	Canada	Soybean (*Glycine max*)	Flax (*Linum usitatissimum*)	Waskada Loam	Rain fed; no rainfall data given	Agronomic	YES	<u>LER</u> 1.36
Ilnicki and Enache, 1992	USA	Subterraneum clover (*Trifolium subterraneum*)	Soybean (*Glycine max*) (also a legume)	No soil data given	No rainfall or irrigation data given	Weed control	YES	<u>Soybean yield</u> IC: 1882 kg ha^{-1} SC: 985 kg ha^{-1} ($p < 0.05$) <u>Weed biomass</u> IC: 5.3 g m^{-2} SC: 231.5 g m^{-2} ($p < 0.05$)
Cadoux et al., 2015	France	Faba bean (*Vicia faba*) Lentil (*Lens culinaris*) Grass pea (*Lathyrus sativus*) Fenugreek (*Trigonella foenum-graecum*) Purple vetch (*Vicia benghalensis*) Common vetch (*Vicia sativa*) Berseem clover	Canola (*Brassica napus*)	Site 1: clay-limestone Site 2: sandy loam Site 3: clay-limestone Site 4: clay loam	Rain fed; annual rainfall: 2010-11 site 1:489mm site 2: 489mm 2011-12 site 1: 679mm site 2: 679mm site 3: 753mm site 4: 630 mm 2012-13 site 1: 769mm site 2: 769mm site 3: 1215 mm site 4:674mm	Weed and nitrogen dynamics	Species dependent	<u>Canola grain yield (kg ha^{-1})</u> Faba-/lentil-canola > SC canola ($p < 0.05$) pea/fenugreek/ lentil-canola vetch/ vetch/ clover-canola not sig diff to SC canola ($p > 0.05$)

Table 2 (*continued*)

Source	Country	Legume component/s	Oilseed component/s	Soil properties	Cropping system conditions	Focus	Intercrop benefit*	Key success metric**
		(*Trifolium alexandrinum*)			2013-14 site 1: 652 mm site 2: 652 mm site 3: 972 mm site 4: 660 mm			
Lorin et al., 2015	France	Fenugreek (*Trigonella foenum-graecum*) Faba bean (*Vicia faba*) Grass pea (*Lathyrus sativus*) Field pea (*Pisum sativum*) Common vetch (*Vicia sativa*) Beerseem clover (*Trifolium alexandrinum*)	Canola (*Brassica napus*)	Silty clay	Rain fed; in-season rainfall: 2012-13: 154mm 2013-14: 164mm Additional irrigation 2012: 50 mm/ha 2013: 20 mm/ha	Nitrogen dynamics and weed control	N level and legume species dependent	Low N: Weed biomass sig reduced in all intercrops compared to SC canola ($p < 0.05$) High N: Weed biomass not sig different to SC canola ($p > 0.05$)
Lorin et al., 2016	France	Fenugreek (*Trigonella foenum-graecum*) Faba bean (*Vicia faba*) Grass pea (*Lathyrus sativus*) Field pea (*Pisum sativum*) Common vetch (*Vicia sativa*) Beerseem clover (*Trifolium alexandrinum*)	Canola (*Brassica napus*)	Silty clay	Rain fed; in-season rainfall: 2012-13: 154mm 2013-14: 164mm additional irrigation: 2012: 50 mm/ha 2013: 20 mm/ha	Nitrogen dynamics	YES	IC resulted in sig increased in canola N accumulation compared with SC canola ($p < 0.05$)
Kandel et al., 1997	USA	Black lentil (*Lens culinaris* Medik.) Hairy vetch (*Vicia villosa*) Alfalfa (*Medicago sativa*) Yellow flowered sweet clover (*Melilotus officinalis*) Snail medic (*Medicago scutellata*)	Sunflower (*Helianthus annuus*)	Site 1 - coarse loam Site 2 - silty-clay loam	Rain fed; in-season rainfall (June-Sept): Site 1 1992: 162 mm Site 2 1992: 369mm Site 1 1993: 492 mm Site 2 1993: 401mm Site 2 1994: 366mm	Agronomic	NO	Simultaneous sowing: sun-vetch, sun-clover, sun-alfalfa, and sun-medic sig less yield (kg ha^{-1}) than SC sun ($p < 0.05$) 29-day legume sowing delay: no sig difference in SC and IC sun yield 46-day sowing delay: no sig difference in SC and IC sun yield
Chalmers, 2014b	Canada	Hairy vetch (*Vicia villosa*)	Sunflower (*Helianthus annuus*)	Sandy loam, pH 9.7	Rain fed; no rainfall data given	Agronomic	NO (grain yield) YES (weed suppression)	Sunflower grain yield (kg ha^{-1}) SC: 2234 kg ha^{-1} IC: 1743 kg ha^{-1} ($p > 0.05$)
Sánchez Vallduví and Sarandón, 2011	Argentina	Red clover (*Trifolium pratense*)	Flax (*Linum usitatissimum*)	Typical Argidol, pH 5.6	Rain fed; in-season rainfall: 2002: 421mm 2003: 452 mm	Agronomic and weed suppression	NO	Seed yield (g m^{-2}) 2002 SC: 150 g m^{-2} IC: 142 g m^{-2} ($p > 0.05$) 2003 SC: 132 g m^{-2} IC: 141 g m^{-2} ($p > 0.05$)

$^{\Psi}$LER$_{alt}$ – LER of intercrop sown in alternate rows; LER$_{mix}$ – LER of intercrop sown in mixed rows

Additional non-oilseed crops used in study: [a]barley (*Hordeum vulgare*), [b]maize (*Zea mays*), [c]wheat (*Triticum aestivum*), [d]oats (*Avena sativa*), [e]potato (*Solanum tuberosum*), [f]rye (*Secale cereale*), [g]phacelia (*Phacelia tanacetifolia*), [h]field mustard (*Brassica campestris)*.

* This section indicates whether the study found an intercrop advantage compared with the respective sole crops. This includes benefits in terms of yield, nutrient-use efficiency, pest and disease reduction, structural integrity, and/or profit.

** The Land Equivalent Ratio, or LER, is a common metric for measuring the yield efficiency of an intercrop. It measures the relative land area a crop requires as a monoculture to produce the same yield it achieves in an intercrop. An LER greater than one (>1) indicates a yield efficiency advantage of the intercrop.

competition for water and nutrients by weeds, and also indirectly, as individuals perceive and react to changes in their surrounding biotic and abiotic environments that may signal the presence of neighbouring plants (Aphalo and Ballare, 1995). The way that a plant responds to such signals will affect its capacity to capture resources, ultimately determining its competitive ability (Aphalo and Ballare, 1995). In the context of legume-oilseed intercrops, interspecific competition for nitrogen can stimulate nitrogen fixation by the legume component, increasing the

overall nitrogen efficiency of the system (section iii). Competition, therefore, when managed, can be manipulated to produce a positive outcome, or at least mitigate the negative effects.

