Legume-oilseed intercropping in mechanised broadacre agriculture in a Mediterranean climate

Alyce Hayes Dowling

A thesis by prior publication submitted to the University of Adelaide, South Australia in fulfilment of the degree of Doctor of Philosophy

Faculty of Sciences

School of Agriculture, Food and Wine

September 2022

TABLE OF CONTENTS

PUBLICATIONS ARISING FROM THIS THESIS

Dowling, A., Sadras, V.O., Roberts, P., Doolette, A., Zhou, Y., Denton, M.D. 2021. Legume-oilseed intercropping in mechanised broadacre agriculture – a review. Field Crop Res. 260, doi: 10.1016/j/fcr/2020.107980.

Dowling, A., Roberts, P. Doolette, A., Zhou, Y., Denton, M.D. 2022. Chickpea-linseed intercropping has greater nitrogen uptake land use efficiency than sole crops, but this does not translate to overyielding. Euro. J. Agron. Submitted manuscript.

Dowling, A., Roberts, P., Doolette, A., Zhou, Y., Denton, M.D., 2023. Oilseed-legume intercropping is productive and profitable in low input scenarios. Agric. Syst. 204, 103551. doi: 10.1016/j.agsy.2022.103551.

Dowling, A., Roberts, P., Zhou, Y., Denton, M.D. 2022. Mycorrhizal colonisation has a limited effect on crop growth and phosphorus nutrition in legume-oilseed intercrops. Plant Soil. Submitted manuscript.

ABSTRACT

Intercropping is a system of farming whereby multiple crop species are grown together for a significant period of time. There are many types of intercropping, differing in layout and species combination, as well as the ecosystem services they provide. In large-scale mechanised systems, intercropping has traditionally utilised cereal-legume pairings with the aim of overyielding (increased combined intercrop yield per unit area compared with the respective monocrops). However, as the price of synthetic inputs such as fertilisers and fungicides rises globally, interest in legume-oilseed intercropping as a low input system is increasing. Legume-oilseed intercropping entails growing a legume and an oilseed species together, often with the goal of harvesting the grain of both crops. Legume-oilseed intercropping provides the same benefits as cereal-legume intercrops whilst mitigating many of the logistical challenges that have previously stymied widespread adoption of the system in broadacre farming.

Although oilseed-legume intercropping is becoming increasingly popular in broadacre agriculture, its adoption has not been uniform. The majority of research is conducted in northern Europe, Canada and China, with data from Mediterranean-type climates lacking. As such, this thesis investigated the potential of legume-oilseed intercropping as a low input system in a Mediterranean climate, with a focus on yield and nutrient uptake efficiency and economic productivity, relative to their respective sole crops. The role of arbuscular mycorrhizal fungi (AMF) in facilitating improved intercrop phosphorus nutrition was also investigated.

It was hypothesised that the legume-oilseed intercrops would be more productive, in both a yield and economic sense, under low input scenarios than their respective sole crops and have greater nutrient uptake and nutrient uptake efficiency than their respective sole crops. It was also hypothesised that mycorrhizal colonisation of roots would improve phosphorus acquisition and that intercropping

would affect mycorrhizal colonisation, with the direction of this affect dependent on intercrop species combinations.

Over the 2019, 2020, and 2021 winter growing seasons a total of seven field experiments were conducted in the Mediterranean climate zone of southern Australia. Three field experiments were conducted in 2019, three in 2020, and one in 2021. Chickpea (*Cicer arietinum* L.) was intercropped with linseed (*Linum usitarissimum* L.) under varying fertiliser regimes across three sites during 2019 and 2020. There were six fertiliser application treatments combining three levels of nitrogen application (0 kg N ha^{-1}, 25 kg N ha^{-1}, and 50 kg N ha^{-1}) and two levels of phosphorus application (0 kg P ha^{-1} and 20 kg P ha^{-1}) (0N0P, 0N20P, 25N0P, 25N20P, 50N0P, 50N20P). Chickpea and linseed were also intercropped under varying fungicide regimes (nil, foliar fungicide, foliar fungicide + desiccant) in 2019 and 2020 at Hart field site, as were chickpea and canola (*Brassica napus* L.) in 2020. Finally, chickpea-linseed, chickpea-canola, and lentil (*Lens. culinaris* L.)-canola intercropping field trials were sampled in 2020 and 2021 at Hart field site. A glasshouse study utilising the same intercrop species combinations and the respective sole crops was also conducted.

Fertiliser treatment did not affect yield in the chickpea-linseed intercrops, and there was no significant difference between total intercrop yield and sole crop yield, with the intercrop yielding 78% and 103% of sole chickpea and linseed, respectively. Intercrop nitrogen uptake land use efficiency was improved, with the sole crops needing 27% more land to achieve the same nitrogen uptake. Intercropping also increased nitrogen fixation in the chickpea, with 36% and 44% Ndfa in the sole and intercrop chickpea, respectively. Conversely, intercrop phosphorus uptake land use efficiency was reduced, with the sole crops needing 8% less land to achieve the same phosphorus uptake.

The land equivalency ratio (LER) of the chickpea-linseed intercrops under nil fertilisation averaged 1.04 compared with 0.94 under high fertilisation. The LER of the intercrops under nil fungicide averaged 1.39 compared with 0.93 under high fungicide. Intercropping provided gross margin stability across environments, while the gross margins of the sole crops varied depending on environment, a pattern that held even when grain prices and input costs varied.

In the chickpea-oilseed and lentil-canola intercrops, mycorrhizal colonisation and the subsequent effect on phosphorus nutrition were host plant dependent. Lentil was the most mycorrhizal plant, followed by linseed, chickpea, and then canola. Only in lentil in the glasshouse was there a correlation between mycorrhizal colonisation and shoot phosphorus ($R = 0.79$, $p<0.001$). Intercropping did not affect AMF colonisation in the field, but in the glasshouse intercropping with canola reduced mycorrhizal colonisation of lentil. The interaction between intercropping and AMF had a limited effect on crop growth and shoot phosphorus. Outside of the AMF-intercropping interaction, intercropping with chickpea increased canola shoot phosphorus.

In summary, I found that legume-oilseed intercropping appears well suited as a low-input system in broadacre cropping in Mediterranean environments. Although the actual yield of the intercrops was similar to those of the respective sole crops, intercropping chickpea with the oilseed species linseed and canola resulted in improved land use efficiency (LER) relative to the sole crops, particularly under reduced fertiliser and fungicide inputs. The intercrops also provided greater gross margins under low input scenarios, and improved yield stability across environments. The results show that legume-oilseed intercropping can be utilised as a risk mitigation strategy and a profitable alternative to traditional high input monocultures in a global environment of rising synthetic input costs.

DECLARATION

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

I acknowledge the copyright if published works contained within this thesis resides with the copyright holder(s) of those works.

I also give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library Search and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

I acknowledge the support I have received for my research through the provision of an Australia Research Training Program Fee-Offset and the Tim Healy AW Howard Memorial Trust Stipend.

Alyce Dowling

02/09/2022

ACKNOWLEDGEMENTS

I would like to say thank you to my supervisors A/Prof. Matt Denton, Dr Yi Zhou, Dr Ashlea Doolette and Dr Penny for their guidance and support. Your intellectual input, experimental guidance, critical editorial review and comments are highly appreciated. In particular, thank you to Penny for your continued encouragement and for involving me in industry events like Field Hart Day. I still don't like public speaking, but I am getting better!

I am grateful to the Australian Government through the Research Training Program for full scholarship and project money. I am also thankful to the AW Howard Memorial Trust for awarding me the Tim Healey top-up stipend.

I am indebted to many people for their assistance throughout this project:
To Dr Victor Sadras, for his expert critique and input into the review paper, right back at the beginning! To the SARDI Clare Agronomy team, for their help with my field trials. In particular, Sarah Day for her patience and guidance when I couldn't tell a chickpea from a lentil, and Dili Mao, for her expert statistical assistance. To Dr Ashleigh Panagaris, Dr Bogumila Tomczak and Andrea Paparella at the University of Adelaide for the time and effort they put into helping me with my sample phosphorus analysis, which formed a core part of the results in Chapters 3 and 5. To Dr Tim Cavagnaro for his help with the experimental design of Chapter 5 and for use of his lab equipment. To Matthias Salomon for teaching me the root staining method. To Ben Fleet and Malinee Thongmee for helping out with my glasshouse trial and watering my plants when I couldn't.

Thank you to my lab friends and colleagues for their support and friendship during my time at the Waite - I would not have made it without you. Seriously! In particular, to Dr Judith Rathjen

thank you for your critical review of Chapter 5, as well as for doing Wordle with me every day and for the innumerable number of coffees you have bought me!

Finally, a note of great appreciation to my friends and family. Thanks for always having my back and for being there when I needed you. Your unconditional love and support have been vital! Thanks especially to mum, dad, and Bouz, as well as Boi and Nubbins. You have been my little rocks throughout this wild ride!

LIST OF KEY TERMS

Legume-oilseed intercropping: A legume and an oilseed species are grown together for a sustained period of time, often with the goal of harvesting the grain of both crops.

LER (Land Equivalent Ratio): An index that 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 indicates a yield advantage of the intercrop.

Yield efficiency: Yield produced per unit area.

Overyielding: Increased combined intercrop yield per unit area compared with the respective monocrops. Synonymous with **land sparing**, **yield efficient**.

Nitrogen/phosphorus efficiency: Uptake of nitrogen/phosphorus (g kg^{-1}) per unit area.

Economic efficiency: Gross profit as a function of input costs

Economic dynamics: Descriptor of the interplay between factors of production (input costs, yield output, market prices etc) and how this affects overall system profit.

CHAPTER 1: Introduction

1.1 Introduction

In the face of rising production costs and a changing climate, farmers are searching for alternatives to the current high input systems that improve resource use efficiency and reduce costs without sacrificing yield. One approach, which embraces the principles of agroecology and conservation agriculture, focuses on the sustainable intensification of agriculture through the utilisation of naturally occurring interspecies interactions and ecosystem services (Giller et al., 2015; Andres & Bhullar, 2016; Gunton et al., 2016; Rillig et al., 2016; Duchene et al., 2017; Li et al., 2020). A central pillar of this approach aims to diversify crops and increase species richness in the field through practices such as intercropping (Ponisio et al., 2015). Intercropping is a system of farming whereby multiple crop species are grown in the same area for a sustained period of time (Betencourt et al., 2012; Dowling et al., 2021). Intercropping aims to harness the principles of *complementarity*, *competition*, and *facilitation*, which classify the types of interspecies interactions that occur in multi-species stands, to promote crop growth and system productivity (Lithourgidis et al., 2011; Brooker et al., 2015). While there are many types of intercropping and different species combinations (as outlined in chapters 2 and 3), this thesis focuses on legume-oilseed intercropping, wherein a legume and an oilseed species are grown together, often with the goal of harvesting the grain of both crops.

Research on intercropping in largescale mechanised farming has focused primarily on intercropping as a means to increase yield per unit area over the sole crops, known as ‘over-yielding’ (Li et al., 2014; Chen et al., 2021). While many studies report increased intercrop yields, it is important to note that intercropping is done for a myriad of reasons beyond over-yielding. Indeed, in Canada, where the implementation of intercropping at large scales is most progressed, farmers cite reduced inputs, increased yield stability, and reduced risk as the key motivations for adopting intercropping (Kirkegaard and Condon, 2019; Fulwood, 2020). This thesis focuses on the potential of legume-oilseed intercropping in mechanised broadacre cropping as a low input alternative to widely adopted high input monocultures. Thus, while over-yielding is viewed as a benefit, it is not the focus. Instead, nutrient use and economic efficiency, and the mechanisms that underpin those processes, are considered as the primary points of investigation.

1.2 Study species

The legume species used in these studies were chickpea (*Cicer arietinum*, cv Genesis 090) and lentil (*Lens culinaris*, cv. ‘Hurricane’). Both chickpea and lentil have high market relevance in Australia and internationally. In Australia, for example, chickpea and lentil have the largest and third largest planted area (‘000 ha) of the winter legumes (ABARES, 2021), and are already included as break crops in cereal dominant rotations (GRDC GrowNotes, 2017, 2018).

The oilseed species used in this research were linseed (*Linum usitatissimum*, cv ‘Croxton’) and canola (*Brassica napus*, cv ‘Thumper’). Linseed was included as it is intercropped with success, both in a commercial and research sense, in the Canadian prairie states of Saskatchewan and Manitoba. Additionally, linseed is a highly mycorrhizal species (Thingstrup et al., 1998; Grant, 2009; McGonigle et al., 2011) and was thus included to explore the interactions of intercropping, arbuscular mycorrhiza fungi (AMF), and phosphorus nutrition. By contrast, canola is a non-mycorrhizal species (Tester et al., 1987), and was thus included as a potential disruptor in the AMF-intercrop-phosphorus interaction. Further, canola has high market relevance, being the third highest earning grain product in Australia (ABARES, 2021).

1.3 Aims and hypotheses

Although oilseed-legume intercropping is becoming increasingly popular in broadacre agriculture, its adoption has not been uniform. The majority of research is conducted in northern Europe, Canada and China, with data from Mediterranean-type climates lacking. Areas with Mediterranean-type climates include the grain production hubs of southern and western Australia, as well as southern

France and Spain (FAOSTAT, 2021). The efficacy of oilseed-legume intercropping in these major cropping regions is understudied, leaving farmers with limited guidelines for undertaking intercropping, despite the economic and productivity benefits it may provide. There is a clear knowledge gap in our understanding of the nutrient and yield dynamics of legume-oilseed intercropping in mechanised broadacre agriculture, particularly in a Mediterranean climate. As such, this study aimed to investigate the viability of legume-oilseed intercropping in mechanised broadacre agriculture, with a focus on the productivity and profitability outcomes of legume-oilseed intercrops in a low input system.

In achieving this overall aim, each chapter of the six chapters of this thesis had its own focus:

- Chapter 2: A review of the literature on legume-oilseed intercropping, which provides both theoretical and real-world context to the experimental studies conducted as part of this thesis.
- Chapter 3: An investigation into the effect of varying nitrogen and phosphorus fertiliser application on the yield and nutrient dynamics of a chickpea-linseed intercrop, relative to the respective sole crops.
- Chapter 4: An investigation into the the yield and economic efficiency of various legume-oilseed intercrops under varying fertiliser and fungicide regimes, relative to their respective sole crops.
- Chapter 5: An investigation into the effect that intercropping has on the mycorrhizal colonisation and phosphorus nutrition of legume and oilseed species, in both the field and the glasshouse.
- Chapter 6: A discussion of the overall findings of this investigation, with recommendations for the future research.

It was hypothesised that the legume-oilseed intercrops would be more productive, in both a yield and economic sense, under low input scenarios than their respective sole crops and have greater nutrient uptake and nutrient uptake efficiency than their respective sole crops. It was also hypothesised that mycorrhizal colonisation of roots would improve phosphorus acquisition and that intercropping would affect mycorrhizal colonisation, with the direction of this affect dependent on intercrop species combinations.

References

ABARES (2021). Agricultural commodities: December quarter 2021 – Statistical tables – data tables XLS. https://www.agriculture.gov.au/abares/research-topics/agricultural-outlook/data#agricultural-commodities. Accessed February 10, 2022.

Andres, C., Bhullar, G.S. 2016. Sustainable intensification of tropical agro-ecosystems: need and potentials. *Front. Environ. Sci.* 4:5. DOI: 10.3389/fenvs.2016.00005.

Betencourt, E., Duputel, M., Colomb, B., Desclauz, D., Hinsinger, P. 2012. Intercropping promotes the ability of durum wheat and chickpea to increase rhizosphere phosphorus availability in a low P soil. Soil Biolg. Biochem. 46, 181-190.

Brooker, R.W., Bennett, A.E., Cong, W-F., Daniell, T.J., George, T.S., Hallett, P.D., Hawes, C., Iannetta, P.P.M., Jones, H.G., Karley, A.J., Li, L., McKenzie, B.M., Pakeman, R.J., Paterson, E., Schöb, C., Shen, J., Squire, G., Watson, C.A., Zhang, C., Zhang, F., Zhang, J., White., P.J. 2015. Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. New Phyto. 206, 107-117. doi: 10.1111/nph.13132

Chen, J., Engberen, N., Stefan, L., Schmid, B., Sun, H., Schöb, C. 2021. Diversity increases yield but reduces harvest index in crop mixtures. Nature plants, 7, 893-898. https://doi.org/10.1038/s41477-021-00948-4

Dowling, A., Sadras, V.O., Roberts, P., Doolette, A., Zhou, Y., Denton, M.D. 2021. Legume-oilseed intercropping in mechanised broadacre agriculture – a review. Field Crops Res. 260, 107980, https://doi.org/10.1016/j fcr.2020.107980

Duchene, O. Vian, J-F., Celette, F. 2017. intercropping with legume for agroecological cropping systems: Complementarity and facilitation processes and the importance of soil microorganisms. A review. *Agric. Ecosyst. Environ.* 240, 148-161. doi: 10.1016/j.agee.2017.02.019.

FAOSTAT (2021). Crops and livestock products. https://www.fao.org/faostat/en/#data/QCL. Accessed July 29, 2022.

Fulwood, J., 20 Jun 2020, “Intercropping study demonstrates potential yield and economic upside”. GroundCover, 147. https://groundcover.grdc.com.au/innovation/industry-insights/profitable-intercrops-give-growers-optioins. Accessed December 10, 2021.

Giller, K.E., Andersson, J.A., Corbeels, M.Kirkegaard, J., Mortensen, D., Erenstein, O., Vanlauwe, B. 2015. Beyond conservation agriculture. Front. Plant Sci. 6. doi: 10.3389/fpls.2015.00870.

Grant, C.A., Monreal, M.A., Irvine, R.B., Mohr, R.M., McLaren, D.L., Khakbazan, M. 2009. Crop response to current and previous season applications of phosphorus as affected by crop sequence and tillage. Can. J. Plant. Sci. 89, 49-66.

GRDC GrowNotes (2017) Chickpea – Southern Region. https://grdc.com.au/resources-and-publications/grownotes/crop-agronomy/chickpea-southern-region-grownotes. Accessed August 5, 2022.

GRDC GrowNotes (2018) Lentil – Southern Region. https://grdc.com.au/resources-and-publications/grownotes/crop-agronomy/lentil-southern-region-grownotes. Accessed August 5, 2022.

Gunton, R.M., Firbank, L.G., Inman, A., Winter, D.M. 2016. How scalable is sustainable intensification? *Nat. Plants*. 2:16065. DOI: 10.1038/nplants.2016.65.

Kirkegaard, J., Condon, G. 2019. Companion cropping – should we be considering it? GRDC update papers. https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2019/02/companion-cropping-should-we-be-considering-it. Accessed April 12, 2022.

Li, L. Tilman, D., Lambers, D., Zhang, F-S. 2014. Plant diversity and overyielding: insights from belowground facilitation of intercropping in agriculture. New Phytologist, 203, 63-69.

Li, C., Hoffland, E., Kuyper, T.W., Yu, Y., Zhang, C., Li, H., Zhang, F., van der Werf, W. 2020. Syndromes of production in intercropping impact grain yield gains. Nat. Plants. 6, 653-660. DOI: 10.1038/s41477-020-0680-9.

Lithourgidis, A.S., Dordas, C.A., Damalas, C.A., Vlachostergios, D.N. 2011. Annual intercrops: an alternative pathway for sustainable agriculture. Aus. J. Crop. Sci. 5(4), 396-410.
https://search.informit.org/doi/10.3316/informit.281409060336481

McGonigle, T.P., Hutton, M., Greenley, A., Karamanos, R. 2011. Role of Mycorrhiza in a Wheat-Flax versus Canola-Flax Rotation: A Case Study. Commun. Soil Sci. Plant. Anal. 42(17), 2134-2142. DOI: 10.1080/00103624.2011.596242

Tester, M., Smith, S.E., Smith, F.A. 1987. The phenomenon of "nonmycorrhizal" plants. Can. J. Bot. 65, 419-431.

Thingstrup, I., Rubæk, G., Sibbesen, E., Jakobsen, I. 1998. Flax (*Linum usitatissimum* L.) depends on arbuscular mycorrhizal fungi for growth and P uptake at intermediate but not high soil P levels in the field. Plant Soil, 203, 37-46.

CHAPTER 2: Review of the literature

Legume-oilseed intercropping in mechanised broadacre agriculture – a review

Alyce Dowling, Victor O Sadras, Penny Roberts, Ashlea Doolette, Yi Zhou, Matthew D Denton

School of Agriculture, Food and Wine, University of Adelaide, Urrbrae, South Australia, 5064, Australia

Field Crops Research, 260, doi: 0.1016/j.fcr.2020.107980

Statement of Authorship

Title of Paper	Legume-oilseed intercropping in mechanised broadacre agriculture – a review
Publication Status	☒ Published ☐ Accepted for Publication ☐ Submitted for Publication ☐ Unpublished and Unsubmitted work written in manuscript style
Publication Details	Dowling, A. Sadras, V.O., Roberts, P., Doolette, A., Zhou, Y., Denton, M.D. 2021. Legume-oilseed intercropping in mechanised broadacre agriculture – a review. Field Crops Res. 260, 107980.