Facilitation occurs when one species enhances the growth, survival, and/or fitness of another species in a stand (Callaway, 1995; Skelton and Barrett, 2005; Fletcher et al., 2016). In line with the stress gradient hypothesis (Bertness and Callaway, 1994; Betencourt et al., 2012), the strength and importance of facilitative interactions increases with increasing environmental stress (Brooker et al., 2005; Betencourt et al., 2012). Facilitation can be direct, wherein one species (facilitator/donor) alters the environment to the advantage of the other species (facilitated/benefactor). Indirect facilitation involves benefits associated with changes to the soil mycorrhizal or microbial communities brought about by the facilitator species (Hinsinger et al., 2011; Betencourt et al., 2012; Montesinos-Navarro et al., 2017; Ryan and Graham, 2018). Facilitation can be asymmetric, whereby the presence of one species benefits another, or symmetric, where there is a mutualistic benefit for both species (Ehrmann and Ritz, 2014).

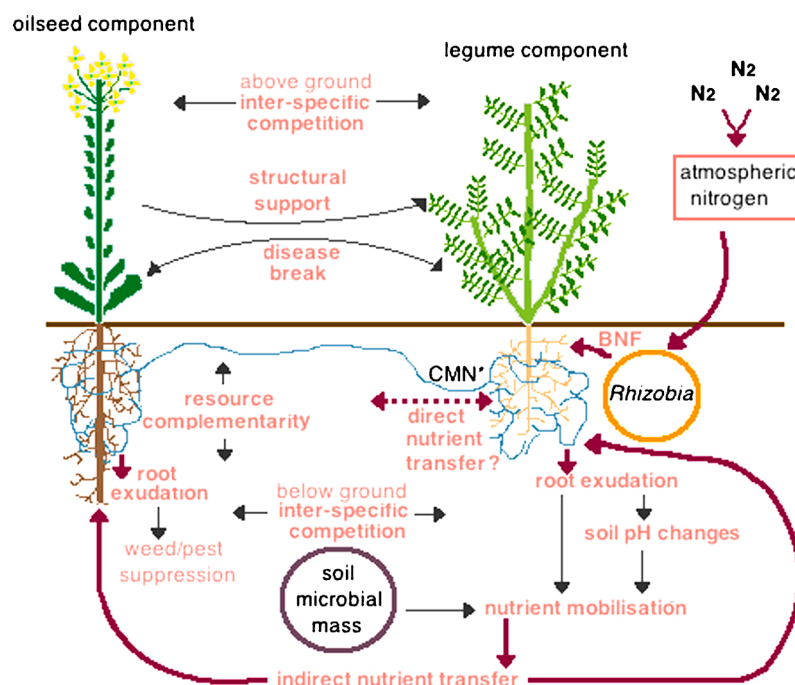## 2.2. LEGUME-OILSEED INTERCROPS: ECOLOGICAL THEORY IN ACTION

Intercrop mixtures often contain components from different functional groups (Skelton and Barrett, 2005; Szumigalski and Van Acker, 2006; Andersen et al., 2007; Li et al., 2016), including legumes and oilseeds (Indian Head Agricultural Research Farm IHARF, 2015; South East Research Farm SERF, 2015). Legumes and oilseeds are grown primarily as sole cash crops or sole break crops in cereal-dominated systems (Krupinsky et al., 2002; Drew et al., 2007; Gan et al., 2011; Angus et al., 2015; Klimek-Kopyra et al., 2015; Maaz et al., 2018). However, increasingly, legumes and oilseeds are being grown together as co-occurring intercrop components (SERF, 2015; Fletcher et al., 2016). Legume-oilseed mixtures have increased yields (Sarkar and Shit, 1993; IHARF, 2015; South East Research Farm SERF, 2017; WADO, 2018a, 2018b, 2018c), and reduced nitrogen fertiliser requirements (Indian Head Agricultural Research Farm IHARF, 2013; IHARF, 2015) compared with their sole crop counterparts. Further, the benefits provided by

legumes and oilseeds grown separately as break crops, such as disruption of host-specific pest and disease cycles (Krupinsky et al., 2002), facilitation of increased nutrient and water use efficiency (Miller et al., 2003; Kirkegaard et al., 2008; Gan et al., 2011), and an improvement in soil nutrient availability (Biederbeck et al., 2005; Gan et al. 2009), are preserved when they are intercropped (IHARF, 2015; SERF, 2015; WARC, 2016). Key to the efficacy of the legume-oilseed mixture is both the legume's ability to fix atmospheric nitrogen (N$_2$) (Gan et al., 2010; IHARF, 2013; WADO, 2018c), and the differences in growth patterns and phenology between many legume and oilseed species (Sarkar and Shit, 1993; Andersen et al., 2004; Gan et al., 2010). This diversity of function allows legume-oilseed mixtures to exploit both the complementary and facilitative benefits associated with increased species diversity, as well as exploit interspecific competitive interactions (Fig. 1).

2.2.1. Crop components

2.2.1.1. Oilseeds. Popular oilseed species in legume-oilseed mixtures include flax (*Linum usitatissimum*), hemp (*Cannabis sativa*), canola (*Brassica napus*), mustard (*Brassica juncea, Brassica campestris*) and sunflower (*Helianthus annuus*); all have been successfully cropped with legumes (IHARF, 2013, IHARF, 2015; De la Fuente et al., 2014; ICDC, 2017; SERF, 2017; Chalmers, 2017, WADO, 2018c).

2.2.1.2. Legumes. Legumes are often included in intercrops because of their ability to fix nitrogen (Wooley et al., 1991; Dilworth et al., 2008; Gan et al., 2010; Unkovich et al., 2010; Hinsinger et al., 2011; Fletcher et al., 2016), as well as mobilise nutrients bound in the soil through rhizosphere processes (Nuruzzaman et al., 2005; Hinsinger et al., 2011; Zhou et al., 2020). In combination, these factors can increase the bioavailability of nitrogen and phosphorus in the soil, benefiting both the legume and its companion plant. Popular legume species for legume-oilseed intercropping are chickpea (*Cicer arietinum*), field pea (*Pisum sativum*), soybean (*Glycine max*) (which is typically grown for oil production), and faba bean (*Vicia faba*). All have been successfully cropped with oilseeds in both research and commercial production

Fig. 1. Above- and below- ground interactions within a legume-oilseed intercrop. BNF; Biological Nitrogen Fixation, a process that arises from a symbiosis between legume roots and rhizobia that converts atmospheric N$_2$ to plant available NO$_3$- NH$_4^+$. CMN; common mycorrhizal network, a shared network of mycorrhizal hyphae that may carry nutrients from one plant to another. *indicates that only some oilseed species form mycorrhizal associations (i.e. not brassica species).

(Dedio, 1994; Echarte et al., 2011; Coll et al., 2012; IHARF, 2013; IHARF, 2015; Chalmers, 2017; ICDC, 2017; SERF, 2017; WADO, 2018a.

2.2.2. Complementarity in legume-oilseed intercrops

2.2.2.1. Temporal complementarity.
Crop demand for resources peaks during species-specific critical periods for grain set and size determination (Calviño and Monzon, 2009); in intercropping, species selection and sowing times can be manipulated so that the two crop components reach this critical period at different times. To achieve temporal complementarity, one species must be early maturing, and the other late maturing (e.g. sunflower and hairy vetch, respectively; Chalmers, 2014b). Temporal complementarity reduces competition between the two crop components during peak resource demand, such as seed set, creating differential resource niches within time. Further, harvesting the early-maturing crop before the canopy of the later-maturing component closes allows light and air through to the understorey, preventing crop diseases (e.g. Dedio, 1994). A number of legume-oilseed intercrop pairings have been shown to demonstrate temporal complementarity, including sunflower-garden pea (Dedio, 1994; Coll et al., 2012), sunflower-hairy vetch (Chalmers, 2014b); and soybean-canola (Dong et al., 2018). Given the potential productivity and efficiency benefits temporal complementarity may provide in legume-oilseed intercropping, more research is warranted to articulate the particular benefits of altering temporal resource niches in different crop (and cultivar) components, and how this may fit with practical management considerations, such as withholding periods and harvest sprays.

2.2.2.2. Root complementarity.
Root complementarity, wherein the root growth of the intercrop components varies in time or space, contributes to increased water and nutrient use efficiency of an intercrop (Coll et al., 2012; Smith and De Smet, 2012; Ehrmann and Ritz, 2014). Spatial variation in root morphology and placement allow exploration of a greater soil volume (Raghothama, 1999, Denton et al., 2006; Zarea et al., 2009), and a broader utilisation of soil resources. In legume-oilseed intercrops particularly, root complementarity is heavily dependent on species selection. For example, legumes and flax have a shallow, more fibrous root system and are considered shallow rooting crops (Gan et al., 2009), while oilseed brassica species, such as canola or mustard, are strongly tap-rooted, enabling them to uptake water and nutrients from deeper soil layers (Downey et al., 1974; Liu, 2009). In a lysimeter study on rooting depth, the legumes (chickpea, field pea, and lentil) and flax plants had only 3-7% of total root biomass beyond 60 cm, while canola and mustard had 11.2% and 9.2% of roots beyond 60 cm, respectively (Gan et al., 2009). In intercrops, therefore, the rooting depth of brassica oilseeds could be considered complementary to that of legumes (Cortés-Mora et al., 2010; Jamont et al., 2013), while the rooting depth of flax is perhaps too similar to make use of different resource pools. The rooting depth of legumes and sunflower also appears to be complementary. For example, compared with their respective sole crops, a soybean-sunflower intercrop had significantly increased water capture efficiency (Coll et al., 2012). It is likely that root complementarity contributed to the increased water capture efficiency of the intercrop, as soybean and sunflower have different rooting depths and are therefore able to access soil water from different depths; soybean has its maximum rooting density at 0.5 m deep (Kirkham et al., 1998), while sunflower maximum rooting density regularly occurs deeper than 1.0 m (Jaafar et al., 1993).

Temporal separation of roots is also possible, wherein differences in the growth rate of roots enables plants to access soil water and nutrients at different times (Ehrmann and Ritz, 2014; Hauggaard-Nielsen and Jensen, 2005). However, this has not yet been demonstrated in a legume-oilseed intercrop. In a study of root dynamics between oilseeds, legumes and cereals, Gan et al. (2009) report that the pattern of root biomass accumulation was similar in the legume and oilseed plants,

increasing rapidly from seedling to flowering, reaching a maximum at the late flowering to late podding stages, and then decreasing to maturity. This study suggests synchronicity in the growth of the oilseed and legume roots, however, these plants were grown as sole crops only. Given the nutrient efficiency and yield benefits attributed to root complementarity in cereal-legume intercrops (Martin and Snaydon, 1982; Jensen, 1996; Hauggaard-Nielsen and Jensen, 2005), more research is needed to understand the phenological and spatial patterns of root growth in intercropped oilseeds and legumes, as well as appropriate species selection to fully utilise niche complementarity.

2.2.3. Competition in legume-oilseed intercrops

Within an intercrop, one crop component (the dominant crop) often outcompetes the other (the subordinate crop) for resources (Echarte et al., 2011), potentially reducing the yield of the subordinate crop and compromising overall system productivity. For example, under water-constrained conditions, the yield of hemp intercropped with alfalfa, pea, and hairy vetch was reduced (WADO, 2018b). The root zones of these species are similar, and in each of the three species mixtures, the legume outcompeted the hemp for water, compromising intercropped hemp biomass compared with sole crop hemp. Similarly, pea and flax grown as sole crops out-yielded a flax-pea intercrop (Klimek-Kopyra et al., 2015); the authors cite reduced root diameter due to competition in the intercrop as a possible cause of reduced intercrop yield. It is possible, however, to mitigate the negative effects of interspecific intercrop competition through manipulation of competition dynamics. For example, in Saskatchewan, Canada, chickpea-flax intercrops have been grown in regions where chickpeas are usually unable to grow, with the flax effectively expanding the area suitable for chickpea. Flax and chickpea have a similar rooting depth, with the flax outcompeting the chickpea for soil water, reducing the amount of moisture and creating the drought-stress conditions that chickpeas require for maturity in areas that are usually too wet (IHARF, 2015).

2.2.3.1. Manipulation of interspecific competition – sowing time, crop density, and row configuration.
The importance of early growth in determining competition dynamics between species in an intercrop is well known (Tofinga et al., 1993). Intercrop interspecific competition can be manipulated by varying the sowing times of intercrop components (known as relay intercropping; Table 1), which increases the early vigour and competiveness of the first sown crop (Kandel et al., 1997; Echarte et al., 2011; Andrade et al., 2012). Kandel et al. (1997) were able to manipulate the yield of sunflower intercropped with a range of legumes (hairy vetch, sweet clover, alfalfa, snail medic, and black lentil) by delaying legume sowing time. When both crop components were sown simultaneously, all legume species except black lentil reduced sunflower yield compared with the sole crop sunflower. However, when legume sowing was delayed (sunflower stages V4 - fourth leaf emerged, and V10 - tenth leaf emerged) intercropping had no effect on sunflower yield (Kandel et al., 1997). Delayed sowing of the legume allowed the establishment of sunflower, increasing its competitive ability for when the legume was introduced. Similarly, in a sunflower-soybean intercrop, soybean sown 30 days after the sunflower increased sunflower yield (Andrade et al., 2012). However, the sowing delay affected the growth of the soybean component more significantly than that of the sunflower. This translated to increased LER in the no-delay compared with the delay treatment; the growth of the subordinate soybean, and not the dominant sunflower, was most important in determining LER (Andrade et al., 2012). This is in line with a maize-cowpea intercrop study, where LER was more closely associated with the growth of the cow pea, the subordinate crop (Ofori and Stern (1987),