Principal Author

Name of Principal Author (Candidate)	Alyce Dowling		
Contribution to the Paper	Conducted review of the literature, wrote the manuscript.		
Overall percentage (%)	85%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	02/09/2022

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate to include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Victor O. Sadras		
Contribution to the Paper	Supervised development of work, edited the manuscript.		
Signature		Date	7 Sep 2022

Name of Co-Author	Penny Roberts		
Contribution to the Paper	Supervised development of work, edited the manuscript.		
Signature		Date	27/09/2022

Name of Co-Author	Ashlea Doolette		
Contribution to the Paper	Supervised development of work, edited the manuscript.		
Signature		Date	16/09/2022

Name of Co-Author	Yi Zhou		
Contribution to the Paper	Supervised development of work, edited the manuscript.		
Signature		Date	9/9 /2022

Name of Co-Author	Matthew D Denton		
Contribution to the Paper	Supervised development of work, edited the manuscript.		
Signature		Date	7 Sep 2022

Field Crops Research 260 (2021) 107980

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Legume-oilseed intercropping in mechanised broadacre agriculture – a review

Alyce Dowling[a], Victor O Sadras[a,b], Penny Roberts[b], Ashlea Doolette[a], Yi Zhou[a,*], Matthew D Denton[a,*]

[a] School of Agriculture, Food, and Wine, The University of Adelaide, Waite Campus, Urrbrae, SA 5064, Australia
[b] South Australian Research and Development Institute, Waite Campus, Urrbrae, SA 5064, Australia

ARTICLE INFO

Keywords:
Brassica
Competition
Cover crop
Crucifer
Fabaceae
Nitrogen
Nutrient dynamics
Water

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,

---

* Corresponding authors.
E-mail addresses: yi.zhou@adelaide.edu.au (Y. Zhou), matthew.denton@adelaide.edu.au (M.D. Denton).

https://doi.org/10.1016/j.fcr.2020.107980
Received 7 December 2019; Received in revised form 19 September 2020; Accepted 7 October 2020
Available online 13 November 2020

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: $LER_{alt}^{¥}$ 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

(*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**
			Canola (*Brassica napus*)		Rain fed; no rainfall data given			30 lbs N/ac: 1.12 60 lbs N/ac: 1.09
Chalmers, 2014a	Canada	Pea (*Pisum sativum*)	Canola (*Brassica napus*)	Sandy loam, pH 8.1	Rain fed; no rainfall data given	Agronomic and nitrogen dynamics	YES	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% ($p > 0.05$)

(*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**
			(*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	Partial LER for mustard intercropped with: 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	Crop yield 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	1990 & 1991 average LER at diff N fert rates 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	LER at diff N fert rates (kg ha^{-1}) 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	Average LER over two years 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	LER 2013 1.95 LER 2014 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	Strip intercrop No sig IC yield increase compared with SC ($p > 0.05$) Row intercrop 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	LER 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	Soybean yield IC: 1882 kg ha^{-1} SC: 985 kg ha^{-1} ($p < 0.05$) Weed biomass 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	Canola grain yield (kg ha^{-1}) Faba-/lentil-canola > SC canola ($p < 0.05$) pea/fenugreek/ lentil-canola vetch/ vetch/ clover-canola not sig diff to SC canola ($p > 0.05$)

(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**
		(*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

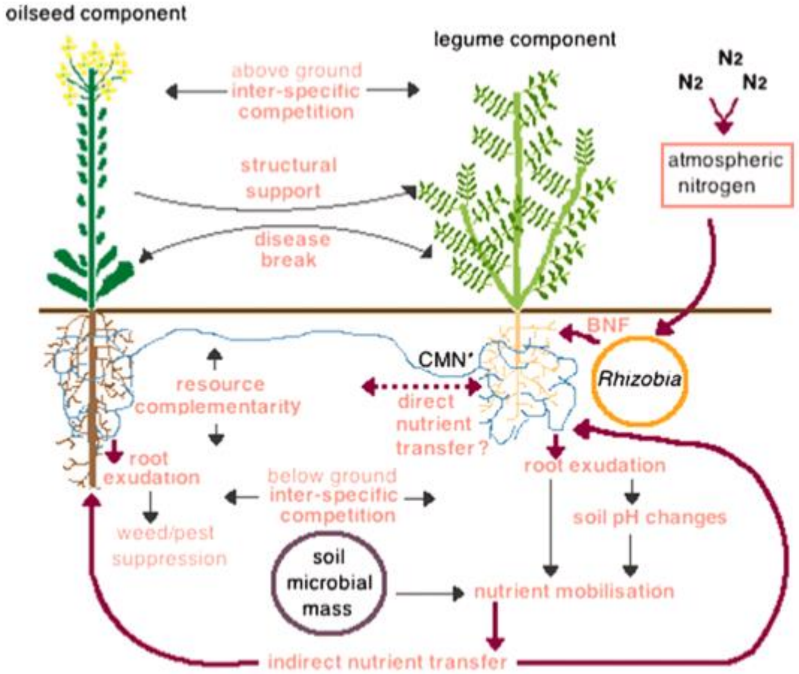

Fig. 1. Above- and below- ground interactions within a legume-oilseed intercrop. BNF; Biological Nitrogen Fixation, a process that arises from a symbiosis between legume roots and rhizobia that converts atmospheric N_2 to plant available NO_3- NH_4^+. CMN; common mycorrhizal network, a shared network 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 intercropping; 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 intercrop. 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 rhizodeposition 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 VanKoughnet (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) (VanKoughnet, 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.

Acknowledgements

Support for this study was provided by the Australia Research Council (project ID: IH140100013) and the University of Adelaide.

References

Agnew, J., 2018. Intercropping after harvest: separation and storage, applying technology for agriculture. Prairie Agricultural Machine Institute, Canada.

Andersen, M.K., Hauggaard-Nielsen, H., Ambus, P., Jensen, E.S., 2004. Biomass production, symbiotic nitrogen fixation and inorganic N use in dual and tri-component annual intercrops. Plant Soil 266, 273–287.

Andersen, M.K., Hauggaard-Nielsen, H., Weiner, P., Jensen, E.S., 2007. Competitive dynamics in two- and three- component intercrops. J. Appl. Ecol 44, 545–551.

Andrade, J.F., Cerrudo, A., Rizzalli, R.H., Monzon, J.P., 2012. Sunflower-soybean intercrop productivity under different water conditions and sowing managements. Agron. J. 104, 1049–1055.

Angus, J.F., Kirkegaard, J.A., Hunt, J.R., Ryan, M.H., Ohlander, L., Peoples, M.B., 2015. Break crops and rotations for wheat. Crop Pasture Sci. 66, 523–552.

Anil, L., Park, J., Phipps, R.H., Miller, F.A., 1998. Temperate intercropping of cereals for forage: a review of the potential for growth and utilization with particular reference to the UK. Grass Forage Sci. 53, 301–317.

Aphalo, P., Ballare, C.L., 1995. On the importance of information-acquiring systems in plant-plant Interactions. Funct. Ecol. 9, 5–14.

Bajwa, A.A., Ehsaullah Anjum, S.A., Nafees, W., Tanveer, M., Saeed, S., 2014. Impact of fertilizer use on weed management in conservation agriculture. A review. Pak. J. Agric. Res 27, 161–171.

Banik, P., Sasmal, T., Ghosal, P.K., Bagchi, D.K., 2000. Evaluation of mustard (*Brassica compestris* Var. toria) and legume intercropping under 1:1 and 2:1 row-replacement series systems. J. Agron. Crop Sci 185, 9–14.

Bashir, U., Javaid, A., Bajwa, R., 2012. Allelopathic effects of sunflower residue on growth of rice and subsequent wheat crop. Chile J. Agric. Res. 72, 326–331.

Bedoussac, L., Journet, E.P., Hauggaard-Nielsen, H., Naudin, C., Corre-Hellou, G., Jensen, E.S., Prieur, L., Justes, E., 2015. Ecological principles underlying the increase of productivity achieved by cereal-grain legume intercrops in organic farming. A review. Agron. Sustain. Dev. 35, 911–935.

Bennet, M., 2009. Peola at Minnipa in 2009. In: Scholz, N., Cook, A., Latta, R., Wilhelm, N., Bennet, M., Paterson, C., Brace, D., McNeill, A., Chirgwin, M. (Eds.), Eyre Peninsula farming systems 2009 summary. South Australian Research & Development Institute, South Australia, pp. 60–62.

Bertness, M., Callaway, R.M., 1994. Positive interactions in communities. Trends in Ecol. Evol. 9, 191–193.

Betencourt, E., Duputel, M., Colomb, B., Desclauz, D., Hinsinger, P., 2012. Intercropping promotes the ability of durum wheat and chickpea to increase rhizosphere phosphorus availability in a low P soil. Soil Biol. Biochem. 46, 181–190.

Bethlenfalvay, G.J., Reyes-Solis, M.G., Camel, S.B., Ferrera-Cerrato, R., 1991. Nutrient transfer between root zones of soybean and maize plants connected by a common mycorrhizal mycelium. Physiol. Planta. 82, 423–432.

Biederbeck, V.O., Zentner, R.P., Campbell, C.A., 2005. Soil microbial populations and activites as influenced by legume green fallow in a semiarid climate. Soil Biol. Biochem. 37, 1775–1784.

Bogatek, R., Gniazdowska, A., Zakrzewska, W., Oracz, K., Gawronski, S.W., 2006. Allelopathic effects of sunflower extracts on mustard seed germination and seedling growth. Biologia Plantarum 50, 156–158.

Boudreau, M.A., 2013. Diseases in intercropping systems. Annu. Rev. Phytopathol. 51, 499–519.

Brader, G., Mikkelsen, M.D., Halkier, B.A., Palva, E.T., 2006. Altering glucosinolate profiles modulates disease resistance in plants. Plant J. 46, 758–767.

Brooker, R., Kikvidze, Z., Punaire, F.I., Callaway, R.M., Choler, P., Lortie, C.J., Michalet, R., 2005. The importance of importance. Oikos 109, 63–70.

Brown, P.D., Morra, M.J., 1996. Hydrolysis products of glucosinolates in Brassica napus tissues as inhibitors of seed germination. Plant Soil. 181, 307–316.

Cadoux, S., Sauzet, G., Valantin-Morison, M., Pontet, C., Champolivier, L., Robert, C., Lieven, J., Flénet, F., Mangenot, O., Fauvin, P., Landed, N., 2015. Intercropping frost sensitive legume crops with winter oilseed rape reduces weed competition, insect damage, and improves nitrogen use efficiency. OCL 22, D302.

Callaway, R.M., 1995. Positive interactions among plants. Bot. Rev. 61, 306–349.

Calviño, P., Monzon, J., 2009. Farming systems of Argentina – yield constraints and risk management. In: Sadras, V., Calderini, D. (Eds.), Crop Physiol.: Applications for genetic improvement and agronomy. Academic Press, USA, pp. 55–70.

Carpenter, J., Gianessi, L., 2000. Value of BT and herbicide resistant cottons. In: Beltwide Cotton Conference. Texas, pp. 76–79.

Chalk, P.M., Peoples, M.B., McNeill, A.M., Boddey, R.M., Unkovich, M.J., Gardener, M.J., Silva, C.F., Chen, D., 2014. Methodologies for estimating nitrogen transfer between legumes and companion species in agro-ecosystems: A review of ^{15}N-enriched techniques. Soil Biol. Biochem. 73, 10–21.

Chalmers, S., 2014a. Intercropping pea and canola based on row orientation and nitrogen rates Final report 2011-2013. Westman Agricultural Diversification Organization 2014 Annual Report. Westman Agricultural Diversification Organization, Manitoba, pp. 107–127.

Chalmers, S., 2014b. Sunflower intercropped with hairy vetch. Westman Agricultural Diversification 2014 Annual Report. Westman Agricultural Diversification Organization, Manitoba, pp. 127–134.

Chalmers, S., 2017. Responses of pea and canola intercrops to nitrogen and phosphorus applications. Westman Agricultural Diversification Organization 2017 Annual Report. Westman Agricultural Diversification Organization, Manitoba, pp. 127–136.

Chapagain, T., Riseman, A., 2014. Barley-pea intercropping: Effects on land productivity, carbon and nitrogen transformations. Field Crops Res. 166, 18–25.

Coll, L., Cerrudo, A., Rizzalli, R., Monzon, J.P., Andrade, F.H., 2012. Capture and use of water and radiation in summer intercrops in the south-east Pampas of Argentina. Field Crops Res. 134, 105–113.

Connolly, J., Goma, H.C., Rahim, K., 2001. The information content of indicators in intercropping research. Agric. Ecosyst. Environ. 87, 191–207.

Corre-Hellou, G., Fustec, J., Crozat, Y., 2006. Interspecific competition for soil N and its interaction with N2 fixation, leaf expansion and crop growth in pea–barley intercrops. Plant Soil. 282, 195–208.

Cortés-Mora, F.A., Piva, G., Jamont, M., Fustec, J., 2010. Niche separation and nitrogen transfer in brassica-legume intercrops. Field Veg. Crop Res. 47, 581–586.

Costa, S.E.V.G.A., Souza, E.D., Anghinoni, I., Carvalho, P.C.F., Martins, A.P., Kunrath, T. R., Cecagno, D., Balerini, F., 2014. Impact of an integrated no-till crop-livestock system on phosphorus distribution, availability and stock. Agric. Ecosyst. Environ. 190, 43–51.

Couëdel, A., Alletto, L., Kirkegaard, J., Justes, E., 2018. Crucifer glucosinolate production in legume-crucifer cover crop mixtures. Eur. J. Agron. 96, 22–33.

Couëdel, A., Kirkegaard, J., Alletto, L., Justes, E., 2019. Crucifer-legume cover crop mixtures for biocontrol: Toward a new multi-service paradigm. Adv. Agron. 157, 55–139.

De la Fuente, E.B., Suárez, S.A., Lendardis, A.E., Poggio, S.L., 2014. Intercropping sunflower and soybean in intensive farming systems: Evaluating yield advantage and effect on weed and insect assemblages. NJAS – Wagen. J. Life Sci. 70–71, 47–52.

Dedio, W., 1994. Potential of intercropping of sunflower with peas. Helia 17, 63–66.

Denton, M.D., Sasse, C., Tibbett, M., Ryan, M.H., 2006. Root distributions of Australian herbaceous perennial legumes in response to phosphorus placement. Funct. Plant Biol. 33, 1091–1102.

Dilworth, M.J., James, E.K., Sprent, J., Newton, W.E. (Eds.), 2008. Nitrogen-fixing leguminous symbiosis. Springer, The Netherlands.

Dong, N., Tang, M.-M., Zhang, W.-P., Bao, X.-G., Wang, Y., Christie, P., Li, L., 2018. Temporal differentiation of crop growth as one of the drivers of intercropping yield advantage. Nat. – Sci. Rep. 8, 10.

Downey, R.K., Klassen, A.J., McAnsh, J., 1974. Rapeseed: Canada's "Cinderella" crop. Rapeseed Assoc., Winnipeg.

Drew, E.A., Gupta, V.V.S.R., Roget, D.K., 2007. Herbicide use, productivity, and nitrogen fixation in field pea (Pisum sativum). Aus. J. Agric. Res. 58, 1204–1214.

Eason, W.R., Newman, E.I., Chiba, P.N., 1991. Specificity of interplant cycling of phosphorus: the role of mycorrhizas. Plant Soil. 137, 267–274.

Echarte, L., Maggiora, A.D., Cerrudo, D., Gonzalez, V.H., Abbate, P., Cerrudo, A., Sadras, V.O., Calviño, P., 2011. Yield response to plant density of maize and sunflower intercropped with soybean. Field Crops Res. 121, 423–429.

Ehrmann, J., Ritz, K., 2014. Plant: soil interactions in temperate multi-cropping production systems. Plant Soil. 376, 1–29.

Fernandez, A.L., Sheaffer, C.C., Wyse, D.L., 2014. Productivity of field pea and lentil with cereal and brassica intercrops. Organ. Agric. Agroecol. 107, 249–256.

Fernández-Aparicio, M., Emeran, A.A., Rubiales, D., 2010. Inter-cropping with berseem clover (*Trifolium alexandrinum*) reduces infection by *Orobanche crenata* in legumes. Crop Protection 29, 867–871.

Fletcher, A.L., Kirkegaard, J.A., Peoples, M.B., Robertson, M.J., Whish, J., 2016. Prospects to utilise intercrops and crop variety mixtures in mechanised, rain-fed, temperate cropping systems. Crop Pasture Sci. 67, 1252–1267.

Francis, C.A., 1989. Biological efficiencies in multiple-cropping systems. Adv. Agron. 42, 1–42.

Fridley, J.D., 2001. The influence of species diversity on ecosystem productivity: how, where, and why? Oikos. 93, 514–526.

Fustec, J., Lesuffleur, F., Mahieu, S., Cliquet, J.-B., 2010. Nitrogen rhizodeposition of legumes: A review. Agron. Sustain. Dev. 30, 57–66.

Gaba, S., Lescourret, F., Boudsocq, S., Enjalbert, J., Hisinger, P., Journet, E.-P., Navas, M.-L., Wery, J., Louran, G., Malézieux, E., Pelzer, E., Prudent, M., Ozier-Lafontaine, H., 2015. Multiple cropping systems as drivers for providing multiple ecosystem services: from concepts to design. Agron. Sustain. Dev. 35, 607–623.

Gan, Y., Campbell, C.A., Janzen, H.H., Lemke, R.L., Liu, P., Basnyat, P., McDonald, C.L., 2009. Root mass for oilseed and pulse crops: growth and distribution in the soil profile. Can. J. Plant Sci. 89, 883–893.

Gan, Y., Campbell, C.A., Janzen, H.H., Lemke, R.L., Liu, P., Basnyat, P., McDonald, C.L., 2010. Nitrogen accumulation in plant tissues and roots and N mineralization under oilseeds, pulses, and spring wheat. Plant Soil. 332, 451–461.

Gan, Y.T., Liang, B.C., Liu, L.P., Wang, X.Y., McDonald, C.L., 2011. C:N ratios and carbon distribution profile across rooting zones in oilseed and pulse crops. Crop Pasture Sci. 62, 496–503.

Génard, T., Etienne, P., Diquélou, Yvin, J.-C., Revellin, C., Laîné, P., 2017. Rapeseed-legume intercrops: plant growth and nitrogen balance in early stages of growth and development. Plant Biol. 3, 2–20.

Génard, T., Etienne, P., Laîné, P., Yvin, J.-C., Diquélou, S., 2016. Nitrogen transfer from Lupinus albus L., Trifolium incarnatum L. and Vicia sativa L. contribute differently to rapeseed (Brassica napus L.) nitrogen nutrition. Plant Biol. 2, 2–15.

Gimsing, A., Kirkegaard, J.A., 2009. Glucosinolates and biofumigation: fate of glucosinolates and their hydrolysis products in soil. Phytochem. Rev. 8, 299–310.

Hamel, C., 2004. Impact of arbuscular mycorrhizal fungi on N and P cycling in the root zone. Can. J. Soil Sci. 84, 383–395.

Hamel, C., Furlan, V., Smith, D.L., 1992. Mycorrhizal effects on interspecific plant competition and nitrogen transfer in legume-grass mixtures. Crop Sci. 32, 991–996.

Hancock, L.M.S., Ernst, C.L., Charneskie, R., Ruane, L.G., 2012. Effects of cadmium and mycorrhizal fungi on growth, fitness, and cadmium accumulation in flax (Linum usitatissimum; Linaceae). Am. J. Bot. 99, 1445–1452.

Hauggaard-Nielsen, H., Gooding, M., Ambus, P., Corre-Hellou, G., Crozat, Y., Dahlmann, C., Dibet, A., Fragstein, P., Pristeri, A., Monti, M., Jensen, E.S., 2009a. Pea–barley intercropping and short-term subsequent crop effects across European organic cropping conditions. Nutr. Cycl. Agroecosyst. 85, 141–155.

Hauggaard-Nielsen, H., Gooding, M., Ambus, P., Corre-Hellou, G., Crozat, Y., Dahlmann, C., Dibet, A., von Fragstein, P., Pristeri, A., Monti, M., Jensen, E.S., 2009b. Pea–barley intercropping for efficient symbiotic N2-fixation, soil N acquisition and use of other nutrients in European organic cropping systems. Field Crops Res. 113, 64–71.

Hauggaard-Nielsen, H., Jensen, E.S., 2005. Facilitative root interactions in intercrops. Plant Soil. 274, 237–250.

Hauggaard-Nielsen, H., Ambus, P., Jensen, E.S., 2001. Interspecific competition, N use and interference with weeds in pea–barley intercropping. Field Crops Res. 70, 101–109.

Hauggaard-Nielsen, H., Jornsgaard, B., Kinane, J., Jensen, E.S., 2008. Grain legume–cereal intercropping: the practical application of diversity, competition and facilitation in arable and organic cropping systems. Renewable Agric. Food Syst. 23, 3–12.

He, X.H., Critchley, C., Bledsoe, C., 2003. Nitrogen transfer within and between plants through common mycorrhizal networks (CMNs). Crit. Rev. Plant. Sci. 22, 531–567.

He, X., Xu, M., Qiu, G.Y., Zhou, J., 2009. Use of ^{15}N stable isotope to quantify nitrogen transfer between mycorrhizal plants. J. Plant Ecol. 2, 107–118.

Hinsinger, P., Betencourt, E., Bernard, L., Brauman, A., Plassard, C., Shen, J., Tang, C., Zhang, F., 2011. P for two, sharing a scarce resource: soil phosphorus acquisition in the rhizosphere of intercropped species. Plant Physiol. 156, 1078–1086.

Hinsinger, P., Plassard, C., Tang, C., Jaillard, B., 2003. Origins of root-mediated pH changes in the rhizosphere and their responses to environmental constraints: a review. Plant Soil. 248, 43–59.

Iderawumi, A.M., Olusola, O.S., Friday, C.E., 2012. Effect of different planting pattern on total dry matter production and maize forage quality in maize (Zea mays) and cowpea (Vigna sinensis) intercropped as whole-crop forage. J. Agric. Vet. Sci. 4, 42–46.

Ilnicki, R.D., Enache, A.J., 1992. Subterranean clover living mulch: an alternative method of weed control. Agric. Ecosyst. Environ. 40, 249–264.

Indian Head Agricultural Research Farm (IHARF), 2013. Exploring the merits of field pea-canola intercrops (Final Report 20100292). Saskatchewan Ministry of Agriculture, Saskatchewan.

Indian Head Agricultural Research Farm (IHARF), 2015. Intercropping chickpea with flax (Final Report 20120412). Saskatchewan Ministry of Agriculture, Saskatchewan.

Irrigation Crop Diversification Corporation (ICDC), 2017. Intercropping marrowfat pea and mustard. Irrigation Crop Diversification Corporation Research and Demonstration Report. Saskatchewan Ministry of Agriculture, Saskatchewan, pp. 154–155.

Jaafar, M.N., Stone, L.R., Goodrum, D.E., 1993. Rooting depth and dry matter development of sunflower. Agron. J. 85, 281–286.

Jahansooz, M.R., Yunusa, I.A.M., Coventry, D.R., Palmer, A.R., Eamus, D., 2007. Radiation- and water-use associated with growth and yields of wheat and chickpea in sole and mixed crops. Eur. J. Agron. 26, 275–282.

Jamont, M., Piva, G., Fustec, J., 2013. Sharing N resources in the early growth of rapeseed cropped with faba bean: does N transfer matter? Plant Soil. 371, 641–653.

Jensen, E.K., 1996. Grain yield, symbiotic N_2 fixation and interspecific competition for inorganic N in pea-barley intercrops. Plant Soil. 182, 25–38.

Jiménez-Calderón, J.D., Martínez-Fernández, A., Benaouda, M., Vicente, F., 2018. A wintercrop of faba bean and rapseed for silage as a substitute for Italian ryegrass in rotation with maize. Arch. Agron. Soil Sci. 64, 983–993.

Johansen, A., Jensen, E.S., 1996. Transfer of N and P from intact or decomposing roots of pea to barley interconnected by an arbuscular mycorrhizal fungus. Soil. Biol. Biochem. 28, 73–81.

Kandel, H.J., Schneiter, A.A., Johnson, B.L., 1997. Intercropping legumes into sunflower at different growth stages. Crop Sci. 37, 1532–1537.

Kirkegaard, J., Christen, O., Krupinsky, J., Layzell, D., 2008. Break crop benefits in temperate wheat production. Field Crops Res.

Kirkham, M.B., Grecu, S.J., Kanemasu, E.T., 1998. Comparison of minirhizotrons and the soil-water-depletion method to determine maize and soybean root length and depth. Eur. J. Agron. 8, 117–125.

Kissen, R., Rossiter, J.T., Bones, A.M., 2009. The 'mustard oil bomb': not so easy to assemble?! Localization, expression and distribution of the components of the myrosinase enzyme system. Phytochem. Rev. 8, 69–86.

Klimek-Kopyra, A., Glab, T., Zajac, T., Stoklosa, A., Kulig, B., 2015. Vertical distribution of the root system of linseed (Linum usitatissimum L.) and legumes in pure and mixed sowing. Acta Agrobotan. 68, 43–52.

Krupinsky, J.M., Bailey, K.M., McMullen, M.P., Grossen, B.D., Turkington, T.K., 2002. Managing plant disease risk in diversified cropping systems. Agron. J. 94, 198–209.

Kuehne, G., Llewellyn, R., Pannel, D.J., Wilkinson, R., Dolling, P., Ouzman, J., Ewing, M., 2017. Predicting farmer uptake of new agricultural practices: A tool for research, extension and policy. Agric. Syst. 156, 115–125.

Lehman, C.L., Tilman, D., 2000. Biodiversity, stability, and productivity in competitive communities. Am. Nat. 156, 534–552.

Li, B., Li, Y.-Y., Wu, H.-W., Zhang, F.-F., Li, C.-J., Li, X.-X., Lambers, H., Li, L., 2016. Root exudates drive interspecific facilitation by enhancing nodulation and N_2 fixation. PNAS 113, 6496–6501.