Competition between intercrop components can be also manipulated by altering sowing density and row configuration. Increasing the density of one crop component tends to increase its competiveness, with a resultant decrease in the yield of the second species. This has been

demonstrated in a chickpea-flax intercrop, where increased chickpea density increased chickpea yield and reduced flax yield (WARC, 2016), and a sunflower-soybean (Echarte et al., 2011), where sunflower yield increased and soybean yield decreased as a result of increased sunflower sowing density. Interestingly, both WARC (2016) and Echarte et al. (2011) found LER greater than one for all intercrop treatments, regardless of sowing densities and competition effects. In Echarte et al. (2011), the size of the intercrop yield advantage, however, did depend on sowing density, specifically its effect on the competitiveness of the subordinate soybean relative to the dominant sunflower. As subordinate crop competitiveness increased (by increasing the ratio of subordinate to dominant crop), LER similarly increased (Echarte et al., 2011).

In a mixed row pea and canola (peaola) study with a canola sowing rate of 3 kg ha^{-1}, pea yield increased from 1610 kg ha^{-1} to 1890 kg ha^{-1} to 2080 kg ha^{-1} as the pea sowing rate increased from 50 to 75 to 100 kg ha^{-1} (Bennet, 2009); this was likely due to the increase in pea competiveness relative to the canola. Interestingly, with a canola sown at 1 kg ha^{-1}, the increase in pea sowing density did not translate to an increase in pea yield. Given the mixed row design of the experiment, this discrepancy in results could be due to differences in intraspecies competition between pea plants at different pea densities. While increased pea density increased competition between pea individuals, canola sown at 3 kg ha^{-1} may have been sufficient to dilute this intraspecies competition and elicit the complementary resource use benefits associated with inter-cropping; the 1 kg ha^{-1} canola density may not have been sufficient to invoke such a relationship. Indeed, in a sunflower-pea intercrop with 1:1 alternate row configuration, intercrop yield advantage increased as space between the sunflower and peas rows decreased (Dedio, 1994). Closer row spacing may increase positive interspecies interactions between the crop components, which in turn may reduce the negative effects of direct intraspecific competition between individuals of the same species. Pea and canola sown in a mixed row configuration (mixed seed and sown in the same row) had higher LER than pea and canola crop sown in a 1:1 alternate row design (one row pea to one row canola) (Malhi, 2012). The mixed row design may facilitate positive species interactions, and reduce negative competition and resource use more readily than the alternate row design. Mixed row intercropping tends to benefit the dominant crop, while alternate rows benefit the subordinate crop (Chalmers, 2014a). In a peaola intercrop, although combined total yield was not significantly different, the canola (dominant species) had a significantly higher yield in the mixed row treatment compared with the alternate row (1377 kg ha^{-1} and 925 kg ha^{-1}, respectively), while pea yield was significantly higher in the alternate row design compared with the mixed (3400 kg ha^{-1} vs 2820 kg ha^{-1}, respectively). Regardless of row design, intercropping had a higher yield efficiency compared with their respective sole crops; of the studies that reported LERs, all but one reported an average LER greater than one.

2.2.3.2. Interspecific competition and Biological Nitrogen Fixation (BNF).
A high concentration of soil inorganic nitrogen reduces BNF (Sprent and Minchin, 1985; Peoples et al., 1995; Génard et al., 2016). The inverse relationship between high soil nitrogen status and BNF has been demonstrated in a number of legume-Brassica studies; high-N input treatments had decreased BNF compared with low-N input treatments (Waterer et al., 1994; Andersen et al. 2004; Génard et al., 2016, 2017; Chalmers, 2017). Intercropping a legume with a non-leguminous crop, such as an oilseed, however, can help to stimulate BNF through interspecific competition for soil nitrogen (Chapagain and Riseman, 2014; Ehrmann and Ritz, 2014). In a pot study of three legumes (lupin, clover and vetch) intercropped with oilseed canola, the percentage of nitrogen derived from air (%Ndfa) in the legume was higher when intercropped than when grown as monocrops (+34%, +140%, and +290%, respectively) (Génard et al. 2017). The canola, which has a high N demand and is competitive against legumes (Liu, 2009), decreased the soil inorganic N concentration, stimulating BNF in the legume and increasing the

nitrogen use efficiency of the system.

In intercropping, increasing the available soil NO_3^- through promotion of legume BNF by interspecific competition is known as a *sparing effect*; the legume component is unable to outcompete the non-legume for soil nitrate, forcing it to rely largely on BNF, leaving a significant proportion of the soil N pool for the non-legume to use (Vandermeer, 1989; Anil et al., 1998; Przednowek, 2003). Greater concentrations of NO_3^- were observed in the soil of wheat or canola intercropped with field pea, as opposed to soil from the monocropped wheat and canola (Szumigalski and Van Acker, 2006). The authors suggest that the high N pools in the intercrops most likely developed due to the sparing effect and not the mineralization of pea residues and subsequent uptake by the non-legume components, given the relatively short length of the experiment (Szumigalski and Van Acker, 2006). Nitrate sparing as a result of interspecific competition has also been reported in many cereal-legume intercropping studies (Hauggaard-Nielsen et al., 2001; Corre-Hellou et al., 2006; Naudin et al., 2010; Ehrmann and Ritz, 2014; Bedoussac et al., 2015).

As well as affecting the nitrogen cycle directly, interspecific competition can indirectly affect BNF through competition for non-nitrogen resources, such as light, water, or other nutrients (Ehrmann and Ritz, 2014; Klimek-Kopyra et al., 2015). For example, in a flax-soybean intercrop the application of urea encouraged flax plant vigour to such an extent that it outcompeted the soybean for moisture, stunting its growth and compromising nodulation and BNF (WADO, 2018a).

To achieve a high intercrop nutrient efficiency, wherein the intercrop components collectively utilise the available soil nutrients more effectively than if planted as sole crops (Francis, 1989), plant interspecific competition must reach an equilibrium; the oilseed must be able to compete with the legume to induce and sustain a high rate of BNF, but not to such a degree that it dominates the legume and reduces its ability to form and sustain BNF (Stern, 1993). This was demonstrated in a dual and three- component intercrop study of canola, barley, and pea (Andersen et al. 2004). In the study, the rate of BNF in the pea was higher in the pea-canola intercrop compared with the pea-barley inter-crop. The authors suggest that this was due to the higher competitive ability of barley to capture available soil nitrogen compared with canola (Andersen et al., 2004).

In legume-oilseed intercrops, increased BNF under low soil N might contribute to increased yield. A number of legume-oilseed intercrops, utilising a range of species parings, report higher LER under low-N input (Banik et al., 2000; Andersen et al., 2004; Szumigalski and Van Acker, 2006; IHARF, 2013; VanKoughnet, 2016). It is possible that the inverse relationship between soil N status and BNF is driving, to some degree, this intercrop yield advantage.

2.2.4. Facilitation in legume-oilseed intercrops

2.2.4.1. Root exudation. The root exudates of many legume species mobilise soil nutrients, such as phosphorus, facilitating increased nutrient bioavailability (Nuruzzaman et al., 2005; Fletcher et al., 2016). Legume intercropping increases phosphorus bioavailability in the top 20 cm of soil and encourages its efficient cycling within the system (Costa et al., 2014; Nie et al., 2016). For example, Li et al. (2003) found that chickpea mobilized soil organic P and left more inorganic P available for the intercropped wheat. Plant roots excrete phosphatase enzymes and phosphorus mobilising carboxylates such as malate and citrate. In the soil, these root exudates hydrolyse organic and inorganic phosphorus, making it available for plant uptake from the rhizosphere (Hamel, 2004; Denton et al., 2006; Hauggaard-Nielsen et al., 2009a, 2009; Hinsinger et al., 2011). Both legumes and oilseeds release phosphatases and carboxylates (Denton et al., 2006; Hinsinger et al., 2011; Fletcher et al., 2016). Additionally, BNF releases protons into the soil via plant roots and lowers soil pH, facilitating the mobilisation of nutrients, including

P, K, and Mg (Hinsinger et al., 2003; Hamel, 2004; Hauggaard-Nielsen and Jensen, 2005; Li et al., 2007; Ehrmann and Ritz, 2014). Soil nutrient mobilisation as a result of root exudation has been demonstrated in a number of cereal-legume intercrops, as have the yield and nutrient-benefits associated with these processes. However, data are lacking on the effects of rhizosphere processes that could be modified through management to provide potential benefits to legume-oilseed intercrop productivity.

2.2.4.2. Nitrogen transfer in an intercrop – direct and indirect pathways
2.2.4.2.1. Indirect nutrient transfer. The indirect transfer of fixed N from the legume to the non-legume via the soil has been demonstrated in both legume-oilseed and cereal-legume intercrops. Part of the nitrogen fixed by the legume is deposited into the soil where it can be absorbed by the roots of the non-fixing component (Jensen, 1996; Fustec et al., 2010; Chalk et al., 2014; Lorin et al., 2016; Génard et al., 2016, 2017). In a study on forage legumes (lupin, clover and vetch) intercropped with oilseed canola, Génard et al. (2017) reported that total soil N in the canola-lupin and canola-clover after three months of growth was 50% higher than in the monocrop control treatments, and 25% higher than in the canola-vetch intercrop. These results indicate the potential rhizo-deposition of fixed-N_2 by the lupin and clover for subsequent uptake by the canola. Given the early growth stage of the plants (3 months) it is possible that the canola would use the N deposited by the legumes in later growth stages, from bolting onwards (Génard et al., 2017). Canola undersown with a legume 'living mulch' resulted in increased N uptake by the canola compared with the sole canola, especially under low soil N, while canola undersown with a lentil-faba bean mixture accumulated significantly more N than sole canola (68 kg N ha^{-1} and 52 kg N ha^{-1}, respectively) (Lorin et al., 2016). In a legume-oilseed intercrop, up to 10% of early nitrogen accumulation of the oilseed component can come directly from the legume (Cortés-Mora et al., 2010).

2.2.4.2.2. Direct nutrient transfer. Facilitation has been reported in legume-cereal intercrops through direct plant-to-plant nutrient transfer (Jahansooz et al., 2007; Chalk et al., 2014; Fletcher et al., 2016; Nie et al., 2016), but has been less often reported for legume-oilseed intercrops (Génard et al., 2016). However, this lack of reporting likely reflects the relative novelty of legume-oilseed mixtures, and not the absence of direct transfer; clearly further research is needed to investigate the issue and the extent of direct nutrient transfer. In legume-cereal intercrops, arbuscular mycorrhizal fungi (AMF) facilitate direct transfer of nutrients by forming interlinked networks within the shared rhizosphere (Hamel et al., 1992; Stern, 1993; Hauggaard-Nielsen and Jensen, 2005; Nie et al., 2016). Using the common mycorrhizal network (CMN; Simard et al., 2012) nutrients can flow from the nutrient-rich to the nutrient-poor plant along a source-sink gradient, a phenomenon that has been demonstrated between a number of plant species in glasshouse experiments (Bethlenfalvay et al., 1991; Eason et al., 1991), in the field (Hamel et al., 1992) and in natural vegetation communities (Simard et al., 2012; Montesinos-Navarro et al., 2017). Except for Brassicaceae oilseeds, which are never mycorrhizal, this fungi-facilitated direct transfer can similarly be expected in legume-oilseed intercrops (Hancock et al., 2012; Génard et al., 2016). Flow direction is dependent on many factors, such as the nutrient content of the donor and receiver plants wherein the strength of the sink appears to be more influential than the strength of the source (Simard et al., 2012). In legume-cereal intercrops, nitrogen transfer is expected to follow a unidirectional facilitative pathway from the legume to the non-legume (He et al., 2009; Hinsinger et al., 2011; Chalk et al., 2014), as legume N concentrations are usually higher than those of non-legumes, particularly under low soil-N conditions (Hamel et al., 1992). The amount of N transferred varies significantly. Chapagain and Riseman (2014) report that between 5 and 20% of total N in receiver plants is directly transferred (Johansen and Jensen, 1996; He et al., 2003, 2009), while Rasmussen et al. (2007) and Montesinos-Navarro et al. (2017) report transfers of 30-40%. Direct

interplant transfer of phosphorus via CMNs has also been demonstrated (Bethlenfalvay et al., 1991; Eason et al., 1991; Simard et al., 2012; Montesinos-Navarro et al., 2017). In a pot study the transfer of nutrients such as phosphorus can be significant and bi-directional, as opposed to the mostly one-way flow of nitrogen from the legume (Bethlenfalvay et al. 1991). However, more research is needed to understand the mechanisms involved in direct nutrient transfer, and the relative importance of this facilitative interaction to the overall nutrient acquisition of legume-oilseed intercrops (Nie et al., 2016), particularly in field conditions.