Li, L., Li, S.-M., Sun, J.-H., Zhou, L.-L., Bao, X.-G., Zhang, H.-G., Zhang, F.-S., 2007. Diversity enhances agricultural productivity via rhizosphere phosphorus facilitation on phosphorus-deficient soils. PNAS 104, 11192–11196.

Li, L., Tang, C., Rengel, Z., Zhang, F., 2003. Chickpea facilitates phosphorus uptake by intercropped wheat from an organic phosphorus sources. Plant Soil. 248, 297–303.

Lithourgidis, A.S., Vasilakoglou, I.B., Dhima, K.V., Dordas, C.A., Yiakoulaki, M.D., 2011. Forage yield and quality of common vetch mixtures with oat and triticale in two seeding ratios. Field Crops Res. 99, 106–113.

Liu, L., 2009. Root systems of oilseed and pulse crops – morphology, distribution and growth patterns. University of Saskatchewan, Saskatoon, SK.

Lorin, M., Jeuffroy, M.-H., Butier, A., Valantin-Morison, M., 2015. Undersowing winter oilseed rape with frost-sensitive legume living mulches to improve weed control. Eur. J. Agron. 71, 96–105.

Lorin, M., Jeuffroy, M.-H., Butier, A., Valantin-Morison, M., 2016. Undersowing winter oilseed rape with frost-sensitive legume living mulch: Consequences for cash crop nutrition. Field Crops Res. 193, 24–33.

Maaz, T., Wulfhurst, J.D., McCracken, V., Kirkegaard, J., Huggins, D.R., Roth, I., Kaur, H., Pan, W., 2018. Economic, policy, and social trends and challenges of introducing oilseed and pulse crops into dryland wheat cropping systems. Agric. Ecosyst. Environ. 253, 177–194.

Malézieux, E., Crozat, Y., Dupraz, C., Laurans, M., Makowski, D., Ozier-Lafontaine, H., Rapidel, B., de Tourdonnet, S., Valantin-Morison, M., 2009. Mixing plant species in cropping systems: concepts, tools and models. A review. Agron. Sustain. Dev. 29, 43–62.

Malhi, S.S., 2012. Improving crop yield, N uptake and economic returns by intercropping barley or canola with pea. Agric. Sci. 3, 1023–1033.

Martin, M.P.L.D., Snaydon, R.W., 1982. Root and shoot interactions between barley and field beans when intercropped. J. Appl. Ecol. 19, 263–272.

Miller, P.R., Gan, Y., McConkey, B.G., McDonal, C.L., 2003. Pulse crops for the Northern Great Plains: II. Cropping sequence effects on cereal, oilseed, and pulse crops. Agron. J. 95, 980–986.

Montesinos-Navarro, A., Verdo, M., Querejeta, J.I., Valiente-Banuet, A., 2017. Nurse plants transfer more nitrogen to distantly related species. Ecol. 98, 1300–1310.

Motisi, N., Montfort, F., Faloya, V., Lucas, P., Doré, T., 2009. Growing Brassica juncea as a cover crop, then incorporating its residues provide complementary control of Rhizoctonia root rot of sugar beet. Field Crop Res. 113, 238–245.

Naudin, C., can der Werf, H.M.G., Jeuffroy, M.H., Corre-Hellou, G., 2014. Life cycle assessment applied to pea-wheat intercrops: A new method for handling the impacts of co-products. J.Clean. Prod 73, 80–87.

Naudin, C., Corre-Hellou, G., Pineau, S., Crozat, Y., Jeuffroy, M.H., 2010. The effect of various dynamics of N availability on winter pea-wheat intercrops: crop growth, N portioning and symbiotic N_2 fixation. Field Crops Res. 119, 2–11.

Nie, Z., McLean, T., Clough, A., Tocker, J., Christy, B., Harris, R., Riffkin, P., McCaskill, M., 2016. Benefits, challenges and opportunities of integrated crop-livestock systems and their potential application in the high rainfall zone of southern Australia: A review. Agric. Ecosyst. Environ. 235, 17–31.

Nuruzzaman, M., Lambers, H., Bolland, M.D.A., Veneklaas, E.J., 2005. Phosphorus benefits of different legume crops to subsequent wheat grown in different soils of Western Australia. Plant Soil 271, 175–187.

Nybo, B., Sluth, D., 2015. Mixed row intercropping demonstration (Final Report 20130428). Wheatland Conservation Area Inc., Saskatchewan.

Ofori, F., Stern, W.R., 1987. Maize/cowpea intercrop system: effect of nitrogen fertilizer on productivity and efficiency. Field Crops Res. 14, 247–261.

Omirou, M., Rousidou, C., Bekris, F., Papadopoulou, K.K., 2011. The impact of biofumigation and chemical fumigation methods on the structure and function of the soil microbial community. Microb. Ecol. 61, 201–213.

Paulsen, H.M., Schochow, M., Ulber, B., Kühne, S., Rahmann, G., 2006. Mixed cropping systems for biological control of weeds and pests in organic oilseed crops. Asp. Appl. Biol. 79, 215–220.

Peoples, M.B., Herridge, D.F., Ladha, J.K., 1995. Biological nitrogen fixation: An efficient source of nitrogen for sustainable agricultural production? Plant Soil. 174, 3–28.

Powlson, D.S., Gregory, P.J., Whalley, W.R., Quinto, J.N., Hopkins, D.W., Whitmore, A. P., Hirsch, P.R., Goulding, K.W.T., 2011. Soil management in relation to sustainable agriculture and ecosystem services. Food Policy 36, 572–587.

Premasthira, C., Zungsontiporn, S., Premasthira, C., Zungsontiporn, S., ChangHung, C., 1999. Allelopathic effects of sesame (Sesamum indicum L.) residues on crop growth. In: Proceedings of PSA Symposium. 15-19 Nov 1999, Taipei, Taiwan, pp. 281–288.

Przednowek, D.W.A., 2003. The effect of pulse crop rotation and controlled-release urea on the nitrogen accumulation and end-use quality of Canada western red spring wheat. M.S thesis. Univ. of Manitoba, Winnipeg, MB, Canada.

Raghothama, K.G., 1999. Phosphate acquisition. Annu. Rev. Plant Physiol. Plant Mol. Biol. 50, 665–693.

Rasmussen, J., Eriksen, J., Jensen, E.S., Esbensen, K.H., Høgh-Jensen, H., 2007. In situ carbon and nitrogen dynamics in ryegrass-clover mixtures: transfers, deposition and leaching. Soil Biol. Biochem. 39, 804–815.

Roberts, P., Moodie, M., Wilhelm, N., 2019. Intercropping increases productivity in the South Australian Mallee. In: Proceedings of the 2019 Agronomy Australia Conference. 25-29 August 2019, Wagga Wagga, Australia.

Robinson, R.G., 1984. Sunflower for strip, row, and relay intercropping. Agron. J. 76, 43–47.

Ryan, M.H., Graham, J.H., 2018. Little evidence that farmers should consider abundance or diversity of arbuscular mycorrhizal fungi when managing crops. New Phytol. 220, 1092–1107.

Sánchez Vallduví, G.E., Sarandón, S.J., 2011. Effects of changes in flax (Linum usitatissimum L.) density and interseeding with red clover (Trifolium pratense L.) on the competitive ability of flax against brassica weeds. J. Sustain. Agric. 35, 914–926.

Sarkar, R.K., Shit, D., 1993. Effect of intercropping cereal, pulse and oilseed crops in redgram on yield, competition and advantage. J. Agron. Crop Sci. 170, 171–176.

Shah, A.N., Iqbal, J., Ullah, A., Yang, G., Yousaf, M., Fahad, S., Tanveer, M., Hassan, W., Tung, S.A., Wang, L., Khan, A., Wu, Y., 2016. Allelopathic potential of oilseed crops in production of crops: a review. Environ. Sci. Pollut. Res. 23, 14854–14867.

Simard, S.W., Beiler, K.J., Bingham, M.A., Deslippe, J.R., Philip, L.J., Teste, F.P., 2012. Mycorrhizal networks: mechanisms, ecology and modelling. Fungal Biol. Rev. 26, 39–60.

Skelton, L.E., Barrett, G.W., 2005. A comparison of conventional and alternative agroecosystems using alfalfa (Medicago sativa) and winter wheat (Triticum aestivium). Renew. Agric. Food Syst. 20, 38–47.

Smith, S., De Smet, I., 2012. Root system architecture: insights from Arabidopsis and cereal crops. Phil. Trans.: Biol. Sci. 367, 1441–1452.

Soetedjo, P., Martin, L.D., Tennant, D., 1998. Productivity and Water Use of Intercrops of Field Pea and Canola. The Regional Institute Online Publishing, accessed 4/2020 < http://www.regional.org.au/au/asa/1998/5/138soetedjo.htm >.

Soetedjo, I.N.P, Martin, L.D., Janes, A.J.V., 2003. Intercropping with canola improves the productivity and sustainability of field pea. The Regional Institute Online Publishing, accessed 4/2020 < http://www.regional.org.au/au/asa/2003/c/4/martin.htm >.

South East Research Farm (SERF), 2015. Intercropping chickpea and flax (Agri-Arm Research Update). Saskatchewan Ministry of Agriculture, Saskatchewan.

South East Research Farm (SERF), 2017. Intercropping of Brassica carinata with various pulse crops (Final Report 20150470). Government of Saskatchewan, Saskatchewan.

Sprent, J.I., Minchin, F.R., 1985. Environmental Effects of Nitrogen Fixation. In: Summerfield, R.J., Roberts, E.H. (Eds.), Grain Legume Crops. Collins, London, pp. 115–144.

Stern, W.R., 1993. Nitrogen fixation and transfer in intercrop systems. Field Crops Res. 34, 335–356.

Szumigalski, A.R., Van Acker, R.C., 2006. Nitrogen yield and land use efficiency in annual sole crops and intercrops. Agron. J. 98, 1030–1040.

Temesgen, A., Fukai, S., Rodriguez, D., 2015. As the level of crop productivity increases: Is there a role for intercropping in smallholder agriculture. Field Crop Res 180, 155–166.

Tilman, D., Snell-Rood, E.C., 2016. Diversity breeds complementarity. Nat. 515, 44–45.

Toffolini, Q., Jeuffroy, M.-H., Mischler, P., Pernel, J., Prost, L., 2017. Farmers' use of fundamental knowledge to re-design their cropping systems: situated contextualisation processes. NJAS - Wageningen J. Life Sci. 80, 37–47.

Tofinga, M.P., Paolini, R., Snaydon, R.W., 1993. A study of root and shoot interactions between cereals and peas in mixtures. J. Agric. Sci. 120, 13–24.

Tongma, S., Kobayashi, K., Usul, K., 2001. Allelopathic activity of Mexican sunflower [Tithonia diversifolia (Hemsl) A. Gray] in soil under natural field conditions and different moisture conditions. Weed Biol. Manag. 1, 115–119.

Trenbath, B.R., 1993. Intercropping for the management of pests and diseases. Field Crop Res. 34, 381–405.

Unkovich, M.J., Baldock, J., Peoples, M.B., 2010. Prospects and problems of simple linear models for estimating symbiotic N_2 fixation by crop and pasture legumes. Plant Soil 329, 75–89.

van Dam, N.M., Tytgat, T.O.G., Kirkegaard, J.A., 2009. Root and shoot glucosinolates: a comparison of their diversity, function and interactions in natural and managed ecosystems. Phytochem. Rev. 8, 171–186.

Vandermeer, J.H., 1989. The ecology of intercropping. Cambridge University Press, New York.

VanKoughnet, B., 2015. On-farm evaluation of peaola intercropping. Agri Skills Inc., Manitoba Pulse and Soybean Growers, Manitoba.

VanKoughnet, B., 2016. On-farm evaluation of peaola intercropping – an intercrop of peas and canola. Agri Skills Inc., Manitoba Pulse and Soybean Growers, Manitoba.

Verret, V., Pelzer, E., Bedoussac, L., Jeuffroy, M.-H., 2020. Tracking on-farm innovative practices to support crop mixture design: The case of annual mixtures including a legume crop. Eur. J. Agron. 115, 126018.

Waterer, J.G., Vessey, J.K., Stobbe, E.H., Soper, R.J., 1994. Yield and symbiotic nitrogen fixation in a pea-mustard intercrop as influenced by N fertilizer addition. Soil Biol. Biochem. 26, 447–453.

Wendling, M., Büchi, L., Amossé, C., Jeangros, B., Walter, A., Charles, R., 2017. Specific interactions leading to transgressive overyielding in cover crop mixtures. Agric. Ecosyst. Environ. 241, 88–99.

Western Applied Research Corporation (WARC), 2016. Chickpea flax intercropping: can flax stress chickpea to hasten seed set and maturity and/or act as a barrier to disease spread (Final Report 20130460). Saskatchewan Ministry of Agriculture, Saskatchewan.

Westman Agricultural Diversification Organization (WADO), 2018a. Effect of applied urea and agrotain treated urea in soybean and flax intercrop. Westman Agricultural Diversification Organization 2018 Annual Report. Westman Agricultural Diversification Organization, Manitoba, pp. 61–65.

Westman Agricultural Diversification Organization (WADO), 2018b. Relay crop/ intercrop legumes in hemp grain production. Westman Agricultural Diversification Organization 2018 Annual Report. Westman Agricultural Diversification Organization, Manitoba, pp. 66–70.

Westman Agricultural Diversification Organization (WADO), 2018c. Effect of fungicide and alfalfa understory with pea-canola intercrop production. Westman Agricultural Diversification Organization 2018 Annual Report. Westman Agricultural Diversification Organization, Manitoba, pp. 74–81.

Wooley, J., Lepiz, R., Aquinas-Portes, Y., Castro, T., Voss, J., 1991. Bean cropping systems in the tropics and subtropics and their determinants. In: van Schoonhoven, A., Voysest, O. (Eds.), Common beans: Research for crop improvement. CIAT, Colombia, pp. 679–706.

Zarea, M.J., Ghalavand, A., Goltapeh, E.M., Rejali, F., Zamaniyan, M., 2009. Effects of mixed cropping, earthworms (Pheretima sp.), and arbuscular mycorrhizal fungi (Glomus mosseae) on plant yield, mycorrhizal colonization rate, soil microbial biomass, and nitrogenase activity of free-living rhizosphere bacteria. Pedobiol. 52, 223–235.

Zarea, M.J., Karimi, N., Goltapeh, E.M., Ghalavan, A., 2011. Effect of cropping systems and arbuscular mycorrhizal fungi on soil microbial activity and root nodule nitrogenase. J. Saudi Soc. Agric. Sci. 10, 109–120.

Zentner, R.P., Wall, D.D., Nagy, C.N., Smith, E.G., Young, D.L., Miller, P.R., Campbell, C. A., McConkey, B.G., Brandt, S.A., Lafond, G.P., Johnston, A.M., Derksen, D.A., 2002. Economics of crop diversification and soil tillage opportunities in the Canadian prairies. Agron. J. 94, 216–230.

Zhou, Y., Coventry, D.R., Gupta, V.V.S.R., Fuentes, D., Merchant, A., Kaiser, B.N., Li, J., Wei, Y., Liu, H., Wang, Y., Gan, S., Denton, M.D., 2020. The preceding root system drives the composition and function of the rhizosphere microbiome. Genome Biol. 21, 89.

CHAPTER 3: Chickpea-linseed intercropping has greater nitrogen uptake land use efficiency than sole crops, but this not does translate to overyielding

Alyce Dowling, Penny Roberts, Ashlea Doolette, Yi Zhou, Matthew D Denton

School of Agriculture, Food and Wine, University of Adelaide, Urrbrae, South Australia, 5064,

Australia

European Journal of Agronomy

Submitted manuscript

Statement of Authorship

Title of Paper	Chickpea-linseed intercropping has greater nitrogen uptake land use efficiency than sole crops, but this does not translate to overyielding.
Publication Status	☐ Published ☒ Submitted for Publication ☐ Accepted for Publication ☐ Unpublished and Unsubmitted work written in manuscript style
Publication Details	submitted manuscript to European Journal of Agronomy

Principal Author

Name of Principal Author (Candidate)	Alyce Dowling		
Contribution to the Paper	Planned the study, conducted all experiments, analysed and interpreted data, wrote the manuscript		
Overall percentage (%)	85%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	02/09/2022

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate to include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Penny Roberts		
Contribution to the Paper	Supervised development of work, helped with set-up of studies, helped with data interpretation, edited the manuscript.		
Signature		Date	27/09/2022

Name of Co-Author	Ashlea Doolette		
Contribution to the Paper	Supervised development of work, edited the manuscript.		
Signature		Date	16/09/2022

Name of Co-Author	Yi Zhou

Contribution to the Paper	Supervised development of work, edited the manuscript.		
Signature		Date	9/9/2022

Name of Co-Author	Matthew D Denton		
Contribution to the Paper	Supervised development of work, edited the manuscript.		
Signature		Date	21/09/2022

Chickpea-linseed intercropping has greater nitrogen uptake land use efficiency than sole crops, but this not does translate to overyielding

Alyce Dowling[a**], Penny Roberts[b], Ashlea Doolette[a], Yi Zhou[a**], Matthew D Denton[a*]

[a]School of Agriculture, Food, and Wine, The University of Adelaide, Waite Campus, Urrbrae, SA 5064, Australia

[b]South Australian Research and Development Institute, Clare, SA 5453, Australia

*Corresponding author: Matthew D Denton matthew.denton@adelaide.edu.au, Main Waite Building, The University of Adelaide, Waite Campus, Urrbrae, SA 5064, Australia

**Co-corresponding authors: Alyce Dowling alyce.dowling@adelaide.edu.au, Yi Zhou Yi.Zhou@adelaide.edu.au, Main Waite Building, The University of Adelaide, Waite Campus, Urrbrae, SA 5064, Australia

Keywords

Legume-oilseed intercropping, yield, nitrogen dynamics, low input system

Abstract

In large-scale mechanised systems, intercropping has traditionally utilised cereal-legume pairings with the aim of overyielding. However, as the price of fertiliser rises globally, interest in legume-oilseed intercropping as a low input system is increasing. Legume-oilseed intercropping provides the same benefits as cereal-legume intercrops, whilst also mitigating many of the logistical challenges that have previously stymied widespread adoption of intercropping in broadacre systems. In this study, four legume-oilseed intercropping field experiments were established over the 2019 and 2020 winter growing seasons, utilising chickpea (*Cicer arietinum* L.) and linseed (*Linum usitatissimum* L.). The intercrop was compared to the respective sole crops for its yield and nitrogen and phosphorus uptake efficiency under varying nitrogen (N) and phosphorus (P) fertiliser treatments. There were three levels of nitrogen treatment (0 kg N ha^{-1}, 25 kg N ha^{-1}, 50 kg N ha^{-1}), and two levels of phosphorus treatment (0 kg P ha^{-1}, 20 kg P ha^{-1}) combined to create six overall fertiliser treatments (0N0P, 0N20P, 25N0P, 25N20P, 50N0P, 50N20P). Yield was not affected by fertiliser treatment, and there was no significant difference between total intercrop yield and sole crop yield, with the intercrop yielding 78% and 103% of sole chickpea and linseed, respectively). Intercrop nitrogen uptake land use efficiency was improved, with the sole crops needing 27% more land to achieve the same nitrogen uptake. Intercropping also increased nitrogen fixation in the chickpea, with 36% and 44% Ndfa in the sole and intercrop chickpea, respectively. Conversely, intercrop phosphorus uptake land use efficiency was reduced, with the sole crops needing 8% less land to achieve the same phosphorus uptake. Overall, chickpea-linseed intercropping shows promise as a more nitrogen efficient system that provides yield stability, but does not appear to offer any grain overyielding or phosphorus efficiency benefits in a Mediterranean climate.

1. Introduction

Intercropping is the practice of growing multiple crop species together in the same area for a sustained period of time (Betencourt et al., 2012; Dowling et al., 2021). Intercrops are often associated with improved yield efficiency (yield produced per unit area) compared with their monocrop counterparts, owing to increased resource use efficiency (Chapagain and Riseman, 2014; Temesgen et al., 2015), reduced disease (Lithourgidis et al., 2011; Dowling et al., 2021), and improved weed competition (Ilnicki and Enache, 1992; Sánchez Vallduví and Sarandón, 2011) facilitated by the multi-species interactions. Despite these reported advantages, intercropping is largely confined to more easily manipulated smaller-scale subsistence systems, due to the increased complexity of managing multiple species (Lithourgidis et al., 2011; Brooker et al., 2015; Fletcher et al., 2016). However, as the price of fertiliser (Li et al., 2019; Randive et al., 2021) and other management inputs rise, there is increasing grower interest in, and adoption of, intercropping at the broadacre scale as a lower input and lower cost system that doesn’t sacrifice yield (Khanal et al., 2021). Grower adoption of intercropping in mechanised farming is motivated primarily by a desire to lower costs, achieved through a reduced need for inputs and a reduced risk of total crop failure

(Fulwood, 2020; Bremer and Greer, 2021). Many of the logistical challenges that have previously prevented the adoption of intercropping in broadacre systems can be overcome through recent improvements in crop varieties and herbicide management options, as well as innovative use of current farm machinery and careful consideration of species combinations (Fletcher et al., 2020; Bremer and Greer, 2021; Dowling et al., 2021).

Intercrop species selection can be manipulated to suit different environments and to fulfil different purposes (Table 1). Across multiple environments legume-oilseed mixtures have shown the most consistent benefits (Collis, 2020; Bremer and Greer, 2021). For example, peaola (pea-canola) and faba bean-canola show potential in the Mediterranean climatic zone of southern Australia (Collis, 2020). Similarly, peaola and chickpea-linseed are popular options among growers in the Canadian prairie cropping regions (Bremer and Greer, 2021; Government of Canada, 2021a,b). Legume-oilseed intercrops mitigate many of the logistical issues associated with the more traditional cereal-legume pairings at the broadacre level (Dowling et al., 2021). Unlike cereal-legume mixtures, legume-oilseed intercrops provide a break crop benefit in the cereal dominated crop rotations common to many cropping systems globally. As broadleaf crops, the combination of legumes and oilseeds offers a broader range of in-season herbicide management options than cereal-legume pairings. Current seeding equipment can be altered to sow the legume and oilseed in one pass (SERF, 2015), with extra time and cost (relative to sole crops) required only at the seed cleaning stage (Dowling et al., 2021).