2.3. AGRONOMIC AND LOGISTICAL POTENTIAL OF LEGUME-OILSEED INTERCROPPING IN BROADACRE AGRICULTURE

The literature reviewed in this paper largely report the benefits of legume-oilseed intercropping, which is at odds with the relative scarcity of legume-oilseed intercrops in real-world mechanised farming systems. Fletcher et al. (2016) describe a framework for categorising the success of an intercropping system based on the resource use and farming system benefits that it provides. Wide scale adoption of an intercrop system requires a strong basis in both dimensions (Fletcher et al., 2016). While recent evidence supports the ecological merits of legume-oilseed intercrops, the practicalities and logistics of their implementation have been investigated to a lesser extent. Legume-oilseed intercrops have a strong basis in Fletcher et al.'s (2016) resource use dimension, but consideration of the farm system dimension has been lacking in the literature. Here we attempt to evaluate the potential of legume-oilseed intercrops in mechanised, broadacre agriculture.

2.3.1. System benefits
A number of studies report LER > 1 for legume-oilseed intercrops, which has indicated their potential value in agricultural systems (Table 2). Further, improved ease of grain legume harvest is a significant benefit derived from legume-oilseed intercropping (Fernandez et al., 2014). Intercropping with an oilseed can provide structural support, reduce lodging, and increase plant height in legumes compared with sole crops (Agnew, 2018). This has been demonstrated in peaola intercrops, where pea height and stability were encouraged by climbing on the canola plants (Bennet, 2009; IHARF, 2013; VanKoughnet, 2015). Soetedjo et al., 1998 and SERF, 2015 report significantly (p < 0.05) reduced lodging scores (lodging severity (angle from vertical) and the proportion of crop affected) in peas intercropped with canola compared with sole pea crops. Peaola has also been shown to decrease canola shattering compared with a sole canola crop (IHARF, 2013; VanKoughnet, 2015). Reduced shattering of canola, as well as increased height and lodging resistance in the legume component, makes harvesting the intercrop easier, increasing yield relative to sole crops on a per unit area basis (Fernandez et al., 2014).

2.3.2. Weed, pest, and disease dynamics
Weeds compete with crop plants for resources, reducing crop yield and quality (Bajwa et al., 2014; Shah et al., 2016). In intercropping, due to the mixing of crops from different functional groups, the use of herbicides can be an issue. However, recent developments in variety characteristics and herbicide technologies, such as ethyl methanesulfonate mutation to create herbicide tolerance in both legumes and canola, mean that broadleaf herbicide management for legume-oilseed intercrops is increasingly easier to manage than it has been in the past. Bennet (2009) reports that Terbyne, a group C herbicide (inhibition of photosynthesis at photosystem II) used for peas, can be used in concert with triazine tolerant (TT) canola cultivars. Further, the use of cv Clearfield canola with peas allows the use of some group B herbicides (active ingredient imidazolinone). Group B herbicide (inhibition of acetolactate synthase ALS) tolerant lentil and faba bean varieties can also be grown with Clearfield® canola or sunflower. Clearfield® sunflower and soybean can be planted in an intercrop to control a large

number of cereal and broad leaf weeds. Group A herbicides (Inhibition of acetyl CoA carboxylate) can be used for grass weed control.

Legume-oilseed intercrops can themselves facilitate significant weed suppression. Due to the complementary use of resources between the intercrop components, legume-oilseed mixtures can more readily utilise available resources, such as light (Lorin et al., 2015), space (Ilnicki and Enache, 1992; Paulsen et al. 2006; Cadoux et al., 2015) and nitrogen (Sánchez Vallduví and Sarandón, 2011) compared with sole crops. Increased use of resources by the crop components reduces availability, suppresses weed growth and vigour, and reduces weed biomass (Ilnicki and Enache, 1992), abundance (Lorin et al., 2015), and reproductive vigour (Sánchez Vallduví and Sarandón, 2011), compared with weeds growing in monocultures.

The interaction between nitrogen fertilisation and intercropping affects weed abundance in legume-oilseed intercrops (Cadoux et al., 2015). At low rates of fertiliser N, the suppressive effect of intercropping on weed biomass is magnified (Cadoux et al., 2015; Lorin et al., 2015), suggesting a facilitative relationship between crop components at low levels of N fertilisation. Weed growth is hampered by the increased competition for soil N, and in this scenario the weeds cannot outcompete either crop component, resulting in reduced weed abundance.

Legume-oilseed intercropping has also been found to reduce the incidence of disease in comparison with sole crops, minimising the need for pesticides. Less disease was identified at harvest in plants from a peaola intercrop compared with a sole crop of peas or canola Van-Koughnet (2015). Multiple studies from the Westman Agricultural Diversification Organization (Chalmers, 2017; WADO, 2018c) report that a peaola intercrop had reduced incidence of pea aphid (*Acyrthosiphon pisum*) infestation and infection from *Mycosphaerella* fungi compared with monocropped peas. Reduced infection rate of aphids in the intercrop was attributed to difficulties accessing the peas, whereby the canola formed a physical barrier (Chalmers, 2017). Fernández-Aparicio et al. (2010) suggested that the intercropping of immune non-host species with host plants reduces host plant density, making it harder for pathogen populations to grow and spread. Research also suggests that reduced fungal infection in the peaola intercrop could be due to an allelopathic deterrent posed by the presence of canola (Chalmers, 2017). Indeed, many oilseed species, such as sesame (Premasthira et al., 1999), sunflower (Tongma et al., 2001; Bogatek et al., 2006; Bashir et al., 2012), and mustard (Motisi et al., 2009), have demonstrated allelopathic properties, supressing the growth of soil-borne pathogens and pests, such as nematodes, fungi and some weeds (Shah et al., 2016).

Brassica species release compounds toxic for fungi and bacteria (Brader et al., 2006, Van Dam et al., 2009; Couëdel et al., 2019), which are a product of the hydrolysis of glucosinolates (GSLs), (Gimsing and Kirkegaard, 2009; Kissen et al., 2009). The enzyme myrosinase facilitates the hydrolysis of GSLs. Within the plant, the degradation of GSLs occurs in the plant cell vacuole upon damage to the tissue, which causes the usually separate compounds to mix and react (Brown and Morra, 1996; Gimsing and Kirkegaard, 2009; Kissen et al., 2009). Externally, intact GSLs are released from the plant root into the rhizosphere where they may be hydrolysed by microbial myrosinases, releasing the compound into the soil (Gimsing and Kirkegaard, 2009). While the use of brassica species as allelopathic break crops has been successfully demonstrated (Couëdel et al., 2019), their root exudates may have a negative effect on beneficial microbe and insect communities (Omirou et al., 2011). Trenbath (1993) and Boudreau (2013) suggest sowing brassica species in brassica-legume intercrops may negate the negative effect of beneficial microfauna. Legume-brassica intercrops have outperformed brassica sole crops in multiple measures, including allelopathic effectiveness and reduced incidence of pests and disease (Fletcher et al., 2016; Couëdel et al., 2018, 2019). Couëdel et al. (2018) report brassica species produced more GSL per plant in a mixture with a legume component (sown at half the sole crop density) compared with the corresponding brassica sole crop. The pest suppressive capacity of the sole crop was largely retained in the legume-brassica mixture.