Table 1. Types of intercropping in broadacre systems

Intercropping System	Key Species Pairings	Advantages	Disadvantages	Example
legume-oilseed	soybean-sunflower pea-canola (peaola) chickpea-linseed faba bean-canola	• legume nitrogen fixation • cereal weed herbicide options • emerging broadleaf herbicide options • retain break crop advantage • reduced disease • maintain soil AMF populations • risk reduction (can be cut for silage and sold as high-quality feed) • reduce lodging, elevate low-habit legumes on rocky soils	• difference in optimum grain moisture content at harvest leading to different moisture content in stored mixed seed	Wendling et al., 2017 Dong et al., 2018
legume-legume	faba bean-lentil	• legume nitrogen fixation • herbicide compatibility • ease of harvest (reduce lodging, elevate low-habit legumes on rocky soils) • risk reduction (can be cut for silage and sold as high-quality feed)	• disease	Mikić et al., 2015
cereal-legume	wheat-pea wheat-faba barley-pea maize-soybean	• legume nitrogen fixation • well studied – abundant research • ease of harvest (reduce lodging, elevation of low-habit legumes on rocky soils) • increased yield efficiency (overyielding) • risk reduction through multiple uses (can be cut for silage and sold as high-quality feed)	• poor fit for current rotations: (either sacrifice cereal yield or legume break crop benefit) • herbicide incompatibilities • difference in optimum grain moisture content at harvest leading to different moisture content in stored mixed seed	Jensen et al., 2020 Layek et al., 2018

cereal-oilseed	wheat-sunflower barley-canola	• potential biofumigation benefits (brassica)	• no nitrogen fixation benefits • difference in optimum grain moisture content at harvest leading to different moisture content in stored mixed seed	Andersen et al., 2005 Andersen et al., 2007
grain-companion **(grain harvested as cash crop, companion terminated in-season)**	wheat-tillage radish canola-vetch canola-clover	• weed suppression • potential nitrogen benefits (legume) • potential biofumigation benefits (brassica) • potential use as a grazing option	• compromise grain yields • no break crop benefit in cereal-dominant systems	Lorin et al., 2015 Emery et al., 2021

Chickpea-linseed intercrops have been successfully adopted in the prairie cropping regions of Canada (WARC, 2016; Fletcher, 2020), and may be viable for broadacre systems in Mediterranean-type climates. Chickpea (*Cicer arietinum* L.) is a high value pulse crop with large markets in the Middle East and India, and, after beans and peas, is the most important legume crop grown. Australia is the third largest chickpea producer globally (Merga and Haji, 2019). Linseed (*Linum usitatissimum*) is a high value oilseed crop with select, but profitable, markets for both the oil and whole seed. Chickpea and linseed intercrops can act as physical barriers to host-specific diseases (WARC, 2016), have complementary rooting patterns (Gan et al., 2009), and are ecologically compatible in terms of time to maturity. Importantly, the combination of a legume and non-legume engages the complementary and facilitative nutrient acquisition and nutrient use niches of these two crop types; legumes can fix their own nitrogen, leaving the soil pool for the non-legume, and many also excrete root exudates that can mobilise phosphorus bound up in the soil (Veneklaas et al., 2003). This potentially reduces the need for additional fertiliser, which is increasingly one of the largest input costs for farmers (Li et al., 2019; Randive et al., 2019).

In these experiments I investigated the effect of varying nitrogen and phosphorus fertiliser regimes on the yield and nutrient dynamics of chickpea-linseed intercrop as a means to examine the viability of oilseed-pulse intercropping as a low-input nutrient management strategy in mechanised broadacre systems in low to medium rainfall Mediterranean environments. I hypothesised i) that intercrop yield would be greater than sole crop yields, ii) that intercrop yield would be less affected by variation in fertiliser application than the sole crop, and iii) that intercrop nitrogen and phosphorus concentrations in above ground biomass would be higher than in their respective sole crops.

2. Methods

2.1 Study sites and management

A total of four field experiments were undertaken over the course of the 2019 and 2020 winter growing seasons (May-early December) in the lower mid-North region of South Australia, Australia (two experiments per year). In 2019, two rainfed experiments were established at Karawatha farm, Pinery, (34°19’28.7”S, 138°29’25.4”E), and the University of Adelaide Roseworthy Campus, Roseworthy (34°30’38.4”S, 138°40’37.4”E). In 2020, one rain fed experiment and one irrigated experiment were established at Turretfield Research Farm in Kingsford, South Australia (34°31’27.0”S, 138°41’29.3”E). Experiments undertaken in 2019 at Pinery and Roseworthy are referred to as P2019 and RW2019 respectively, and the rainfed and irrigated experiments undertaken at Kingsford in 2020 are referred to as K2020 and I2020, respectively.

The experimental locations have a Mediterranean-type climate, with a winter growing season that is generally cool and wet (May-August), followed by a drying and warming spring-summer period (September-Dec) during which grain filling occurs (Table 2).

Table 2. Environmental variables at the four site-years.

	P2019	**RW2019**	**K2020**	**I2020**
Pre-season rainfall (mm) (Rainpre)	36.0	64.0	122.4	122.4
Sowing to flowering rainfall (mm) (RainStoF)	108.2	103.4	116.8	116.8
Flowering to maturity rainfall (mm) (RainFtoM)	43.5	49	118.2	138.2
Season cumulative rainfall (mm) (RainSea)	151.7	152.4	235	255
Annual cumulative rainfall (mm) (RainYr)	187.7	216.4	357.4	377.4
Background soil nitrate 0-10cm (mg/kg) (PreN)	11	52.3	21	21
Background soil Colwell phosphorus 0 to 10cm (mg/kg) (PreP)	21	82	64	64
Soil pH (H2O) 0 to 10cm (soilpH)	8.5	7.9	7.6	7.6
Soil organic C 0 to 10cm (%) (organicC)	1.6	2.2	2.1	2.1
EC 0 to 10cm (dS/m) (EC)	0.195	0.210	0.194	0.194
Thermal time to flowering (°C) (GDDflow)	851	851	940	940
Thermal time to podding (°C) (GDDpod)	1205	1205	1328	1328
Thermal time to harvest (°C) (GDDharv)	1784	1784	2304	2304

In the year preceding, barley cv Compass, was grown at both P2019 and RW2019, and the pasture legume *Medicago truncatula* was grown at K2020 and I2020.

2.2 Study species

In all experiments, kabuli chickpea, *Cicer arietinum* L., cultivar Genesis 090, was used as the legume crop component and linseed, *Linum usitatissimum* L., cultivar Croxton, was used as the oilseed component.

2.3 Field experiments

Prior to sowing, field sites were treated with pre-seeding herbicides Round Up (active ingredient 410 g L^{-1} glyphosate) at 1.5 L/ha, Hammer 400EC (active ingredient 400 g L^{-1} carfentrazone-ethyl) at 0.03 L ha^{-1}, and Trifluralin 480 g L^{-1} at 1.4 kg ha^{-1}). Subsequent control of weeds was achieved through a mixture of hand weeding and controlled application of glyphosate using a hand-held brush. Although hand-weeding is not possible in broadacre farming, its use was necessary to properly investigate nutrient and yield dynamics in a system where weeds were sufficiently controlled. Further, as in-season herbicide options and herbicide-tolerant crop varieties improve, intercrop weed control will become less problematic. Insecticide (Chlorpyrifos 500 g L^{-1} at 0.9 L ha^{-1} and Bifenthrin 100 g L^{-1} at 0.2 L ha^{-1}) was applied one week after sowing to control pests such as mites and termites.

All experiments were sown in a 3-bay (column) design, with plots of 10 m × 1.83 m, consisting of eight rows spaced 0.229 m apart. The experiments at P2019 and RW2019 were sown on 30 May 2019, and the experiments at K2020 and I2020 sown on 5 June 2020. The rainfed experiments (RW2019, P2019, and K2020) followed a split-plot design with species as the main plot (sole chickpea, sole linseed, intercrop), and nitrogen and phosphorus fertiliser as the split-plot. Sole chickpea and sole linseed were sown at 35 and 40 plants m^{-2}, respectively, while the intercrop was sown at the sole crop densities, but over half the area, in alternating 2:2 rows of chickpea:linseed. There were three N fertiliser treatments: 0N (0 kg N ha^{-1}), 25N (25 kg N ha^{-1}), and 50N (50 kg N ha^{-1}), and two P fertiliser treatments; 0P (0kg P ha^{-1}), and 20P (20 kg P ha^{-1}), that were combined to make six N-P fertiliser treatments in total (0N0P, 0N20P, 25N0P, 25N20P, 50N0P, 50N0P). P fertiliser was applied simultaneously with the seed as granular SSP (8.8% P), while N fertiliser was applied to the plots post-sowing by hand as urea (46% N). There were four replicates of 18 species × N level × P level combinations, totalling 72 plots for each experiment.

The irrigated experiment (I2020) followed a split- plot design, with species as the main plot, and N fertiliser application as the split- plot. Species and N fertiliser application included the same levels as the rainfed experiments, with 20 kg P ha^{-1} applied to all plots as granular SSP

(8.8% P). There were four replications of nine species × N fertiliser combinations, totalling 36 plots for the experiment. The irrigated experiment was irrigated with 20 mL water on 27/October/2020 (early podding stage of chickpea) using dripper lines.

2.3 Measurements

Plant emergence was measured 37 and 48 days after sowing (DAS) at P2019 and RW2019, and 34 and 47 DAS at I2020 and K2020, and a mean of these used. In the sole crop, the number of plants from five randomly selected 1 m lines were counted and averaged to give the number of plants m^{-2}. In the intercrop, three randomly selected 1m lines from each species were used.

Above ground biomass production was assessed at mid vegetative, mid flowering, pod filling, and maturity stages of the chickpea, which corresponded with 72, 111, 138, and 167 DAS at P2019 and RW2019, and 87, 117, 150, and 181 DAS at K2020 and I2020. At each of the four sampling stages, 1m × 8 rows of biomass were collected by hand for each plot, with the first 50 cm being discarded to account for edge effects and the second 50 cm dried and weighed. In the intercrop plots, species were processed separately. For the sample taken at maturity, vegetative biomass and grain were weighed separately to calculate Harvest Index (Equation 1). On the 14 November 2019 (175 DAS) at P2019 and RW2019, and on the 10 December 2020 (195 DAS) at K2020 and I2020, all plots were harvested using an 8-row harvester. Due to the four in-season biomass harvests of 1 m × 8 rows, plots were only 6m long by the time of grain harvest. Intercrops were harvested together and later separated into species by hand thrashing and sieving.

Dried plant material collected from the 0N0P, 0N20P, and 50N0P plots during the mid-vegetative and maturity stages was ground, acid digested and run through an Inductively Coupled Plasma (ICP) spectrometer to measure the phosphorus content (mg g^{-1}). Dried plant material collected from the 0N0P, 0N20P, and 50N0P (50N20P at I2020) plots during the mid-flowering and maturity stages were ground, milled to a fine powder, and then analysed using mass spectrometry to measure the total N (μg) and $\delta^{15}N$ content. All fertiliser levels were not included in nutrient analysis due to cost restraints.

NDVI was measured using a hand-held Trimble Green Seeker ® at the same flowering and harvest on the same time as the biomass cuts.

2.4 Calculations

Harvest Index (HI) was calculated from the biomass samples taken at maturity using equation 1:

$$HI = GY/AGB \qquad (1)$$

Where GY is grain yield (g $plot^{-1}$) and AGB is aboveground biomass (g $plot^{-1}$).

The Land Equivalency Ratio (LER) is an index used to measure the relative area a crop requires as a monoculture to produce the same yield it achieves in an intercrop (Mead and Wiley, 1980). A value greater than one indicates an advantage of the intercrop per unit area. To measure the relative efficiency of the intercrop in terms of nitrogen and phosphorus yield, a modification of the LER was employed, as per Kwabiah (2005) and Szumigalski and Van Acker (2006). A value greater than one indicates greater land use efficiency in the intercrop as a function of nitrogen and phosphorus yield. Nitrogen and Phosphorus LER were calculated using equations 2 and 3:

$$NLER = N_{ICa} / N_{SCa} + N_{ICb} / N_{SCb} \qquad (2)$$

$$PLER = P_{ICa} / P_{SCa} + P_{ICb} / P_{SCb} \qquad (3)$$

Where N_{ICa} and P_{ICa} are the nitrogen and phosphorus amounts (kg ha^{-1}) of the first species in the intercrop, N_{SCa} and P_{SCa} are the nitrogen and phosphorus amounts of the first species as a sole crop, N_{ICb} and P_{ICb} are the nitrogen and phosphorus amounts of the second species in the intercrop, and N_{SCb} and P_{SCb} are the nitrogen and phosphorus amounts of the second species as a sole crop. As per Szumigalski and Van Acker (2006) and Oyejola and Mead (1982), each intercrop replicate was calculated individually using the replicate values for the numerators (N_{ICa} and N_{ICb} or P_{ICa} and $_{ICb}$) and the mean sole crop value of all the replicates for the denominators (N_{SCa} and N_{SCb} or P_{SCa} and P_{SCb}). The values for each replicate were then averaged to give a mean value for each fertiliser level.

Partial LER (pLER) is an index that measures the relative yield productivity of one component within the intercrop. It can also be used as a measure of competition. Where the pLERs of each crop component are the same, interspecies competition is at equilibrium. pLER is calculated as a section of the LER equation. Nitrogen and Phosphorus pLERs were calculated as follows in Equation 4 and 5:

$$pNLER_a = N_{ICa} / N_{SCa} \qquad (4)$$

$$pPLER_a = P_{ICa} / P_{SCa} \qquad (5)$$

Where N_{ICa} and P_{ICa} are the nitrogen and phosphorus amounts (kg ha^{-1}) of crop A in the intercrop, and N_{SCa} and P_{SCa} are the nitrogen and phosphorus amounts of crop A in sole crop.

The %Ndfa (percent of nitrogen derived from the atmosphere) was calculated using the ^{15}N natural abundance method (equation 6):

$$\%\text{Ndfa} = \frac{\delta^{15}\text{N linseed} - \delta^{15}\text{N chickpea}}{\delta^{15}\text{N linseed} - B} \times 100 \qquad (6)$$

Where δ^{15}N linseed is δ^{15}N of the linseed in the closest proximity to the chickpea plant and B is the δ^{15}N of shoots of legumes that are fully dependent on N_2 fixation and sampled at the same growth stage as the field plants (-1.75, from Unkovich et al., 2008).

2.5 Data analysis

Data were initially analysed using ASReml-R in the statistical program R (Rstudio Team, 2020). Each site by year was considered a separate environment, 'site-year', and data were combined across sites for Multiple Environment Trial (MET) analysis. A separate linear mixed model was built for all yield and yield component variables measured, as well as NLER and PLER values. The model specified site-year × species × N fertiliser × P fertiliser as the fixed effects and replicate × site-year as the random effects. The residual errors for each site were modelled using spatial analysis. Spatial analysis attempts to account (as much as possible) for differences within and between experimental sites that are hard to control (e.g. slope, moisture gradients etc.) by building them into the model. In this way, site-year and significant row or column effects were included in the random and residual sections of the model.

Repeated measures were analysed using a linear mixed model to assess variables measured over time. The structure was similar to the earlier linear mixed models, but the repeated measures was specified in the residual error by sample number.

The association between the soil and weather conditions at each site-year and the measurement variables was explored through principal component analysis (PCA), using the FactoMineR package (Lê et al., 2008) in R. A PCA was performed that included all fertiliser combinations (0N0P to 50N20P) as treatments, with yield, yield components, NDVI and biomass as the measurement variables. The PCA was based on a Pearson correlation matrix, and the biplot was constructed from the two principal components explaining the largest percentages of variance.

3. Results

3.1 Grain yield and biomass

Fertiliser treatment did not affect the grain yield of either the sole chickpea or linseed, or the intercrop. Grain yield was influenced more by environmental conditions than by crop nutrition, being more strongly correlated to site-year rainfall, particularly pre-season rainfall, and thermal time (GDD) than to either fertiliser treatment or soil background levels of nitrogen and phosphorus (Fig 1; Table 3).

Table 3. Correlation coefficient between key environmental conditions and experimental variables and chickpea and linseed grain yield (cpGY, linGY, respectively)

	cpGY	**linGY**
Pre-season rainfall (preRain)	0.67	0.84
Rainfall: sowing-flowering (RainStoF)	0.59	0.72
Rainfall: flowering-maturity RainFtoM)	0.68	0.83
In-season rainfall (seaRain)	0.67	0.83
Annual rainfall (annRain)	0.68	0.85
Background soil P (PreP)	0.3	0.4
Background soil N (PreN)	-0.09	-0.08
Growing degree days to flowering (GDDflow)	0.67	0.82
Growing degree days to podding (GDDpod)	0.67	0.82
Growing degree days to harvest (GDDharv)	0.67	0.82
Phosphorus treatment (Pfert)	0.13	0.15
Nitrogen treatment (Nfert)	0.03	0.02

Principal component scores of the first two dimensions (Dims) explained 63.3% of the variability at the site-year × treatment level (Fig. 1). Component Dim1 had significant loadings for nine crop measurements (0.94-0.43, $P < 0.01$), five environmental variables (0.91-0.56, $P < 0.01$), and one treatment variable (intercropping, -0.68, $P < 0.05$). Component Dim 2 had significant loadings for 5 crop measurements (0.62- -0.42, $P < 0.01$) and 5 environmental variables (0.94- -0.68, $P < 0.001$). Plots were clustered by site-year, and within site-years there was clustering of the intercrop and sole crop plots (Fig 1).

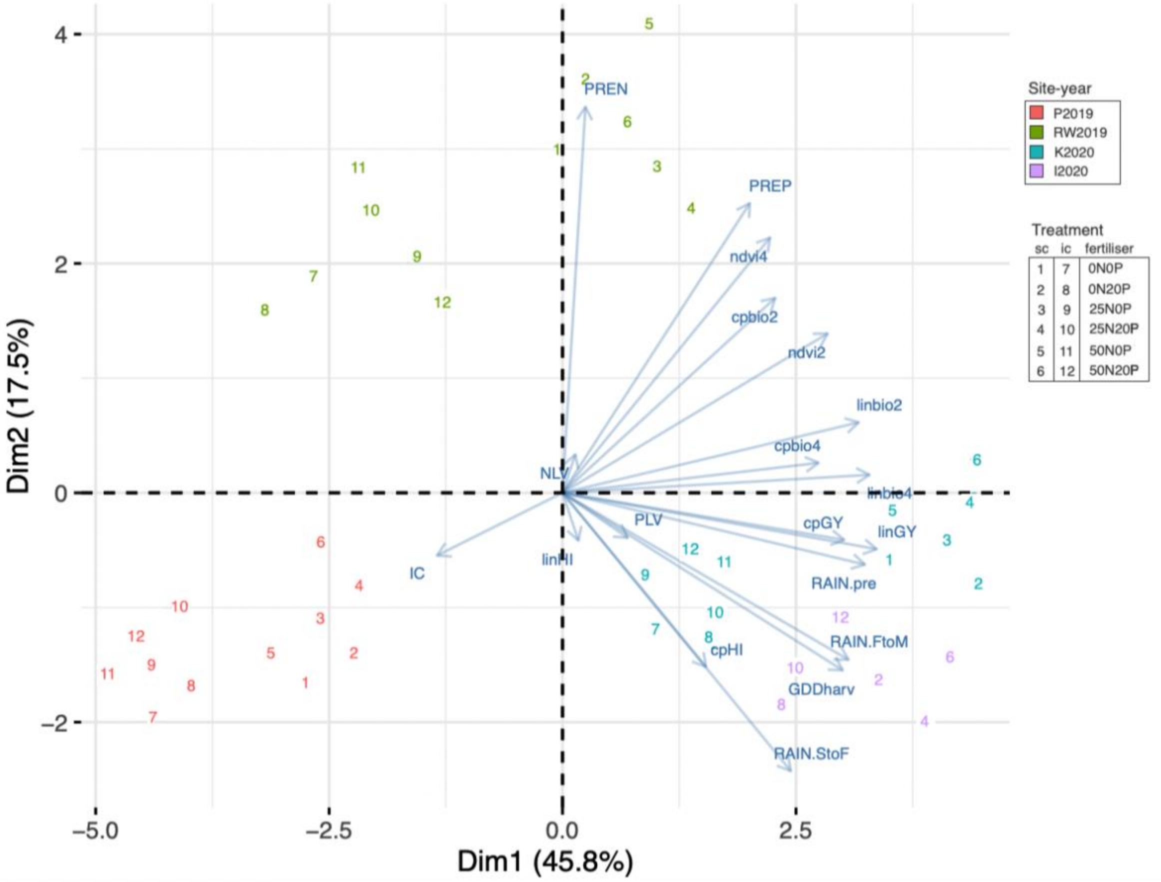

Figure 1. Biplot from the principle component analysis of the relationship between soil and weather conditions (soil background nitrogen *PREN*, soil background phosphorus *PREP*, pre-season rainfall *Rain.pre*, rainfall sowing to flowering *Rain.StoF*, rainfall flowering to maturity *Rain.FtoM*, thermal time to harvest *GDD.harvest*) treatment variables (nitrogen fertiliser *NLV*, phosphorus fertiliser *PLV*, and intercropping *IC*), and crop measurements (grain yield *GY*, plot greenness at flowering and harvest *ndvi2 ndvi4*, chickpea and linseed harvest index *cpHI linHI,* and chickpea and linseed biomass at flowering and harvest *cpbio2 cpbio4 linbio2 linbio4*) at the four different site-years. 'sc' indicates sole crop, 'ic' indicates intercrop and 'fertiliser' indicates fertiliser treatment.

The effect of site-year on yield was significant (*P* < 0.001). Although the chickpea and the linseed grain yield followed the same trend, grain yield of the linseed was more strongly correlated with environmental conditions than the chickpea was (Table 3). Both sole crop and intercrop linseed yielded highest at I2020 and K2020, followed by RW2019, and then P2019. Grain yield of the sole crop chickpea was greatest at I2020 and K2020 followed by RW2019 and then P2019. There was no difference in intercrop chickpea yield between P2019, RW2019 and I2020, while yield at K2020 was greater than at P2019 and RW2019, but similar to that at I2020 (Fig 2).

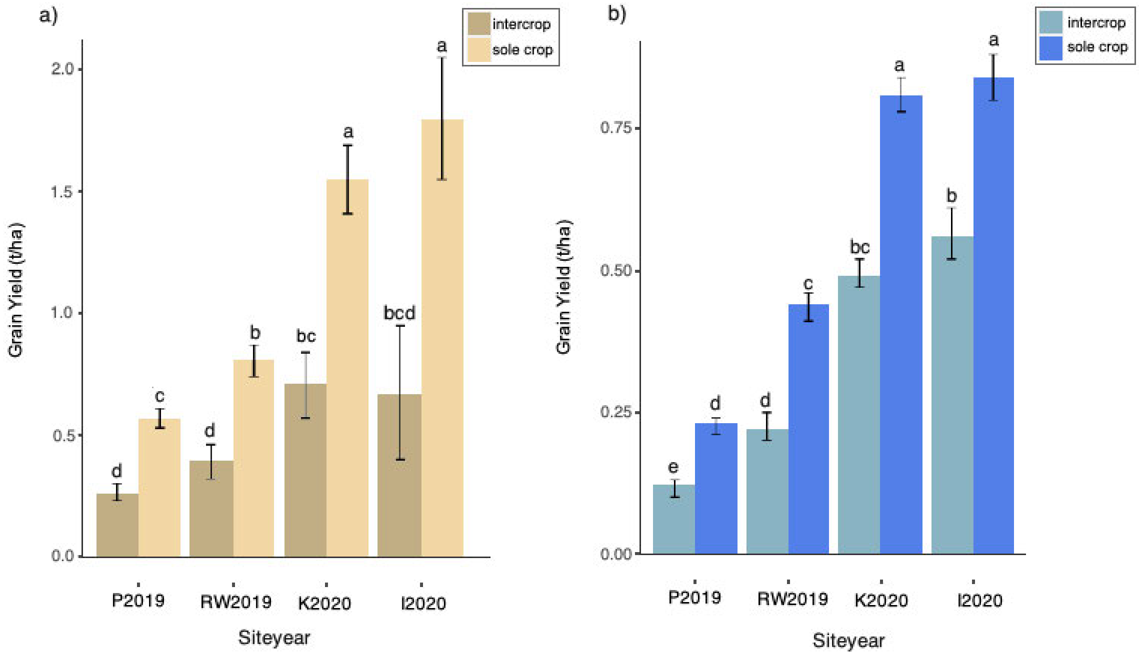

Figure 2. Intercrop and sole crop a) chickpea and b) linseed grain yield at the four site-years, averaged across the fertiliser treatments. Different letters indicate significant difference at $p<0.05$. Error bars indicate ± 1 95% confidence interval.