The allelopathic and/or physical barrier characteristics reported in legume-oilseed intercrops do not always significantly reduce the incidence of pests compared with monocrops (IHARF, 2013). Similarly, intercropping does not always facilitate weed suppression compared with monocropping, and sometimes a neutral effect is observed, wherein weed biomass is similar in both crop arrangements (Sánchez Vallduví and Sarandón, 2011; de la Fuente et al., 2014). One hypothesised outcome of intercropping is that it will reduce overall weed biomass, but increase weed species richness (Sánchez Vallduví and Sarandón, 2011), as the presence of a second species should create more niches for a greater variety of species without increasing the number of weeds overall. However, this has not yet been demonstrated in legume-oilseed intercropping, with species richness instead being comparable between sole and intercrops (Sánchez Vallduví and Sarandón, 2011). Given the variability of the intercropping effect on the incidence of weeds and pests, more research is warranted on the suppressive characteristics of mixtures, and their interaction with biotic and abiotic environmental factors that potentially impact their strength and effectiveness.

2.3.3. Nutrient management

Reduced rates of N fertiliser not only reduce weed infestation (as above) but also increase nutrient use efficiency and/or yield in legume-oilseed intercrops (Waterer et al., 1994; Andersen et al., 2004; Lorin et al., 2015; VanKoughnet, 2016; Chalmers 2017). In a peaola intercrop, for example, increasing N rate correlated with a decline in LER (LER of 1.16, 1.12, and 1.09 for 0, 30, and 60 kg N ha^{-1}, respectively) (Van-Koughnet, 2016). This finding is supported by Andersen et al. (2004), who found that a peaola intercrop yielded more under low nitrogen conditions (5 kg N ha^{-1}) compared with high nitrogen conditions (40 kg N ha^{-1}), with LERs of 1.32 and 1.16, respectively.

Altering N nutrition also alters the proportion of crop components in the intercrop. Generally, the proportion of yield made up by the oilseed increases with N supply at the expense of legume yield. For example, under low N conditions, intercropped pea yielded more than the mustard component (1.78 t ha^{-1} and 1.5 t ha^{-1}, respectively) (Wendling et al., 2017) while under high N the mustard yielded more than the pea (2.6 t ha^{-1} and 0.73 t ha^{-1}). In legume-oilseed intercrops the oilseed component is often more vigorous, and outcompetes the legume for resources such as nitrogen (Andersen et al., 2004; VanKoughnet, 2016). However, reduced N availability coupled with the superior competiveness of the oilseed stimulates BNF in the legume, benefiting the legume component. As such, under low N the differences in grain and biomass production between the legume and oilseed components are typically small, and increase with application of N. For example, with no additional N fertiliser (0 N), the difference in grain yield between intercropped pea and canola was 121 kg ha^{-1} (pea yielding slightly more) (VanKoughnet, 2016). However, as the amount of applied N was increased to 33.63 kg N ha^{-1} and to 67.25 kg N ha^{-1}, so too did the differences between intercrop component yield (780 and 1331.57 kg ha^{-1}, respectively, with canola yielding more than pea in both cases). The addition of N fertiliser inhibits BNF in the legume, increasing competition between the crop components (Lorin et al., 2015), with the oilseed, as the stronger competitor, assimilating the majority of the available nitrogen, resulting in increased oilseed growth, and a reduction in legume yield. In this way, N fertilisation can be used to manipulate crop component yield proportion to suit the market.

2.3.4. Economic analysis

The management and processing of two crops should increase costs for the additional machinery, labour, and time needed. Roberts et al. (2019) report that seed cleaning using an external provider reduced peaola and lentil-canola gross margins by AUD$60 ha^{-1} in 2016 and AUD $30 ha^{-1} in 2017. Similarly, Chalmers (2014a) and WADO (2018c) identified the need for an extra auger, an extra rotary cleaner during seed processing, and extra labour increased costs of a peaola intercrop

accounted for CAD$2.50 ha^{-1}, CAD$2.50 ha^{-1}, and CAD$2/trial, respectively. However, for all these trials, the extra costs of intercropping were offset by the combination of intercrop overyielding, the high market prices of oilseed grains and a reduced requirement for fertiliser.

A number of studies have observed that income generated by legume-oilseed intercrops is higher than that of the respective sole crops (Bennet, 2009; SERF, 2015; VanKoughnet, 2015, 2016; Roberts et al., 2019). For example, Bennet (2009) reports that, compared with canola and pea monocrops, the peaola intercrop returned the highest gross margin. Legume-oilseed intercrops require less pest suppression and fertiliser inputs, potentially reducing crop management costs. Compared with a peaola intercrop treated with fungicide, peaola without fungicide yielded a higher net return (-CAD$93 ha^{-1} and CAD$37 ha^{-1}, respectively) (WADO, 2018c). In a nitrogen fertility study, VanKoughnet (2016) reports the highest economic return for the peaola in the unfertilised treatment compared with fertilised peaola and non-fertilised sole crops. VanKoughnet (2015) consistently found the greatest economic return under low N conditions compared with peaola under mid-and-high N conditions, as well as pea and canola monocrop under low N conditions. Furthermore, legume-oilseed intercrops combine the increased N accumulation of legumes with the higher market price of oilseeds (Bennet, 2009; Fernandez et al., 2014; SERF, 2015; VanKoughnet, 2015, 2016, Roberts et al., 2019). In an on-farm study, the peaola intercrop returned a gross profit of AUD$544 ha^{-1} (sowing rate of 75 kg pea +2 kg canola ha^{-1}), while the pea grown alone returned a gross profit of AUD$399 ha^{-1} (sowing rate of 75 kg ha^{-1}) (Bennet, 2009). This increase in return is partially due to higher pea yield in the intercrop compared with the sole crop (2.17 ha^{-1} and 2.03 t ha^{-1}, respectively), as well as the higher market price of canola. In the peaola intercrop, the 0.33 t ha^{-1} yield of canola earned an extra AUD$125 ha^{-1}, and an extra AUD$28 ha^{-1} by the pea overyielding (Bennet, 2009).