Intercropping and the intercropping × site-year interaction affected grain yield (P <0.001). At each of the four site-years the intercrop yield was lower than its sole crop counterpart ($P <$ 0.05; Fig 2). However, when intercrop linseed and intercrop chickpea yield were combined to form a total intercrop plot yield there was little difference between sole and intercrop yields (Fig 3). At I2020, K2020 and RW2019 sole chickpea, sole linseed and the intercrop all had similar grain yield, excepting at I2020 in the 50N20P treatment where sole chickpea yielded more than the intercrop, and at RW2019 in the 25N20P, where sole chickpea yielded more than both sole linseed and the intercrop (P < 0.05; Fig 3). At P2019 sole chickpea yielded significantly higher for all fertiliser treatments, with the intercrop yielding more highly than the linseed under the 0N0P, 25N20P, 50N0P and 50N20P, and similarly to the linseed under 0N20P and 25N0P (Fig 3).

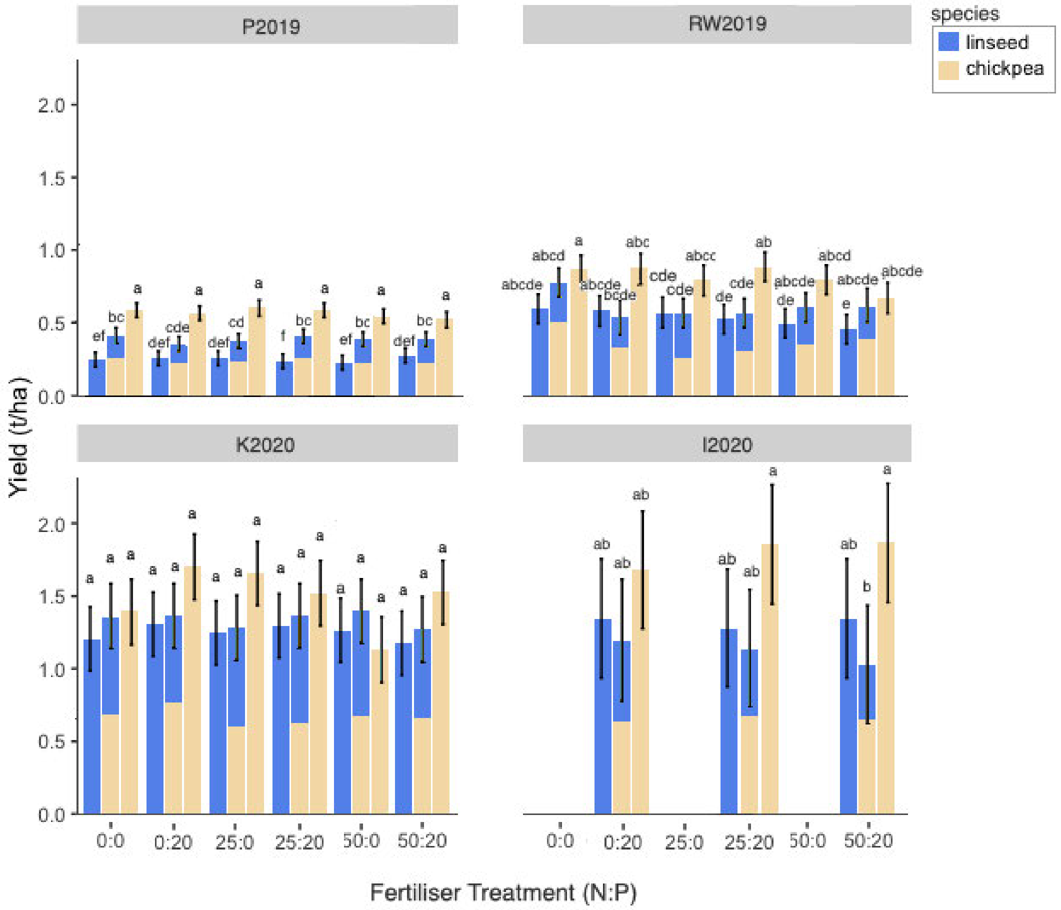

Figure 3. Grain yield of sole crop linseed (left column), sole crop chickpea (right column) and the combined intercrop (middle column) for each fertiliser treatment across the four site-years. Within each site-year, different letters indicate significant difference at $p<0.05$. Error bars indicate ± 1 95% confidence interval.

Aboveground biomass (t ha^{-1}) differed between plant growth stages ($P < 0.001$), being greatest at podding, followed by maturity, flowering, and then the early vegetative stage (Fig. 4). The aboveground biomass of the combined intercrop was greater than that of both sole crops ($P < 0.001$) when averaged across site-years, plant growth stages, and fertiliser levels. The site-year × species ($P < 0.001$) and the site-year × species × plant growth stage ($P < 0.001$) interactions affected aboveground biomass. At I2020 and K2020 the intercrop in the podding stage had greater biomass than the other treatments, while at P2019 the greatest biomass was achieved by the sole chickpea at maturity. At RW2019, biomass was greatest at both the podding and maturity growth stages, and was similar between the sole chickpea, sole linseed and the intercrop (Fig 4). Aboveground biomass was also affected by N treatment (*P* = 0.002), and was greater in the 50N treatment compared with the 0N treatment. The 25N was middling, being similar to both other treatments.

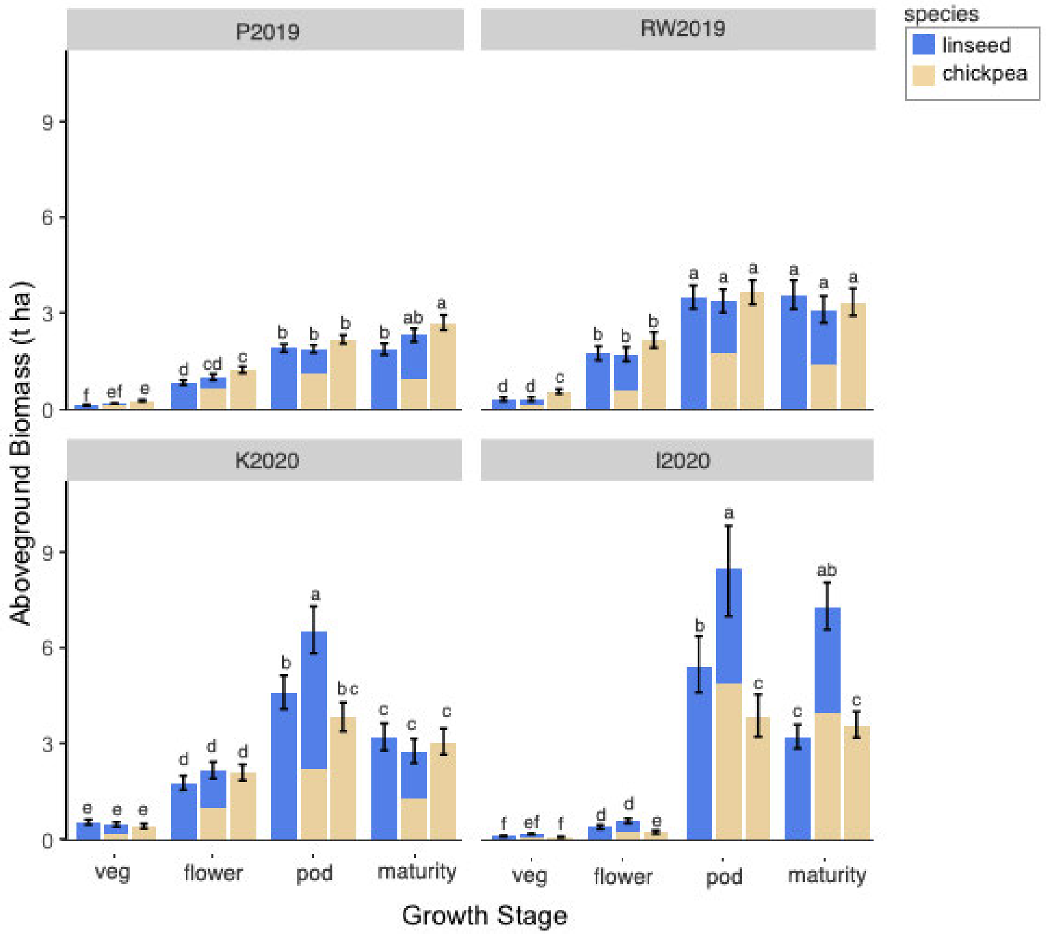

Figure 4. Aboveground Biomass (t ha^{-1}) of sole crop linseed (left column), sole crop chickpea (right column) and the combined intercrop (middle column) at four plant growth stages across the season across the four site-years. Within each site-year, different letters indicate significant difference at p<0.05. Error bars indicate ± 1 95% confidence interval.

3.2 Nutrient dynamics

In analysing nitrogen and phosphorus uptake in above ground biomass, fertiliser treatments were constrained to 0N0P, 0N20P and 50N0P (50N20P at I2020), and 0N0P and 0N20P at

K2020, P2019 and RW2019 in analysing nitrogen fixation (site-year I2020 was excluded from N fixation analysis as it did not have 0P treatments).

Nitrogen and phosphorus uptake (kg ha^{-1}) were affected by site-year (*P* < 0.001), crop type (*P* < 0.001), and plant growth stage (*P* = 0.002 and *P* <0.001 for nitrogen and phosphorus, respectively; Fig 5). Similarly to yield, the nutrient uptake of the intercrop components was reduced when compared with that of their respective sole crops (*P* < 0.001; Fig 5). However, when combined, intercrop nitrogen uptake (53.2 kg ha^{-1}) was similar to that of the sole chickpea (52.7 kg ha^{-1}) and greater than that of the sole linseed (38.0 kg ha^{-1}), while intercrop phosphorus uptake (2.6 kg ha^{-1}) was less than the sole chickpea (3.0 kg ha^{-1}) but similar to the sole linseed (2.4 kg ha^{-1}).

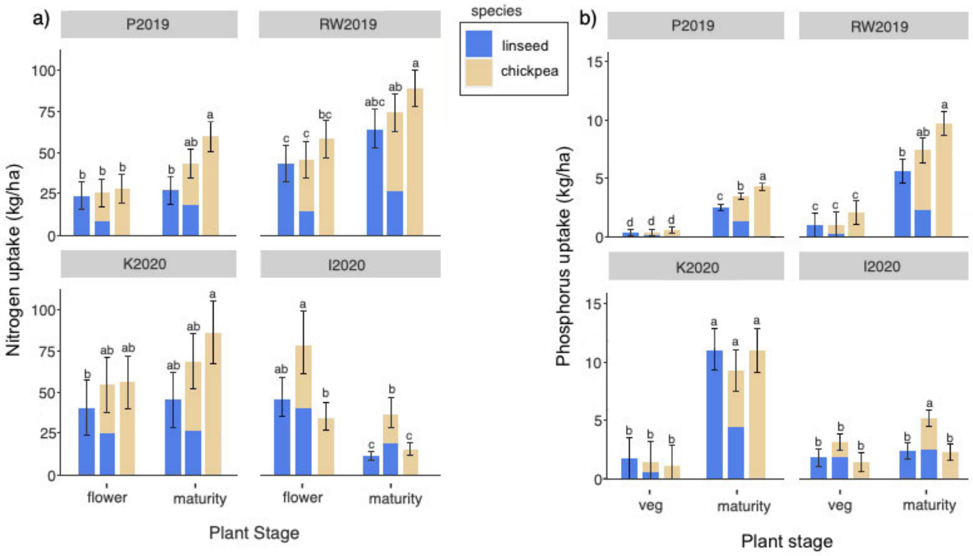

Figure 5. Nitrogen (a) and phosphorus (b) uptake (kg ha^{-1}) in the sole linseed (left column), sole chickpea (right column), and combined intercrop (middle column) at the flowering/vegetative and maturity plant stages at the four site-years. Within each site-year, different letters indicate significant difference at p<0.05. Error bars indicate ± 1 95% confidence interval.

Nitrogen and phosphorus treatments affected nutrient uptake. Averaged across the site-years and species, there was significantly greater nitrogen uptake in the 50N treatment compared with the 0N treatment (51.2 kg ha^{-1} and 44.0 kg ha^{-1}, respectively; *P* = 0.003). However, within each site-year, the difference in uptake between the 0N and 50N treatments was not significant (Table 5). Further, the species × N treatment interaction was not significant, meaning there was no difference in uptake within a species between the 0N and 50N treatments. Phosphorus uptake was affected by phosphorus treatment; across site-years and species there was greater phosphorus uptake in the 20P treatment compared with the 0P treatment (2.6 kg ha^{-1} and 2.9 kg ha^{-1}, respectively; $P < 0.001$). The difference in uptake between the 0P and 20P treatments was significant at K2020 and P2019, but not RW2019 (Table 5).

Table 5. Nitrogen and phosphorus uptake (kg ha^{-1}) in the different nitrogen and phosphorus treatments at the four site-years. Different letters indicate significant difference at p<0.05 within the nutrient uptake type

	Nitrogen uptake kg ha^{-1}		**Phosphorus uptake kg ha^{-1}**	
	0N	**50N**	**0P**	**20P**
P2019	33.1 d	35.8 cd	1.3 e	1.7 d
RW2019	54.9 ab	70.1 a	3.4 ab	3.0 bc
K2020	54.4 abc	57.0 ab	3.6 b	4.7 a
I2020	33.7 cd	44.6 bcd	-	2.4 c

Intercropping improved the nitrogen LER (NLER) of the system ($P < 0.001$), with an intercrop NLER of 1.27 (Fig 6). Conversely, intercropping reduced system phosphorus LER (PLER); the intercrop had a PLER value of 0.92 compared with 1.00 for the sole crops ($P < 0.001$; Fig 7). Siteyear affected both NLER and PLER ($P < 0.001$). Averaged across intercropping and fertiliser treatments, NLER and PLER were highest at I2020 followed by the other three site-years, which were all similar. Neither phosphorus nor nitrogen treatment affected NLER. Interestingly, while PLER was not affected by phosphorus treatment, it was affected by nitrogen treatment, being higher in the 0N treatment than the 50N ($P = 0.03$).

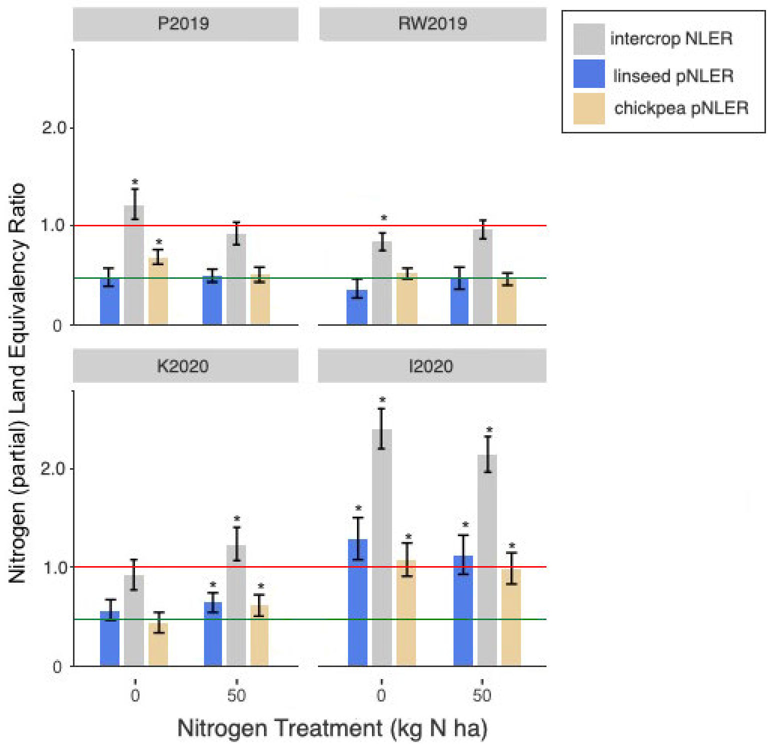

Figure 6. Partial and total Nitrogen Land Equivalency Ratio (intercrop linseed = blue left column, intercrop chickpea= beige right column, total intercrop = grey middle column) in the 0N and 50N treatments at each of the four site-years. Red line indicates sole crop LER of 1, green line indicates sole crop pLER of 0.5, * indicates significant difference from sole crop NLER of 1 ($p<0.05$) or sole crop pNLER of 0.5 ($p<0.05$). Error bars indicate ± 1 95% confidence interval.

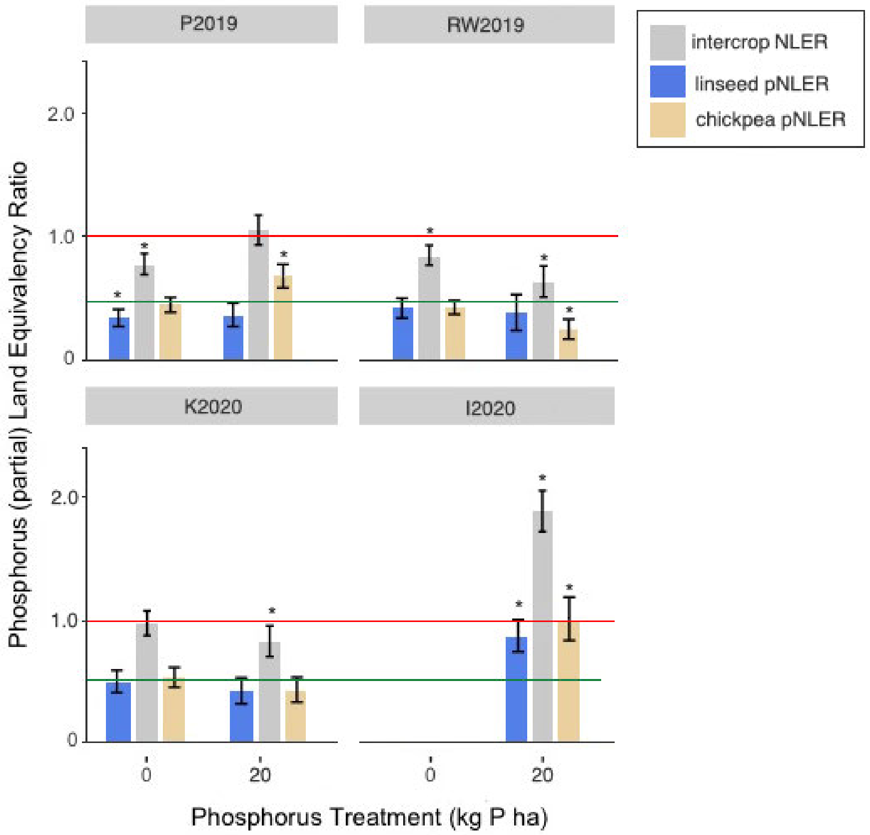

Figure 7. Partial and total Phosphorus Land Equivalency Ratio (intercrop linseed = blue left column, intercrop chickpea= beige right column, total intercrop = grey middle column) in the 0N and 50N treatments at each of the four site-years. Red line indicates sole crop LER of 1, green line indicates sole crop pLER of 0.5, * indicates significant difference from sole crop LER of 1 ($p<0.05$) or sole crop pPLER of 0.5 ($p<0.05$). Error bars indicate ± 1 95% confidence interval.

Across the site-years, %Ndfa (percent of nitrogen derived from atmosphere) in the chickpea was affected by intercropping, with greater fixation in the intercrop chickpea than in the sole crop chickpea (*P* = 0.004; Fig 8). %Ndfa also differed between site-years (*P* = 0.005), being greatest at RW2019 (52% Ndfa), followed by P2019 and K2020 (28% and 29% Ndfa, respectively; Fig 8).

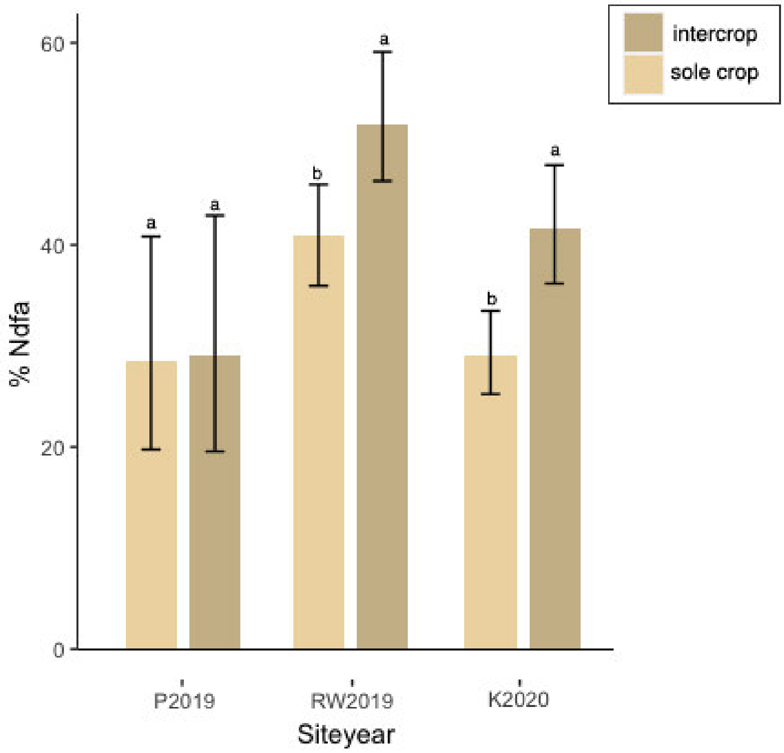

Figure 8. Percent of nitrogen derived from the atmosphere (%Ndfa) in the sole crop (left column) and intercrop (right column) chickpea at K2020, P2019, and RW2019. Within each site-year, different letters indicate significant difference at $p<0.05$. Error bars indicate ± 1 95% confidence interval.

Across the siteyears, %Ndfa was not affected by phosphorus treatment or plant growth stage. However, at RW2019 specifically, fixation was greater at flowering compared with at maturity (57 and 44% Ndfa, respectively; $P = 0.02$).

Discussion

In contrast to our hypothesis, there was no difference between sole crop yields and those of the combined intercrop. This is in also contrast to the literature, which reports overyielding in a range of oilseed-legume pairings (e.g. pea-canola Holzapfel, 2013; VanKoughnet, 2016, soybean-sunflower Dedio, 1994; Echarte et al., 2011, chickpea-linseed SERF, 2015; WARC, 2016). However, intercropping can be utilised for a number of reasons beyond increased yield; indeed, farmer adoption of intercropping is primarily motivated by the reduced cost of inputs and reduced risk, with overyielding viewed as a secondary benefit (Kirkegaard and

Condon, 2019; Fulwood, 2020). In this way, an intercrop with improved resource use efficiency or increased yield stability across environments can add value overall, even in the absence of overyielding. In our experiments, the intercrops were more nitrogen efficient (had greater nitrogen uptake (g kg^{-1}) per unit area) but less phosphorus efficient (had reduced uptake (g kg^{-1}) per unit area) than the sole crops, and intercropping appeared to improve chickpea yield stability.

In line with our second hypothesis, fertiliser treatment had no effect on the grain yield of the intercrop; however, the grain yields of the sole chickpea and linseed were similarly unaffected. Regardless of differences in environmental conditions between the site-years, the 'nil' fertiliser treatment (0N0P) had similar grain yield to the 'high' fertiliser treatment (50N20P). Even at the irrigated site-year, where water was not a limiting factor, there was no fertiliser treatment yield response. The PCA biplot highlighted the weak relationship between fertiliser treatment and crop outcomes. This null fertiliser response suggests that the background soil nitrogen and phosphorus levels were sufficient to support crop requirements. Indeed, the background Colwell-P values of the soil at all site-years (Table 2) were well above the critical range for most oilseeds (16-19 mg kg^{-1}) and legumes (20-29 mg kg^{-1}) in low to mid rainfall environments (Bell et al., 2013).

However, in typical monoculture systems it would be unsustainable in the long term to rely on background soil resources to fulfil crop nutrient requirements. Such practices will lead to depletion of soil nutrient pools, negatively affecting crop growth and yield over time (Cadot et al., 2018). While legume crops, such as the chickpea, can fulfil their own nitrogen requirements through Biological Nitrogen Fixation (BNF), oilseed crops, such as linseed, will deplete soil reserves without adequate fertilisation. Further, both chickpea and linseed require additional phosphorus to sustain growth over multiple seasons. By contrast, intercrops have been shown to maintain yield over the long term under low fertilisation, through synergistic interspecies interactions that improve overall system resource use efficiency (Holzapfel et al., 2013; Cadoux et al., 2015; VanKoughnet et al., 2016; Jensen et al., 2020). In our experiments, in partial support of our third hypothesis, this appeared to be the case in terms of intercrop nitrogen, but not phosphorus, dynamics.

At three of the four site-years (excluding RW2019), the intercrop showed significantly improved land use efficiency in terms of nitrogen uptake compared with the sole crops, and greater or similar absolute N uptake (kg N ha^{-1}). The intercrop NLER of 1.27 indicates that to uptake the same amount of nitrogen as the intercrop, the respective sole crops would need 27% more land. Moreover, fertiliser treatments had no effect on NLER, suggesting improved nitrogen uptake efficiency in the intercrop under varying soil nitrogen availabilities. The improved nitrogen uptake efficiency in the intercrop could be a function of the increased biological nitrogen fixation (BNF) of the chickpea component. The intercrop chickpea had increased %Ndfa compared with the sole chickpea. BNF is inhibited by high levels of soil inorganic nitrogen (Peoples et al., 1995; Génard et al., 2016). In an intercrop, if the non-legume component outcompetes the legume for soil nitrogen, the legume will be forced to fix atmospheric nitrogen, improving the overall nitrogen use efficiency of the system. The increased NLER in the intercrop compared with the sole crop suggests just this; the chickpea fixed its own nitrogen while the linseed utilised the soil pool or fixed nitrogen released by the chickpea (Jensen, 1996; Fustec et al., 2010; Chalk et al., 2014; Lorin et al., 2016; Génard et al., 2016, 2017). In utilising these complementary sources of nitrogen, intercropping may present the possibility to reduce nitrogen fertiliser application, reducing input costs, without any yield penalty.

In contrast to the high NLER, the intercrop had reduced phosphorus land use efficiency and absolute P uptake (kg P ha^{-1}) compared with the sole crops. I2020 was the only site-year at which the intercrop had a greater PLER and greater P uptake (kg ha^{-1}) than the sole crops. While one out of four site-years does not provide sufficient evidence to suggest that intercropping improves system phosphorus efficiency, it is interesting to note. I2020 had the highest rainfall of the four site-years, suggesting an interaction between water availability and phosphorus efficiency that affects the intercrop more than the respective sole crops. One possible mechanism could simply be the inherent increase in uptake due to the increased intercrop biomass; the greater the biomass per unit area, the greater demand for phosphorus uptake (Eichler-Löbermann et al., 2020). At I2020, intercrop biomass was greater than that of the sole chickpea at all of the growth stages measured, and was greater than that of the sole linseed at the podding stage. Having increased biomass relative to the sole crops from the vegetative stage may have allowed the intercrop to uptake more phosphorus than the sole crops over the season. P acquisition from the soil during the vegetative phase is particularly important, as by the podding stage, remobilisation of P from senescing tissues becomes the greatest source of P for the growing grain, rather than uptake from the soil (Gavito and Miller, 1998; Grant et al., 2005; Veneklaas et al., 2012). That the intercrop at I2020 had greater P uptake (kg ha^{-1}) than both sole crops at maturity supports the idea of increased uptake throughout the season as a consequence of greater biomass. However, more work into the effect of water availability on intercrop nutrient dynamics is needed, as I have limited data from this study.

The greater intercrop biomass relative to the sole crops is itself an interesting result. At all growth stages at I2020 and at the podding stage at K2020, the intercrop had significantly greater biomass than both the sole chickpea and linseed. I2020 and K2020 received the most rainfall of the site-years, with I2020 receiving an additional 20ml of irrigation at podding. It is possible that the intercrop was able to utilise the rainfall more effectively than the sole crops, as observed through increased biomass, which in turn enabled even greater water capture. Intercrops have been shown to acquire and consume more water than their sole crop counterparts, largely as a result of an improved canopy development and extended growing period (Soetedjo et al., 1998; Andrade et al., 2012; Coll et al., 2012; Yin et al., 2020). In our study, canopy structure differed among treatments, with increased canopy cover in the intercrop compared with sole linseed. Increased canopy cover reduces evaporation and water loss, thereby increasing water availability, particularly early in the season when the top layers of the soil are moist (Turner, 1996; Soetedjo et al., 1998; Jahansooz et al., 2007; Zhang et al., 2012). Further, the intercrop linseed showed signs of an extended growing period (delayed maturity and prolonged greenness) compared with the sole crop.

Intercropping appears to have improved chickpea yield stability across the varying environmental conditions. While yield of the chickpea sole crop decreased with decreasing rainfall, intercrop chickpea yield was similar among P2019, K2020, and I2020, despite the latter two site-years having considerably more rainfall during the critical pre-season and flowering to maturity periods. Compared with the sole chickpea, the yield of the chickpea in the intercrop was more stable across environments and varying water availabilities.

While the findings of this study begin to answer some questions surrounding nutrient and yield dynamics in oilseed-legume intercropping, more research is needed. Future studies should be implemented at sites where the background soil nutrient profile is not sufficient to maintain plant growth to the extent that it was in our study, in order to properly gauge the effect of varying fertiliser treatments on chickpea-linseed intercrop and sole crop yields. This would entail running trials at the same site over multiple years, as well as at locations with nutrient-limited soils. Further, different oilseed-legume pairings should be investigated, particularly as linseed has a limited global market. In the Mediterranean cropping region of southern Australian, chickpea-canola and lentil-canola combinations may be interesting, given the relative planting areas of these crops. Finally, the effect of water availability on the nutrient dynamics and growth of intercrop compared with sole crop warrants investigation.

Conclusions

The combined yield of the intercrop was similar to that of the respective sole crops. Further, both intercrop and sole crop yield were unaffected by fertiliser treatments, with the nil application treatment having a similar yield to the high application treatment at all site-years. Intercrop phosphorus uptake was similar to that of the linseed and reduced compared with sole chickpea, while intercrop phosphorus uptake land use efficiency was less than the sole crops. The intercrop chickpea had improved nitrogen fixation compared with the sole chickpea, and the combined intercrop had greater nitrogen uptake land use efficiency and absolute uptake than the sole crops. This improved N efficiency may make it feasible to reduce application of fertiliser N, reducing input costs, but more research is needed.

In summary, chickpea-linseed intercropping shows promise as a more nitrogen efficient system that provides yield stability, but does not appear to offer any grain overyielding or phosphorus efficiency benefits in a Mediterranean climate.

Acknowledgements

Support for this study was provided by the Australia Research Council (project ID: IH140100013). Mr Andrew Barr kindly provided land for the experiment at Pinery. Alyce Dowling was supported by the Tim Healey Memorial Scholarship and an Australian Government Research Training Program (RTP) scholarship.

References

Andersen, M.K., Hauggaard-Nielsen, H., Ambus, P., Jensen, E.S. 2005. Biomass production, symbiotic nitrogen fixation and inorganic N use in dual and tri- component annual intercrops. Plant Soil 266, 273–287. doi: 10.1007/s11104-005-0997-1

Andersen, M.K., Hauggaard-Nielsen, H., Weiner, P., Jensen, E.S. 2007. Competitive dynamics in two- and three- component intercrops. J. Appl. Ecol 44, 545–551. doi:10.1111/j.1365-2664.2007.01289.x

Andrade, J.F., Cerrudo, A., Rizzalli, R.H., Monzon, J.P., 2012. Sunflower-soybean intercrop productivity under different water conditions and sowing managements. Agron. J. 104, 1049–1055. doi:10.2134/agronj2012.0051

Bell, M.J., Moody, P.W., Anderson, G.C., Strong, W. 2013. Soil phosphorus – crop response calibration relationships and criteria for oilseeds grain legumes and summer cereal crops grown in Australia. Crop Pasture Sci. 64, 499-513. doi: 10.1071/CP12428

Betencourt E., Duputel, M., Colomb, B., Desclauz, D., Hinsinger, P. 2012. Intercropping promotes the ability of durum wheat and chickpea to increase rhizosphere phosphorus availability in a low P soil. Soil. Biol. Biochem. 46, 181-190. doi: 10.1016/j.soilbio.2011.11.015

Bremer, E., Greer, K. Intercropping Pulse and Oilseed Crops in Southern Alberta. Crops & Soils Magazine, American Society of Agronomy. 2, 52-56. doi: 10.1002/crso.20104

Brooker, R.W., Bennett, A.E., Cong, W-F., Daniell, T.J., George, T.S., Hallett, P.D., Hawes, C., Iannetta, P.P.M., Jones, H.G., Karley, A.J., Li, L., McKenzie, B.M., Pakeman, R.J., Paterson, E., Schöb, C., Shen, J., Squire, G., Watson, C.A., Zhang, C., Zhang, F., Zhang, J., White., P.J. 2015. Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. New Phyto. 206, 107-117. doi: 10.1111/nph.13132

Cadot, S., Bélanger, G., Ziadi, N., Morel, C., Sinaj, S. 2018. Critical plant and soil phosphorus for wheat, maize, and rapeseed after 44 years of P fertilization. Nurt. Cycl. Agroecosyst. 112, 417-433. doi: 10.1007/s10705-018-9956-0

Cadoux, S., Sauzet, G., Valantin-Morison, M., Pontet, C., Champolivier, L., Robert, C., Lieven, J., Flénet, F., Mangenot, O., Fauvin, P., Landé, N. 2015. Intercropping frost-sensitive legume crops with winter oilseed rape reduces weed competition, insect damage, and improves nitrogen use efficiency. Oilseeds Fats Lipids. 22(3), D302.
doi: 10.1051/ocl/2015014

Chalk, P.M, Peoples, M.B., McNeill, A.M., Boddey, R.M., Unkovich, M.J., Gardener, M.J., Silva, C.F., Chen, D. 2014. Methodologies for estimating nitrogen transfer between legumes and companion species in agro-ecosystems: A review of ^{15}N-enriched techniques. Soil Biol. Biochem. 73, 10-21. doi: 10.1016/j.soilbio.2014.02.005

Chapagain, T., Riseman, A. 2014. Barley-pea intercropping: Effects on land productivity, carbon and nitrogen transformations. Field Crops Res. 166, 18-25. doi: 10.1016/j fcr.2014.06.014

Coll, L., Cerrudo, A., Rizzalli, R., Monzon, J.P., Andrade, F.H. 2012. Capture and use of water and radiation in summer intercrops in the south-east Pampas of Argentine.. Field Crops Res. 134, 105-113. doi: 10.1016/j.fcr.2012.05.005

Collis, C., 09 May 2020, “Companion cropping one of five soil health-sensitive measures at Pontifex Farming”. GRDC Ground Cover, 146, accessed 10 Dec 2021, <https://groundcover.grdc.com.au/grower-stories/southern/south-australian-soil-health-strategy-prescribes-crop-diversity >

Dedio, W., 1994. Potential Intercropping of Sunflower with Peas. Helia. 17(20), 63-66.

Dong, N., Tang, M.-M., Zhang, W.-P., Bao, X.-G., Wang, Y., Christie, P., Li, L. 2018. Temporal differentiation of crop growth as one of the drivers of intercropping yield advantage. Nat. Sci. Rep. 8, 10. doi: 10.1038/s41598-018-21414-w

Dowling, A., Sadras, V.O., Roberts, P., Doolette, A., Zhou, Y., Denton, M.D. 2021. Legume-oilseed intercropping in mechanised broadacre agriculture – a review. Field Crops Res. 260:107980. doi: 10.1016/j.fcr.2020.107980

Echarte, L., Maggiora, A.D., Cerrudo, D., Gonzalez, V.H., Abbate, P., Cerrudo, A., Sadras, V.O., Calviño, P. 2011. Yield response to plant density of maize and sunflower intercropped with soybean. Field Crops Res. 121, 423-429. doi: 10.1016/j.fcr.2011.01.011

Eichler-Löbermann, B., Busch, S., Jablonowski, N.D., Kavka, M., Brandt, C. 2020. Mixed Cropping as Affected by Phosphorus and Water Supply. Agron. 10, 1506. doi: 10.3390/agronomy10101506

Emery, S.A., Anderson, P., Carlsson, G., Friberg, H., Larsson, M.C., Wallenhammer, A-C., Lundin, O. 2021. The Potential of Intercropping for Multifunctional Crop Protection in Oilseed Rape (*Brassica napus* L.). Front. Agron. 3. doi: 10.3389/fagro.2021.782686

Fletcher, A.L., Kirkegaard, J.A., Peoples, M.B., Robertson, M.J., Whish, J., Swan., A.D. 2016. Prospects to utilise intercrops and crop variety mixtures in mechanised, rain-fed, temperate cropping systems. Crop Pasture Sci. 67(12), 1252-1267. doi: 10.1071/CP16211

Fletcher, A., Kirkegaard, J., Condon, G., Swan, T., Greer, K., Bremer, E., Holding, J. 26 Feb 2020, “The potential role of companion and intercropping systems in Australian grain farming. Should we be considering them?”. GRDC update papers, accessed 10/12/21 < https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2020/02/the-potential-role-of-companion-and-intercropping-systems-in-australian-grain-farming.-should-we-be-considering-them >

Fulwood, Jo, 20 Jun 2020, “Intercropping study demonstrates potential yield and economic upside”. GroundCover, 147, accessed 10 Dec 2021 <https://groundcover.grdc.com.au/innovation/industry-insights/profitable-intercrops-give-growers-optioins >

Fustec, J., Lesuffleur, F., Mahieu, S., Cliquet, J.-B., 2010. Nitrogen rhizodeposition of legumes: A review. Agron. Sustain. Dev. 30, 57–66. doi: 10.1051/agro/2009003

Gan, Y.T., Campbell, C.A., Janzen, H.H., Lemke, R., Liu, L.P., Basnyat, P., McDonald, C.L. 2009. Root mass for oilseed and pulse crops: Growth and distribution in the soil profile. Can. J. Plant. Sci. 89, 883-893. doi: 10.4141/CJPS08154

Gavito, M.E., Miller, M.H. 1998. Early phosphorus nutrition, mycorrhizae development, dry matter partitioning and yield of maize. Plant Soil. 199, 177-186.

Génard, T., Etienne, P., Diquélou, Yvin, J.-C., Revellin, C., Laîné P., 2017. Rapeseed- legume intercrops: plant growth and nitrogen balance in early stages of growth and development. Plant Biol. 3, 2–20. doi: 10.1016/j.heliyon.2017.e00261

Génard, T., Etienne, P., Laîné, P., Yvin, J.-C., Diquélou, S., 2016. Nitrogen transfer from Lupinus albus L., Trifolium incarnatum L. and Vicia sativa L. contribute differently to rapeseed (Brassica napus L.) nitrogen nutrition. Plant Biol. 2, 2–15. doi: 10.1016/j heliyon.2016.e00150

Government of Canada a, 18 June 2021, “Better Grown Together”. Agriculture and Agri-Food Canada, accessed 10 Dec 2021, < https://agriculture.canada.ca/en/agri-info/better-grown-together >

Government of Canada b, 25 June 2021, “Intercropping – a new planting method for large-scale Prairie agriculture?”. Agriculture and Agri-Food Canada, accessed 10 Dec 2021, <https://agriculture.canada.ca/en/news-agriculture-and-agri-food-canada/scientific-achievements-agriculture/intercropping-new-planting-method-large-scale-prairie-agriculture >

Grant, C., Bittman, S., Montreal, M., Plenchette, C., Morel, C. Soil and fertiliser phosphorus: Effects on plant P supply and mycorrhizal development. Can. J. Plant Sci. 85, 3-14.

Holzapfel, C. 2013. Exploring the Merits of Field Pea-Canola Intercrops. 2012 Annual Project Report for the Agricultural Demonstration of Practices and Technologies (ADOPT) Program. Saskatchewan Ministry of Agriculture. Prepared by Indian Head Agricultural Research Foundation. 26pp.

Ilnicki, R.D., Enache, A.J. 1992. Subterranean clover living mulch: an alternative method of weed control. Agr. Eco. Environ. 40, 249-264. doi: 10.1016/0167-8809(92)90096-T

Jahansooz, M.R., Yunusa, I.A.M., Coventry, D.R., Palmer, A.R., Eamus, D., 2007. Radiation- and water-use associated with growth and yields of wheat and chickpea in sole and mixed crops. Eur. J. Agron. 26, 275–282.

Jensen, E.S. 1996. Grain yield, symbiotic N_2 fixation and interspecific competition for inorganic N in pea-barley intercrops. Plant Soil. 182, 25-38. doi: 10.1007/BF00010992

Jensen, E.S., Carlsson, G., Hauggaard-Nielsen, H. 2020. Intercropping of grain legumes and cereals improves the use of soil N resources and reduces the requirement for synthetic fertiliser N: a global-scale analysis. Agron. Sustain, Dev. 40(5), 9pp. doi: 10.1007/s13593-020-0607-x

Khanal, U. Scott, K.J., Armstrong, R., Nuttall, J.G., Henry, F., Christy, B.P., Mitchell, M., Riffkin, P.A., Wallace, A.J., McCaskill, M., Thayalakumaran, T., O'Leary, G.J. 2021. Intercropping – Evaluating the Advantages to Broadacre Systems. Agric. 11, 453. doi: 10.3390/agriculture11050453

Kirkegaard, J. Condon, G. 19 Feb 2019, "Companion cropping – should we be considering it?". GRDC update papers, accessed 10/12/21 < https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2019/02/companion-cropping-should-we-be-considering-it >

Kwabiah, A.B. 2005. Biological Efficiency and Economic Benefits of Pea-Barley and Pea-Oat Intercrops. J. Sustain. Agric. 25:1, 117-128. doi: 10.1300/J064v25n01_09

Layek, J., Das, A., Mitran, T., Nath, C., Meena, R.S., Yadav, G.S., Shivakumar, B.G., Kumar, S., Lal, R. 2018. Cereal+Legume Intercropping: An Option for Improving Productivity and Sustaining Soil Health. In: Meena, R., Das, A., Yadav, G., Lal, R. (eds) Legumes for Soil Health and Sustainable Management. Springer, Singapore. doi: 10.1007/978-981-13-0253-4_11

Lê, S., Josse, J., Husson, F. 2008. FactoMineR: A Package for Multivariate Analysis. *J. Stat. Softw.* 25(1), 1–18. https://doi.org/10.18637/jss.v025.i01

Li, B., Bicknell, K.B., Renwick, A. 2019. Peak phosphorus, demand trends and implications for the sustainable management of phosphorus in China. Resour. Conserv. Recycl. 146, 316-328. https://doi.org/10.1016/j.resconrec.2019.03.033

Lithourgidis, A.S., Dordas, C.A., Damalas, C.A., Vlachostergios, D.N. 2011. Annual intercrops: an alternative pathway for sustainable agriculture. Aus. J. Crop. Sci. 5(4), 396-410. https://search.informit.org/doi/10.3316/informit.281409060336481

Lorin, M., Jeuffroy, M.-H., Butier, A., Valantin-Morison, M. 2015. Undersowing winter oilseed rape with frost-sensitive legume living mulches to improve weed control. Eur. J. Agron. 71, 96–105. https://doi.org/10.1016/j.eja.2015.09.001

Lorin, M., Jeuffroy, M.-H., Butier, A., Valantin-Morison, M. 2016. Undersowing winter oilseed rape with frost-sensitive legume living mulch: Consequences for cash crop nitrogen nutrition. Field Crops Res. 193, 24-33. http://dx.doi.org/10.1016/j fcr.2016.03.002

Mead, R., Wiley, R.W. 1980. The Concept of a 'Land Equivalent Ratio' and Advantages in Yields from Intercropping. Exp. Agric. 16(3), 217-228. doi: 10.1017/S0014479700010978

Merga, B., Haji, J. 2019. Economic importance of chickpea: Production, value, and world trade. Cogent Food Agric. 5:1, 1615718. https://doi.org/10.1080/23311932.2019.1615718

Mikić, A., Ćupina, B., Rubiales, D., Mihailović, V., Šarūnaitė, L., Fustec, J., Antanasović, S., Krstić, D., Bedoussac, L., Zorić, L., Dordević, V., Perić, V., Srebrić, M. 2015. Models, developments, and perspectives of mutual legume intercropping. Adv. Agron., 130, 337-419. https://doi.org/10.1016/bs.agron.2014.10.004

Oyejola, B.A., Mead, R. 1982. Statistical assessment of different ways of calculating land equivalent ratios (LER). Exp. Agric. 18, 125-138.

Peoples, M.B., Herridge, D.F., Ladha, J.K., 1995. Biological nitrogen fixation: An efficient source of nitrogen for sustainable agricultural production? Plant Soil. 174, 3–28. https://doi.org/10.1007/BF00032239

Randive, K., Raut, T., Jawadand, S. 2021. An overview of the global fertilizer trends and India's position in 2020. Min. Econ. 34, 371-384. https://doi.org/10.1007/s13563-020-00246-z

RStudio Team. 2020. RStudio: Integrated Development for R. RStudio, PBC, Boston, MA < http://www rstudio.com/ >

CHAPTER 4: Oilseed-legume intercropping is productive and profitable in low input scenarios

Alyce Dowling, Penny Roberts, Ashlea Doolette, Yi Zhou, Matthew D Denton

School of Agriculture, Food and Wine, University of Adelaide, Urrbrae, South Australia, 5064, Australia

Agricultural Systems, 204, doi: 10.1016/j.agsy.2022.103551

Statement of Authorship

Title of Paper	Oilseed-legume intercropping is productive and profitable in low input scenarios
Publication Status	☐ **Published** ☒ **Accepted for Publication** ☐ **Submitted for** Publication ☐ Unpublished and Unsubmitted work written in manuscript style
Publication Details	Dowling, A., Roberts, P., Doolette, A., Zhou, Y., Denton, M.D., 2023. Oilseed-legume intercropping is productive and profitable in low input scenarios. Agric. Syst. 204, 103551. doi: 10.1016/j.agsy.2022.103551.

Principal Author

Name of Principal Author (Candidate)	Alyce Dowling		
Contribution to the Paper	Planned the study, conducted Experiment 1, analysed and interpreted all data, wrote the manuscript		
Overall percentage (%)	85%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	02/09/2022

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate to include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Penny Roberts		
Contribution to the Paper	Supervised development of work, conducted Experiment 2, helped with data interpretation, edited the manuscript.		
Signature		Date	27/09/2022

Name of Co-Author	Ashlea Doolette		
Contribution to the Paper	Supervised development of work		
Signature		Date	16/09/2022

Name of Co-Author	Yi Zhou
Contribution to the Paper	Supervised development of work

Signature		Date	9/9/2022

Name of Co-Author	Matthew D Denton		
Contribution to the Paper	Supervised development of work, edited the manuscript.		
Signature		Date	21/9/2022

Oilseed-legume intercropping is productive and profitable in low input scenarios

Alyce Dowling[a*], Penny Roberts[ab*], Ashlea Doolette[a], Yi Zhou[a], Matthew D Denton[a]

[a]School of Agriculture, Food, and Wine, The University of Adelaide, Waite Campus, Urrbrae, SA 5064, Australia

[b]South Australian Research and Development Institute, Clare, SA 5453, Australia

*Corresponding authors: Alyce Dowling alyce.dowling@adelaide.edu.au, and Penny Roberts Penny.Roberts@sa.gov.au

Keywords

LER, gross margins, risk reduction, chickpea, linseed, canola.