Contrary to the studies reviewed above, not all legume-oilseed trials have returned a significant profit. Nybo and Sluth (2015) found that compared with their respective sole crops, a peaola intercrop grossed less (CAD$550 ha^{-1}, CAD$690 ha^{-1}, and CAD$600 ha^{-1} for peaola, sole crop canola, and sole crop pea, respectively). The low profitability of the intercrop with regards to the sole crops correlates with its reduced yield; sole crop canola and pea yielded 1800 kg ha^{-1} and 2400 kg ha^{-1}, while peaola produced 1400 kg ha^{-1} of grain. Aside from an economically successful lentil-radish intercrop, the income earned by other legume-oilseed pairings (Table 2) was variable, and often less than the profit produced by the respective sole crop (Fernandez et al. 2014). The findings of Fernandez et al. (2014) and Nybo and Sluth (2015) highlight the potential yield variability, and thus economic variability, associated with intercrops compared with sole crops.

2.3.5. Increased complexity as a barrier to adoption

Compared with monocultures, increased complexity in the design, sowing, management, harvest, and processing of an intercrop is unavoidable. The addition of a second species requires greater effort and time and may pose an insurmountable barrier to adoption. The ease and convenience of a new farming practice is a key determinant in the speed and extent of its adoption (Kuehne et al., 2017). Practices that will add inconvenience once they are implemented, regardless of the environmental and/or economic benefit they might provide, will limit both the rate and total adoption (Carpenter and Gianessi, 2000). The added inconvenience of intercrops, brought about by their increased complexity, has so far been a major barrier to their adoption in large scale, mechanised broadacre systems, that are geared toward efficiency and streamlining of processes.

Current logistical challenges may be overcome by improvements in farm machinery. For example, conventional seeders can be temporarily modified to allow seeding of two different species at once. In Canada, hundreds of hectares of a flax-chickpea mixed row intercrop have been successfully seeded in one pass by running the chickpea seed through the sideband instead of fertiliser, and seeding the flax normally (SERF,

2015). Similarly, VanKoughnet (2015) seeded peaola by metering the canola and pea seed through different cones that were funnelled to the same seeding boot. More permanent alteration to traditional seeders can be made by adding a cone, which allows the sowing of alternate rows of different species such as chickpea and flax (Roberts et al., 2019). Existing seed cleaning machines can be used to separate intercrop yields successfully using the typical differences between seed characteristics (Agnew, 2018). Up to 79,000 kg of seed can sorted per hour using an aspirator, with gravity tables, rotary seed cleaners, and flat sieve/screens cleaning similar amounts (Agnew, 2018). These examples highlight the potential role of machinery adaptations to allow increased adoption of intercropping.

2.4. DIRECTIONS FOR FUTURE RESEARCH

This review has revealed the need for more research to broaden both our agronomic and ecological understanding of legume-oilseed intercropping. By understanding the ecological mechanisms at play, we will be able to make more informed agronomic decisions. However, at the same time, trials investigating on-farm issues such as intercrop design, fertiliser regimes, weed management, species selection, and intercrop processing and infrastructure are necessary to understand the best options for species mixtures and to highlight the benefits and costs associated with intercropping. In light of this dual research pathway, this review highlights five areas worthy of ongoing research.

2.4.1. Species selection

This includes not only yield data but also investigations into root dynamics, such as spatial niche complementarity, as well as above ground intercrop component interactions, such as climbing and/or shading impacts. Understanding how crop species grow and interact is important to develop intercropping systems that can fully utilize the advantages of species diversity (Connolly et al., 2001; Andersen et al., 2007). Given previously demonstrated yield advantages in mechanised agriculture in a range of environments, particular interest should be paid to canola-field pea (Andersen et al., 2004; IHARF, 2013; Roberts et al., 2019), and sunflower-soybean mixtures (Dedio, 1994; Echarte et al., 2011; Andrade et al., 2012; Coll et al., 2012). Farmer preference and grain prices should also inform research on potential species mixtures.

2.4.2. Farming considerations

The chance of a new farming practice being widely adopted is maximised if the practice is workable under variable conditions (Toffolini et al., 2017; Verret et al., 2020). More effort is needed to integrate scientific research on legume-oilseed intercropping with on-farm innovations in areas such as seed cleaning and nutrient management. Further, more research is needed to investigate the tolerance of legume-oilseed intercrops to abiotic stressors (extreme temperature, drought), and which types of intercropping and species mixtures are suitable to different environmental conditions. For example, the winter oilseed canola-living legume mulch intercrop is suitable for the winter conditions of France (Cadoux et al., 2015), where the frost kills the frost-sensitive legume component, but perhaps not the milder winter conditions such as in the southern cropping region of Australia.

2.4.3. Intercrop design

The use of mixed rows (broadcast sowing) or alternate rows of different crop species can alter intercrop responses in terms of yield and nutrient-use efficiency. This review has also explored the option of legume 'living mulches' in oilseed cash crop stands, as well as 'strip intercropping' and 'relay intercropping', all options that are more compatible with current farm technologies and practices. Given the vast array of intercrop types and design with the 'legume-oilseed intercropping' umbrella, more research is required to investigate what type of intercropping is suitable under different environmental and farm conditions, as well as for different purposes.

2.4.4. Intercrop infrastructure

Although current farm technologies for sowing, harvesting, and processing intercrops do exist, more investment in developing purpose-built machinery is required. If legume-oilseed intercropping is to be a viable option in mechanised farming, purpose built machines are required to address many of the logistical issues that currently dissuade most producers from implementing the practice. We propose that this investment in intercropping-specific machinery is a worthy cause, given the multitude of benefits that legume-oilseed species mixtures have been shown to facilitate.

2.4.5. Weed management

Herbicide application in an intercrop presents a problem at two levels; i) crop species compatibility, and ii) legislative compatibility. Firstly, research is needed to investigate oilseed and legume species, and more specifically cultivars, that are tolerant of herbicide groups with the same modes of action. Given that oilseeds and legumes are both broad leaf crops this will be less difficult than in cereal-legume intercropping; however, dedicated research is still necessary. Secondly, herbicide labels dictate specific application instructions that differ among crops. Research is needed to understand not only species combinations that are physically compatible, but also legally, as dictated by the herbicide legislation and labelling.

While some technological issues may remain for the management, harvest, and processing of intercrops in broadacre mechanised agro-ecosystems, these have been demonstrated to be able to be resolved with modern solutions, and may not pose the constraints that were previously assigned. Through research directed towards the issues indicated above, it is expected that increased gains in productivity and resource use will provide the economic incentives for adoption of intercropping systems.

3. CONCLUSION

Issues such as weed management, herbicide incompatibilities, increased complexity of sowing and harvest have largely precluded the adoption of intercropping in large-scale, mechanised, cropping systems. Legume-oilseed intercropping, may provide an alternative to the more traditional cereal-legume mixtures and contribute to sustainable food supply. This review has highlighted yield, profit, and pest and disease management benefits of legume-oilseed intercrops with economic and environmental implications. We identified six areas that warrant further research from both ecological and agronomic viewpoints: species selection, environmental thresholds and constraints, optimal row configuration patterns, resource dynamics, growth dynamics, and options for weed control.

Declaration of Competing Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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