Abstract

CONTEXT: The cost of fertiliser and fungicide is rising rapidly, increasing farmers' financial risk and reducing gross margins. By utilising the synergistic interspecies interactions that increase system resource efficiency and provide a buffer against disease, oilseed-legume intercropping may provide an opportunity to allow farmers to maintain yield while reducing these input costs.

OBJECTIVE: To investigate the effect of varying fertiliser and fungicide inputs on the yield efficacy and economics of chickpea-linseed and chickpea-canola intercrops in mechanised broadacre systems in a Mediterranean climate

METHODS: The oilseed species linseed (*Linum usitarissimum* L.) and canola (*Brassica napus* L.) were intercropped with Kabuli chickpea (*Cicer arietinum* L.) in a double skip row arrangement under varying fertiliser and fungicide regimes. These intercrops were compared with their respective sole crops for land use efficiency and economic productivity.

RESULTS and CONCLUSIONS: The land equivalency ratio (LER) of the intercrop under nil fertilisation averaged 1.04 compared with 0.94 under high fertilisation. The LER of the intercrops under nil fungicide averaged 1.39 compared with 0.93 under high fungicide. Intercropping provided gross margin stability across environments, while the gross margins of the sole crops varied depending on environment, a pattern which held even when grain prices and input costs varied. In summary, the greatest intercrop land use and economic benefit occurred in the low input treatments.

SIGNIFICANCE: The overyielding and high gross margins of the low input intercrops suggest that oilseed-legume intercropping may have potential as a profitable lower risk alternative to traditional high input monocultures in a Mediterranean climate.

Introduction

Modern broadacre farming systems rely heavily on external synthetic inputs such as fertilisers and fungicides. Nitrogen and phosphorus fertilisers are applied to stimulate crop growth and maintain yield and profits (Jensen et al., 2020), while fungicide is used to protect against legume diseases such Ascochtya blight and *Fusarium* wilt (GRDC GrowNotes, 2017; Kakoti et al., 2020). However, the cost of such inputs is rapidly rising and is projected to increase further for at least the next decade (USDA, 2022). Rising production costs impact farmers by increasing their financial risk and reducing profit. Besides cost, repeated application of ammonium-based fertilisers, urea, and elemental S fertilizer lowers soil pH below the range for optimum plant growth (Goulding, 2016), reducing yields by an average of 0.04 t ha^{-1} yr^{-1} (Orton et al., 2018). As the price, in both an economic and cost-to-production sense, becomes too great, farmers are seeking innovative ways to reduce synthetic inputs. Increasingly, intercropping is being adopted as a lower input cost system that maximises profits (Fletcher et al, 2020; Khanal et al., 2021).

Historically, intercropping has been confined to the smaller and more easily manipulated subsistence farms of the tropics and subtropics, as the management of multiple species has been considered too complex for the highly specific technology used in large scale broadacre systems (Banik et al., 2000). However, by utilising a legume and oilseed pairing, instead of the more traditional cereal-legume intercrop, the benefits of intercropping (pest suppression, increased nutrient efficiency, potential for overyielding) are maintained whilst mitigating some of the previous barriers to adoption. Oilseed-legume intercrops can be incorporated into cereal rotations, have greater in-season herbicide options than cereal-legume intercrops (both being broadleaf plants), and can easily be sown and harvested concurrently, with minimal alterations to current machinery (Fletcher et al., 2020; Dowling et al., 2021).

Both research and on-farm experience demonstrate that oilseed-legume intercrops can maintain yield relative to sole crops in broadacre systems under lower input scenarios, resulting in greater profit. Indeed, farmer adoption of intercropping has primarily been motivated by the reduced need for fertilizer and pesticide inputs, resulting in lower input costs, reduced risks, and maximised earnings (Kirkegaard & Condon, 2019; Fulwood, 2020). For example, South East Research Farm (SERF, 2015) report that yield in a chickpea-linseed intercrop was greater in the nil nitrogen fertilisation treatment relative to both the intercrop in the fertilised treatment and the sole crops in the fertilised and non-fertilised treatments. Similarly, in a pea-canola (peaola) intercrop, both yield and net profit were improved under nil nitrogen fertilisation compared with fertilised treatments. While sole canola fertilised with 118 kg N ha^{-1} had net earnings of US$657 ha^{-1} and peaola fertilised with 67 kg N ha^{-1} had net earnings of US$663 ha^{-1}, peaola under nil fertiliser application had a net earning of US$ 684 ha^{-1} (VanKoughnet, 2016). Further, Westman Agricultural Diversification Organisation

(WADO, 2018) report no yield difference in a peaola intercrop under a fungicide compared with a nil fungicide regime.

Although oilseed-legume intercropping is becoming increasingly popular in broadacre agriculture, its adoption has not been uniform (Alcon et al., 2020; Fletcher et al., 2020). The majority of research has been conducted in China, northern Europe and Canada, with data in a Mediterranean-type climate lacking (Dowling et al., 2021). The efficacy of oilseed-legume intercropping in the major cropping regions of southern and western Australia, as well as Mediterranean Europe, is relatively understudied, leaving farmers with limited guidelines for undertaking intercropping, despite the economic and productivity benefits it may provide. As such, I investigated the effect of varying fertiliser and fungicide inputs on the yield efficacy and economics of chickpea-linseed and chickpea-canola intercrops as a means to examine the viability of oilseed-legume intercropping as a low-input cost-saving strategy in mechanised broadacre systems in a Mediterranean climate. For both experiments I hypothesised i) that the intercrop would over-yield relative to the respective sole crops and generate a higher gross margin, and ii) that intercrop Land Equivalent Ratio (LER) and gross margins would be higher in the low input treatments compared with high input treatments.

Methods

2.1 Overview

Experiment 1 investigated the effect of varying nitrogen and phosphorus input on the yield and economic efficiency of a chickpea-linseed intercrop relative to their respective sole crops (see chapter 3 for actual yield data). Experiment 2 investigated the effect of varying fungicide input on the yield and economic efficacy of chickpea-linseed and chickpea-canola intercrops relative to their respective sole crops.

2.2 Study sites and management

Experiment 1

A total of four field trials were undertaken in the 2019 and 2020 winter growing seasons (May-early December) in the lower mid-north region of South Australia (see chapter 3). In 2019, two rain fed trials were established at Karawatha farm, Pinery, (34°19’28.7”S, 138°29’25.4”E), and the University of Adelaide Roseworthy Campus, Roseworthy (34°30’38.4”S, 138°40’37.4”E). In 2020, one rain fed trial and one irrigated trial were established at Turretfield Research Farm in Kingsford, South Australia (34°31’27.0”S, 138°41’29.3”E). Trials undertaken in 2019 at Pinery and Roseworthy are referred to as P2019 and RW2019 respectively, and the rainfed and irrigated trials undertaken at Kingsford in 2020 are referred to as K2020 and I2020, respectively.

Experiment 2

Two field trials were undertaken in the 2019 and 2020 winter growing seasons at the Hart Field Research station near Hart, in the mid-north region of South Australia, Australia (33°45' 33.3"S, 138°24' 51.1”E). The trial undertaken in 2019 is referred to as H2019 and the trial undertaken in 2020 is referred to as H2020.

All trial locations have a Mediterranean-type climate, with a winter growing season that is generally cool and wet (May-August), followed by a warm spring (September to November) during which grain filling occurs, and a dry and hot summer period (December to February) under which crops mature and are harvested. Environmental variables at the site-years in Experiment 1 and 2 can be found in Table 1.

Table 1. Rainfall and temperature variables and background soil characteristics in Experiment 1 and 2. There were four site-years in Experiment 1 - Kingsford irrigated site in 2020 (I2020), Kingsford site in 2020 (K2020), Pinery site in 2019 (P2019), and Roseworthy site in 2019 (RW2019). There were two site-years in Experiment 2 -Hart site in 2019 (H2019) and Hart site in 2020 (H2020). *The +20 indicates the 20ml of irrigation applied in the flowering to maturity phase at the Kingsford irrigated site 2020 (I2020)

	Experiment 1				**Experiment 2**	
	P2019	**RW2019**	**K2020**	**I2020**	**H2019**	**H2020**
Pre-season rainfall (mm)	36.0	64.0	122.4	122.4	76	211
Sowing to flowering rainfall (mm)	108.2	103.4	116.8	116.8	154	96
Flowering to maturity rainfall (mm)	43.5	49	118.2	118.2(+20)	39	159
Season cumulative rainfall (mm)	151.7	152.4	235	235(+20)	193	255
Annual cumulative rainfall	187.7	216.4	377.4	377.4	277	499
Soil nitrate 0-10cm (mg kg^{-1})	11	52.3	21	21	5	10
Soil Colwell phosphorus 0-10cm (mg kg^{-1})	21	82	64	64	33	35
Soil pH (H_2O) 0-10cm	8.5	7.9	7.6	7.6	8.5	8.5
Soil Organic C (%) 0-10cm	1.6	2.2	2.1	2.1	1.4	1.4
EC 0-10cm (dS m^{-1})	0.195	0.210	0.194	0.194	0.179	0.179
Thermal time to flowering (°C)	851	851	940	940	847	920
Thermal time to podding (°C)	1205	1205	1328	1328	1540	1653
Thermal time to harvest (°C)	1784	1784	2304	2304	2186	2392

In the year preceding, barley (cv Compass) was grown at both P2019 and RW2019, and a medic pasture legume (*Medicago truncatula*) was grown at K2020 and I2020. In the year proceeding, oat hay (cv Mulgara) was grown at H2019 and H2020.

2.3 Study species

Experiment 1

Kabuli chickpea (*Cicer arietinum* L., cultivar Genesis 090) was used as the legume crop component. Kabuli chickpea is a major pulse crop in the southern Australian grain growing region and has high market relevance, both as an export and for domestic consumption (GRDC GrowNotes, 2017). As part of crop rotation, chickpea has helped alleviate problems caused by continuous cereal cropping such as fungal root diseases, the depletion of soil C and N levels, and herbicide resistance in weeds (Siddique et al., 2000). However, the costs associated with chickpea are relatively high compared with other legumes due to the high fungicide inputs required to protect against Ascochyta blight (caused by the fungus *Phoma rabiei*), the most significant fungal disease affecting chickpeas in southern Australia (GRDC GrowNotes, 2017).

Linseed (*Linum usitarissimum* L., cultivar Croxton) was used as the oilseed component. Although linseed is not typically grown in southern Australia, it has been grown successfully in intercrop with chickpea in Canada's prairie cropping provinces of Saskatchewan and Manitoba, thus establishing the compatibility of linseed and chickpeas as intercrop companions (SERF, 2015; Fletcher et al., 2020).

Experiment 2

Kabuli chickpea (*Cicer arietinum* L., cultivar Genesis 090) was used as the legume crop component and canola (*Brassica napus* L., cultivar AV Garnet) and linseed (*Linum usitarissimum* L., cultivar Croxton) were used as the oilseed components. Canola was additionally included in Experiment 2 due to its potential allelopathic properties, as well as its relevance as a major oilseed break crop in the southern growing region of Australia (Kirkegaard et al., 2008).

2.4 Field trials

Experiment 1

Prior to sowing, field sites were treated with pre-seeding herbicides (Round Up (active ingredient glyphosate) at 1.5 L/ha, Hammer 400EC (active ingredient 400 g/L carfentrazone-ethyl) at 0.03 L/ha, and Trifluralin 480g/L at 1.4 kg/ha). Subsequent control of weeds was achieved through a mixture of hand weeding and controlled application of glyphosate using a hand-held brush. Insecticide (Chlorpyrifos 500g/L at 0.9 L/ha, Bifenthrin 100 g/L at 0.2 L/ha) was applied one week after sowing.

All trials were sown in a 3-bay (column) design, with plots of 10 m × 1.83 m, consisting of eight rows spaced 0.229 m apart. The trials at P2019 and RW2019 were sown on 30 May 2019, and the experiments at K2020 and I2020 sown on 5 June 2020. The rainfed trials (RW2019, P2019, and K2020) followed a split plot design, with species as the main plot, and nitrogen × phosphorus fertiliser as the split plot. Species included 3 treatments: sole chickpea, sole linseed, and chickpea-linseed intercrop. Sole chickpea and sole linseed were sown at 35 and 40 plants m^{-2}, respectively, while the intercrop was sown at the sole crop densities, but over half the area, in alternating 2:2 chickpea:linseed rows. There were three nitrogen fertiliser treatments; 0N (0 kg N ha^{-1}), 25N (25 kg N ha^{-1}), and 50N (50 kg N ha^{-1}), and two P fertiliser treatments; 0P (0 kg P ha^{-1}), and 20P (20 kg P ha^{-1}), that were combined to make six N:P fertiliser treatments in total (0N0P, 0N20P, 25N0P, 25N20P, 50N0P, and 50N20P). The high fertiliser treatment (50N20P) is similar to rates of application in southern Australia (GRDC GrowNotes, 2017). Phosphorus fertiliser was applied simultaneously with the seed as granular single super phosphate (SSP, 8.8% P), while nitrogen fertiliser was applied to the plots by hand post-sowing as urea (46% N). There were four replicates of 18 intercropping × species × N level × P level combinations, totalling 72 plots for each trial.

The irrigated trial (I2020) was carried out to reduce the likelihood of water limitation masking any nutrient availability effects, as the 2019 season had periods of limited rainfall. The irrigated trial followed a split plot design, with species as the main plot, and N fertiliser application as the split plot. Species and N fertiliser application included the same levels as the rainfed experiments, with 20 kg P ha^{-1} applied to all plots (i.e. 0N20P, 25N20P, and 50N20P). 0 kg P ha^{-1} treatments were not included due to the high cost of irrigation infrastructure. There were four replications of nine species × N fertiliser combinations, totalling 36 plots for the trial. The irrigated trial was irrigated with 20 mL water on 27/10/2020 (early podding stage of chickpea) using dripper lines.

Experiment 2

Experiment 2 was sown in the same 3-bay design as Experiment 1, with the same plot and row dimensions. The trial at H2019 was sown on 29 May 2019, and the trial at H2020 was sown on 28 May 2020. Trials followed a split-plot design, with species as the main plot, and fungicide treatment as the split plot. At H2019 species had only three levels: sole chickpea, sole linseed and linseed-chickpea, and at H2020 species had five levels: sole chickpea, sole canola, sole linseed, canola-chickpea, and linseed-chickpea. Fungicide treatment had three levels: foliar fungicide and desiccant (FFD), foliar fungicide only (FF) and nil input (nil). Sole chickpea and sole linseed were sown at 35 and 40 plants m^{-2}, respectively, and sole canola at 1.5 kg seed ha^{-1}. The intercrop was sown at the sole crop densities, but over half the area, in alternating 2:2 canola:chickpea or linseed:chickpea rows. The fungicide used in the FFD and FF treatments was Chlorothalonil applied at 2L ha^{-1}, and the desiccant used in the FFD was Spray Seed 250 (active ingredients 135g L^{-1} paraquat dichloride and 115g L^{-1} diquat dibromide) applied at 2L ha^{-1} (as per regional guidelines for southern Australia; GRDC

GrowNotes, 2017). There were three replicates of species × fungicide combinations, totalling 27 plots at H2019 and 45 at H2020. 80kg ha^{-1} of monoammonium phosphate (MAP) was applied at sowing.

2.5 Measurements

Experiment 1

At 175 days after sowing (DAS) (P2019 and RW2019) and 195 DAS (K2020 and I2020), all plots were harvested using an 8-row harvester. Harvest in 2019 occurred on the 14 November 2019, and harvest in 2020 occurred on 10 December 2020. Intercrops were harvested together and later separated into species. Grain was cleaned and weighed to calculate grain yield.

Experiment 2

Throughout the season plots were monitored for the incidence of Ascochyta blight.

181 DAS (H2019) and 202 DAS (H2020), all plots were harvested using an 8-row harvester. Intercrops were harvested together and later separated into species. Grain was cleaned and weighed to calculate grain yield.

2.6 Calculations

The Land Equivalent Ratio (LER) is an index that measures the relative land area a crop requires as a monoculture to produce the same yield it achieves in an intercrop (Bedoussac et al. 2015). An LER greater than one indicates a yield advantage of the intercrop. LER was calculated using Equation 1:

$$\text{LER} = Y_{ICa} / Y_{SCa} + Y_{ICb} / Y_{SCb} \qquad (1)$$

Where Y_{ICa} is the grain or biomass yield of the first species in the intercrop, Y_{SCa} is the grain or biomass yield of the first species as a sole crop, Y_{ICb} is the grain or biomass yield of the second species in the intercrop, and Y_{SCb} is the grain or biomass yield of the second species as a sole crop. LER was calculated as per Szumigalski & Van Acker (2006) and Oyejola & Mead (1982), wherein the LER for each intercrop replicate was calculated individually using the replicate yield (g/plot) values for the numerators (Y_{ICa} and Y_{ICb}) and the mean sole crop value of all the replicates for the denominators (Y_{SCa} and Y_{SCb}). The LERs for each replicate were then averaged to give a mean LER for each fertiliser level.

Partial LER (pLER) is an index to measure the relative yield productivity of one component within the intercrop (Szumigalski & Van Acker, 2006). It can also be used as a measure of competition. Where the pLERs of each crop component are the same, interspecies competition is at equilibrium. pLER is calculated as a section of the LER equation (equation 1) as follows in Equation 2:

$$pLER_a = Y_{ICa} / Y_{SCa} \qquad (2)$$

Where Y_{ICa} is the grain or biomass yield of crop A in the intercrop, and Y_{SCa} the grain or biomass yield of crop A in sole crop.

Economic Analysis was a gross margin, calculated using Equation 3:

$$\text{income} - \text{costs} = \text{profit (US\$)} \qquad (3)$$

All calculations are based on 2021 input costs (Tables 2, 3 for variable costs, Tables S1, S2 for static costs) and market prices (Table 4) sourced from the Primary Industry Research South Australia (PIRSA) 2021 Farm Gross Margin and Enterprise Planning Guide (PIRSA, 2021). A sensitivity analysis was also conducted. Costs were varied for nitrogen fertiliser (Experiment 1) and foliar fungicide spray (Experiment 2) inputs, using the 5-year (2017-2021) high and low prices (Table 2,3). Phosphorus fertiliser prices were not varied as the price did not vary between 2017-2021. Grain market prices were also varied in line with the 5-year high and low (Table 4). There were five scenarios in the sensitivity analysis; 1. high grain price:high cost (*high:high*), 2. high grain price:low cost (*high:low*), 3. low grain price:high cost (*low:high*), 4. low grain price:low cost (*low:low*), 5. 2021 grain price: 2021 cost (*2021*).

Table 2. 2021 price and 5-year (2017-2021) high and low prices for nitrogen and phosphorus fertilizer and total treatment input costs (US$ ha-^{1}) for Experiment 1

		Fertiliser Treatment					
		0N0P	**0N20P**	**25N0P**	**25N20P**	**50N0P**	**50N20P**
P fertiliser *		-	10.50	-	10.50	-	10.50
N fertiliser	5-year high**	-	-	20.55	20.55	41.10	41.10
	5-year low	-	-	16.75	16.75	33.50	33.50
Sole chickpea	**5-year high**	145.50	156	166.05	176.55	186.60	197.10
	5-year low	145.50	156	162.25	172.75	179.00	189.50
Sole linseed	**5-year high**	202.30	212.80	222.85	233.35	243.40	253.90
	5-year low	202.30	212.80	219.05	229.55	235.80	246.30
Intercrop	**5-year high**	187.90	198.40	208.45	218.95	229.00	239.50
	5-year low	187.90	198.40	204.65	215.15	221.40	231.90

*The price for phosphorus fertiliser remained steady in the 2017-2021 period, so no 5-year high or low was necessary

** The 5-year high nitrogen fertiliser price is also the 2021 price, as the highest price from 2017-2021 occurred in 2021

Table 3. 2021 price and 5-year (2017-2021) high and low prices for fungicide and desiccant and total treatment input costs (US$ ha-^{1}) for Experiment 2

		Fungicide Treatment		
		Nil	**FF**	**FFD**
Fungicide	2021*	2.35	19.95	19.95
	5-year low	2.35	17.35	17.35
Desiccant	2021*	-	-	14.00
	5-year low	-	-	12.95
Sole chickpea	**2021**	112.05	132.00	146.00
	5-year low	112.05	129.40	142.35
Sole linseed	**2021**	166.50	186.70	200.70
	5-year low	166.50	184.10	197.05
Sole canola	**2021**	107.95	127.90	141.90
	5-year low	107.95	125.30	138.25
Chickpea-linseed intercrop	**2021**	154.45	174.40	188.40
	5-year low	154.45	171.80	184.75
Chickpea-canola intercrop	**2021**	125.05	145.00	159.00
	5-year low	125.05	142.40	155.35

*** The 2021 fungicide and desiccant prices are also the 5-year high price, as the highest price from 2017-2021 occurred in 2021

Table 4. 2021 and 5-year (2017-2021) high and low market grain prices

	Grain Price (US$ t-^{1})		
	2021	**5-year high (2017-2021)**	**5-year low (2017-2021)**
Chickpea	379.50	518.30	379.50
Linseed	690.00	760.10	621.90
Canola	379.50	379.50	345.50

2.7 Data Analysis

Experiment 1

Data were initially analysed using ASReml-R in the statistical program R (Rstudio Team, 2020). Each site by year was considered a separate environment, ‘site-year’, and data were combined across sites for multiple environment trial (MET) analysis. A separate linear mixed model was built for the LER, component pLERs and gross margins (sole crop LER and pLER were automatically set at 1 and 0.5, respectively). The model specified treatment (intercropping × N fertiliser × P fertiliser) as the fixed effect and replicate × site-year as the random effect. N fertiliser and P fertiliser were treated as categorical variables. The residual errors for each site were modelled by using spatial methods. Site-year was included in the random and residual sections of the model to allow for spatial analysis, which attempts to account (as much as possible) for differences between experimental sites that are hard to control (e.g. slope, moisture gradients etc.) by building them into the model.

The association between weather conditions at each site-year, intercropping, phosphorus and nitrogen treatments, chickpea and linseed pLERs and total LER was explored through Pearson correlation using the corrplot package (Wei et al., 2018) in R.

For gross margin calculations ‘crop’ was used as a treatment instead of ‘intercropping’, as the costings/earning of the separate intercrop components are less relevant than the costings/earnings of the combined intercrop. ‘Crop’ treatments were sole chickpea, sole linseed, and the intercrop. The I2020 irrigated site-year is included in the gross margin analysis as a slightly wetter year in a rain fed system, and not as an irrigated trial, as irrigated systems are uncommon in the study location and only provided a small proportion of total water provision. That is, the cost of irrigation was not factored into the analysis.

Experiment 2

Data were analysed similarly to Experiment 1. Data were combined across site-years for multiple environment trial (MET) analysis and a separate linear mixed model was built for the LER, component pLERs, and gross margins. The model specified treatment (species × fungicide) as the fixed effect and replicate × site-year as the random effects. Additional site-year-specific extraneous fixed and random terms were included as needed. The residual errors for each site were modelled by using spatial methods.

Results

Grain Land Equivalency Ratio (Experiment 1)

Averaged across treatments, the intercrop had a lower grain LER than the sole crops ($p<0.001$). While the intercrop in the 0N0P treatment had an LER greater than 1, the intercrops in the 0N20, 25N0P and 25N20P had LERs less than 1 ($p<0.05$, Fig 1). Intercropping reduced chickpea pLER relative to the sole crop($p<0.001$), while linseed pLER was not affected. Both intercrop component grain pLERs were positively correlated with grain total LER, but the chickpea more so than the linseed ($r = 0.84$ and $r = 0.45$, respectively).

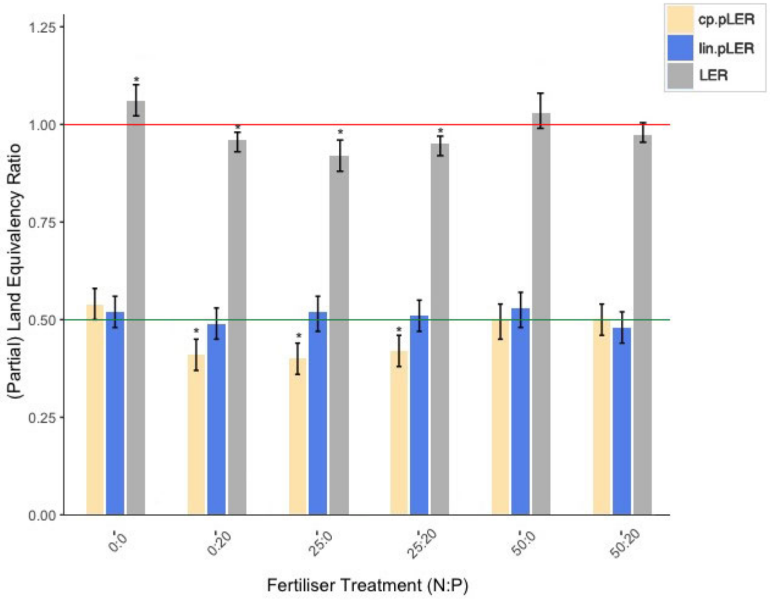

Figure 1. Grain partial Land Equivalency Ratio **(**pLER) (ic (intercrop) chickpea = beige left column, ic linseed = blue middle column) and total Land Equivalency Ratio (LER) (grey right column) in each of the six fertiliser treatments (N:P) averaged across site-years. Red line indicates sole crop LER of 1, green line indicates sole crop pLER of 0.5, * indicates significant difference from sole crop LER of 1 ($p<0.05$) for intercrop total LER or sole crop pLER of 0.5 ($p<0.05$) for component pLER. Error bars indicate ± 1 95% confidence interval.

The effect of nitrogen and phosphorus treatments on grain LER was insignificant (Fig 1). Similarly, neither the chickpea nor linseed grain pLERs were affected by fertiliser treatment.

Grain LERs were the same between the site-years and were not highly correlated to environmental variables. Likewise, neither the chickpea nor linseed grain pLERs were affected by site-year alone. However, both the intercrop chickpea and linseed grain pLERs were affected by the intercropping × site-year interaction ($p<0.01$, df =3, F=13 and $p<0.05$, df = 3, F=8.2, respectively).

Biomass LER (Experiment 1)

The intercrop had a greater LER than the sole crops (1.28 compared with 1.00, $p<0.01$, df = 2, F = 10.78), averaged across site-years and fertiliser treatments (Fig 2).

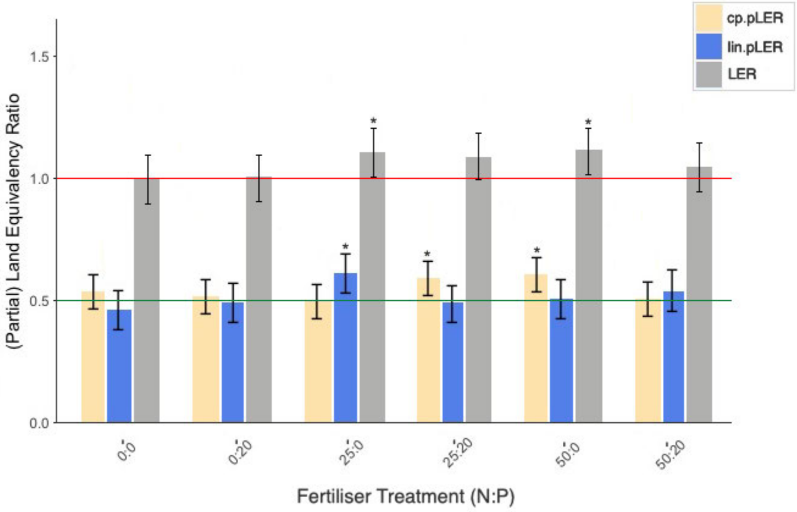

Figure 2. Aboveground biomass partial Land Equivalency Ratio **(**pLER) (ic (intercrop) chickpea = beige left column, ic linseed = blue middle column) and total Land Equivalency Ratio (LER) (grey right column) in each of the six fertiliser treatments (N:P) averaged across the four site-years. Red line indicates sole crop LER of 1, green line indicates sole crop pLER of 0.5, * indicates significant difference from sole crop LER of 1 ($p<0.05$) for intercrop total LER or sole crop pLER of 0.5 for component pLER. Error bars indicate ± 1 95% confidence interval.

Neither biomass LER nor component biomass pLERs were different between fertiliser treatments, but the biomass LERs in the 25N0P and 50N0P treatments were larger than 1 ($p<0.05$; Fig 2). Biomass LERs were different between site-years ($p<0.01$, df = 3, F = 77.6), being bigger at I2020 compared with the other three site-years.

Grain LER (Experiment 2)

Intercropping increased grain LER ($p<0.001$). In the canola-chickpea intercrop, grain LER was larger ($p<0.05$) than the sole crop LER of 1 in the nil and FF treatments, with grain LERs of 1.72 and 1.37, respectively (Fig 3). In the linseed-chickpea intercrop, the grain LER (1.30) was larger than 1 in the FF treatment and less than 1 in FFD treatment (Fig 3).

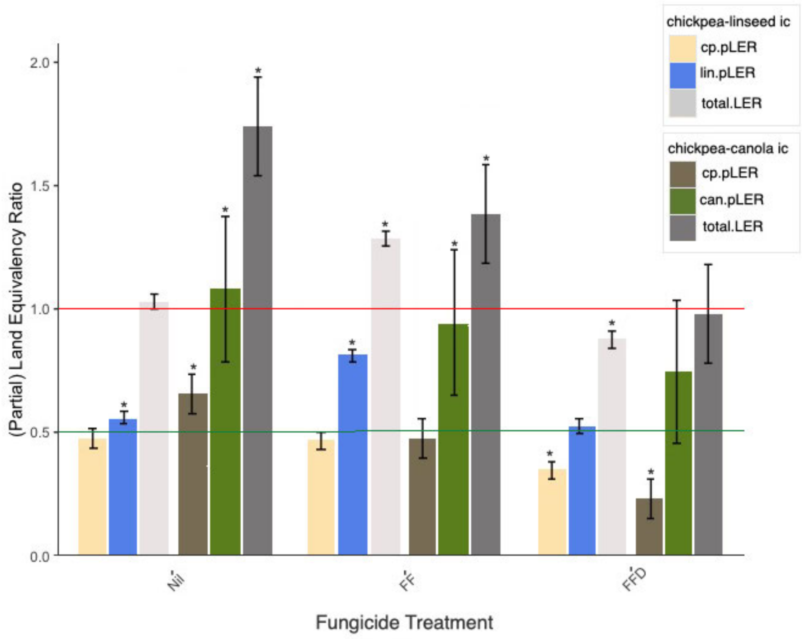

Figure 3. Grain partial Land Equivalency Ratio **(**pLER) and total Land Equivalency Ratio (LER) for the chickpea-linseed intercrop (chickpea pLER = beige, linseed pLER = blue, total LER = light grey) and the chickpea-canola intercrop (chickpea pLER = brown, canola pLER = green, total LER = dark grey) under the three fungicide treatments (Nil-nil application, FF-foliar fungicide, FFD-foliar fungicide + desiccant) averaged across site-years. Red line indicates sole crop LER of 1, green line indicates sole crop pLER of 0.5, * indicates significant difference from sole crop LER of 1 ($p<0.05$) for intercrop total LER or sole crop pLER of 0.5 for component pLER. Error bars indicate ± 1 95% confidence interval.

Grain LER differed among fungicide treatments ($p<0.001$). The highest grain LER in the linseed-chickpea intercrop was in the FF treatment (1.29; $p<0.05$), followed by the nil and then FFD treatments, which were not larger than 1 (1.03 and 0.88, respectively). The LER of the chickpea-canola intercrop was greater in the nil and FF treatments compared with the FDD treatment ($p<0.05$; Fig 3).

The intercropping × fungicide treatment interaction affected component grain pLERs ($p<0.05$; Fig 3). Notably, in the nil treatment all grain pLERs were greater than the sole crop value of 0.5, excepting that of the chickpea component in the chickpea-linseed intercrop ($p<0.05$; Fig 3). Further, in the chickpea-canola intercrop, the canola pLER in the nil treatment was greater than that in the FF and FFD treatments ($p<0.05$; Fig 3). Finally, in the FFD treatment, the pLER of the chickpea component of both intercrops was lower than 0.5 ($p<0.05$; Fig 3).

Biomass LER (Experiment 2)

Intercropping increased aboveground biomass LER ($p<0.01$). The biomass LER was larger than 1 in in the linseed-chickpea intercrop in the nil and FF treatments, and in all treatments in the chickpea-canola intercrop ($p<0.05$; Fig 4).

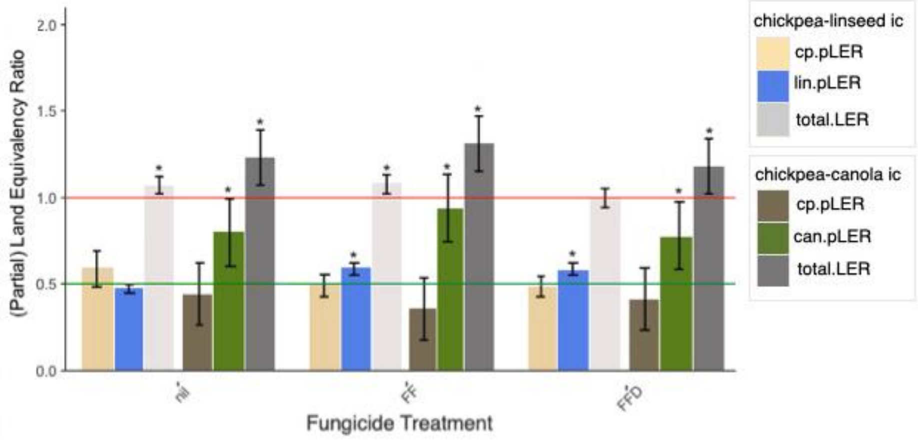

Figure 4. Aboveground biomass partial Land Equivalency Ratio **(**pLER) and total Land Equivalency Ratio (LER) for the chickpea-linseed intercrop (chickpea pLER = beige, linseed pLER = blue, total LER = light grey) and the chickpea-canola intercrop (chickpea pLER = brown, canola pLER = green, total LER = dark grey) under the three fungicide treatments (Nil-nil application, FF-foliar fungicide, FFD-foliar fungicide + desiccant) at H2019 and H2020. Red line indicates sole crop LER of 1, green line indicates sole crop pLER of 0.5, * indicates significant difference from sole crop LER of 1 ($p<0.05$) for intercrop total LER or sole crop pLER of 0.5 for component pLER. Error bars indicate ± 1 95% confidence interval.

Chickpea and linseed biomass pLERs were not affected by intercropping, while canola biomass pLER was increased by intercropping ($p<0.05$; Fig 4). Fungicide treatment affected neither biomass LER nor pLERs in either of the intercrops ($p>0.05$).

Gross Margins (Experiment 1)

Gross margins decreased with increasing nitrogen application, being largest in the 0N treatment (US$ 295.52 ha^{-1}), followed by the 25N (US$ 270.70 ha^{-1}) and then the 50N treatment (US$ 242.14 ha^{-1}) ($p<0.001$, SE ± US$ 10.55 ha^{-1}). Conversely, gross margins were larger in the 20P treatment than the 0P treatment (US$ 303.84 ha^{-1} and US$ 223.61 ha^{-1}, respectively; $p<0.01$, SE. ± $US 10.92 ha^{-1}). Site-year and the site-year × species interaction affected gross margins ($p<0.001$). Notably, at I2020, P2019 and RW2019, the intercrop had a similar gross margin to the higher earning sole crop (Fig 5); at I2020 the linseed and intercrop grossed similarly, at P2019 the chickpea and intercrop grossed similarly, and at RW2019 all three crops grossed similarly. Conversely, at K2020 the sole linseed gross more highly than the intercrop, which in turn grossed more highly than the sole chickpea ($p<0.05$; Fig 5).

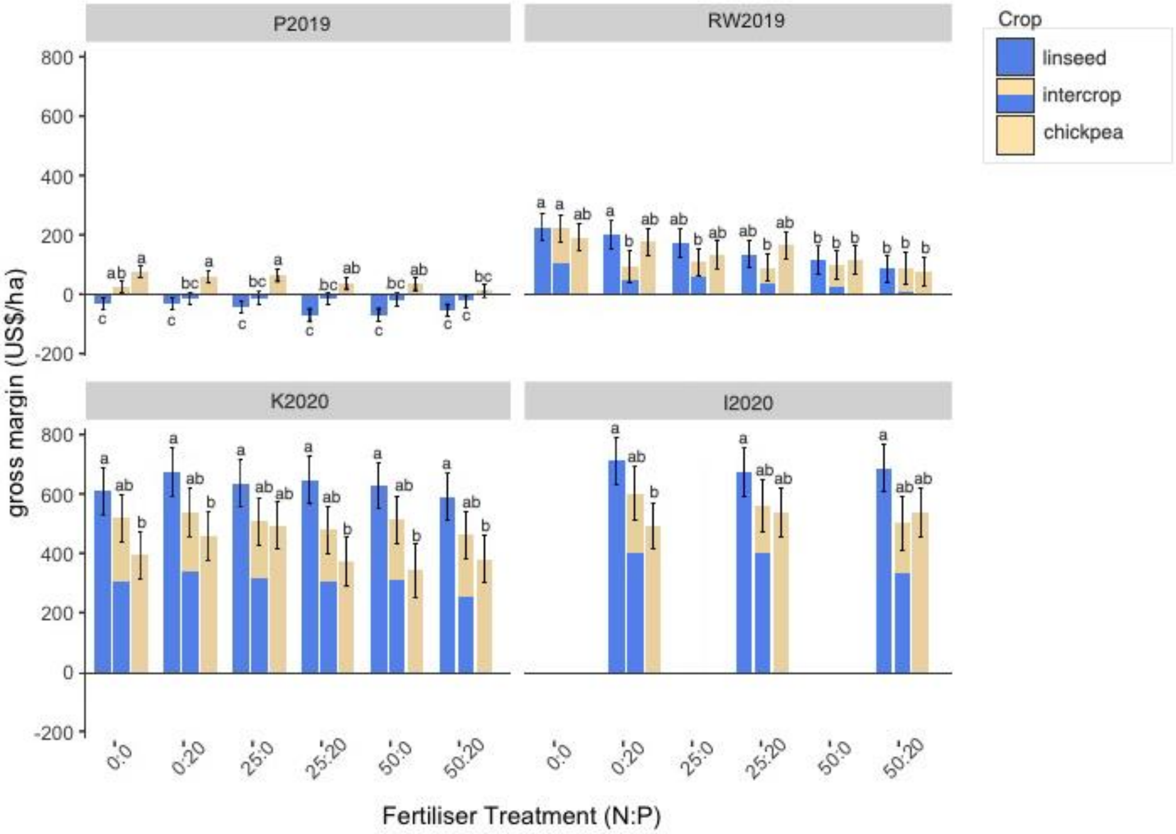

Figure 5. 2021 gross margin (US$ ha^{-1}) for sole linseed (blue; left column), sole chickpea (beige; right column), and intercrop (stacked bar; middle column) for the six fertiliser treatments (N:P) at the four site-years. Error bars indicate ± 1 95% confidence interval. Different letters within a site-year indicate significant difference at $p<0.05$.

Averaged across site-years and fertiliser treatments, gross margins were greater in the high grain price scenarios (*high:high* and *high:low*) compared with the 2021 and low grain price scenarios ($p<0.05$). This was true for both sole crops and the intercrop, with the relative difference between the intercrop, sole linseed and sole chickpea being maintained across all five scenarios.

Gross Margins (*Experiment 2*)

Gross margins were greater at H2020 than at H2019 ($p<0.001$), but were similar between crops within a site-year. The one exception to this was sole canola, which earned less than the other crops at H2020 ($p<0.05$; Fig 6).

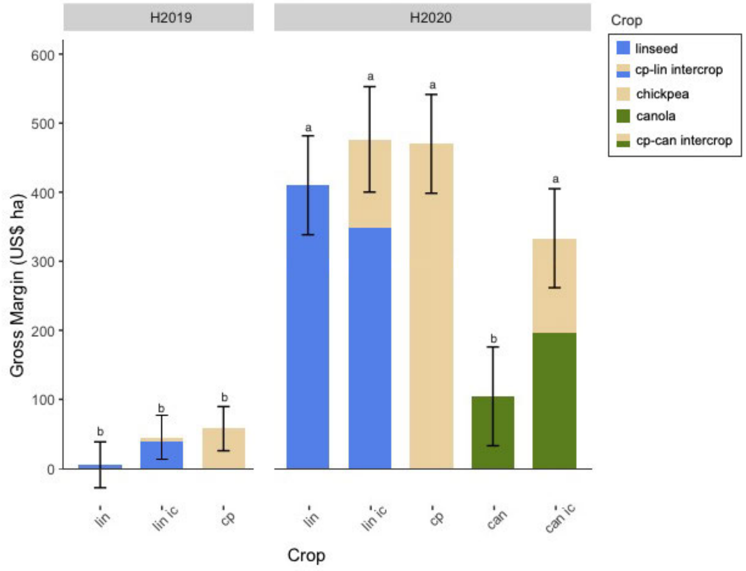

Figure 6. 2021 gross margins (US$ ha^{-1}) at H2019 and H2020 for sole chickpea (beige), sole linseed (blue), sole canola (green), linseed-chickpea intercrop (stacked blue and beige) and canola-chickpea intercrop (stacked green and beige). Different letters indicate significant difference at $p< 0.05$. Error bars indicate ± 1 confidence interval.

Intercrop canola had increased earnings compared with sole canola, while intercrop chickpea had reduced earnings compared with sole chickpea ($p<0.05$). There was no difference between intercrop and sole crop linseed earnings ($p<0.01$; Fig 6). Fungicide treatment and the crop × fungicide treatment interaction did not affect gross margins.

Averaged across the two site-years, there was no difference in gross margins between the five sensitivity analysis scenarios for any of the sole crops or intercrops.

Discussion

In the present study, I investigated the effect of varying fertiliser and fungicide regimes on the yield and profitability of chickpea-linseed and chickpea-canola intercrops to determine the value of oilseed-legume intercropping as a low-input broadacre system. The results indicate that oilseed-legume intercrops appear to be well-suited to low-input scenarios.

Intercropping can be a more resource efficient system than sole cropping, due to the synergistic interspecies interactions between the intercrop components (Jiao et al., 2021). Moreover, in line with the stress gradient hypothesis (Bertness & Callaway, 1994), these interspecies interactions tend more toward facilitation under higher abiotic stress (Maestre et al., 2009), such as the lower nutrient availability conditions in the nil fertiliser treatment in Experiment 1. In Experiment 1, the highest intercrop gross margin was achieved under the nil (0N0P) or low (0N20P) fertiliser treatment at each site-year. Further, intercropping improved land use efficiency in the nil treatment specifically. Across site-years, the nil treatment had the highest grain LER out of all the fertiliser treatments. The intercrop may be most effective, relative to sole crops, under the low nutrient input treatment for several reasons. Due to differences in root morphology and rooting depths, intercrop components can access different nutrient pools, more effectively utilising available soil resources (Tosti & Thorup-Kristensen, 2010; Andersen et al., 2014). Further, in legume-based intercrops, such as legume-oilseed intercrops, competition for nitrogen between the legume and the non-legume often results in increased nitrogen fixation by the legume, as nitrogen use by the non-legume often limits available nitrogen, favouring nitrogen fixation (Andersen et al., 2014; Homulle et al., 2022). This brings nitrogen into the system without supplementary fertilisation. Additionally, nitrogen can be transferred, either directly or indirectly, from the one crop component to the other (Chalk et al., 2014; Génard et al., 2016, 2017). Nutrient transfer follows a resource gradient, flowing from a source to a sink (Bethlenfalvay et al., 1991; Hamel et al., 1992; Montesinos-Navarro et al., 2017); thus, in low input scenarios, it is often expected that nitrogen is transferred from the legume to the non-legume (Fustec et al., 2010). As well as nitrogen, phosphorus locked up in the soil can be mobilised by root exudates from one or both intercrop species components, facilitating increased phosphorus availability in the system as a whole (Denton, 2006; Hinsinger et al., 2011; Fletcher et al., 2016). While replacement rates of phosphorus would eventually need to be added to the system to ensure longer term crop growth, the cost of phosphorus fertiliser is less than the cost of nitrogen fertiliser (Table 2).

In Experiment 2, dry and windy conditions at both H2019 and H2020 meant that disease pressure was low at both site-years. In this low disease context, grain LER and crop component pLERs were reduced under fungicide and desiccant application. The grain LER of both the chickpea-linseed and chickpea-canola intercrops was consistently below the sole crop score of 1 in the foliar fungicide and desiccant (FFD) treatment, but consistently above 1 in the nil fungicide treatment. I.e. relative to their respective sole crops yields, the intercrops had increased yield in the nil treatment compared with the FFD treatment. This may be due to improved disease protection in the nil fungicide intercrops relative to the nil fungicide sole crops. Intercrops have been shown to supress disease through reduced host-plant density, which provides a physical barrier to the spread of disease (Fernández-Aparicio et al., 2010). Moreover, in the chickpea-canola intercrop, the canola may act as an allelopathic deterrent to pathogens, due to the compounds release by its roots (Chalmers et al., 2017; Couëdel et al., 2019; Dowling et al., 2021). Thus, relative to the completely unprotected nil fungicide sole crops, the nil fungicide intercrops had relatively better disease suppression, resulting in the higher intercrop LER in the nil fungicide treatment. However, as the incidence of disease was low in our study, and there was no overall difference between the effect of disease on the sole crops compared with the intercrops (data not shown), more studies are needed under environmental conditions that promote pathogen spread. This will allow the interaction between intercropping, fungicide input and disease, and its effect on yield and grain quality, to be properly investigated.

In Experiment 1 the improved nutrient efficiency of intercropping relative to sole cropping suggests that fertiliser inputs can be lowered without sacrificing profitability. At RW2019, the intercrop in the nil treatment grossed higher than the intercrop in all other treatments, suggesting an optimum balance between input costs and yield outputs. Moreover, the grain LER of the nil intercrop at RW2019 was significantly higher than the sole crop LER of 1, while at the same time having the lowest input costs, driven by the savings on fertiliser. By comparison, the 50N20P treatment had a grain LER similar to the sole crop, but because of the high cost of fertiliser, had a significantly lower gross margin than the nil treatment and the lowest intercrop gross margin at RW2019. The comparatively close LERs but highly disparate gross margins of the nil and 50N20P treatments at RW2019 highlight that productivity does not necessarily equate to profitability, reinforcing the suitability of intercropping in a low input scenario. While replacement rates of phosphorus would need to be added to the system to sustain growth over the long term, P fertiliser is less expensive and less variable in cost than nitrogen fertiliser (Table 2).

In Experiment 2, fungicide treatment, unexpectedly, had no effect on gross margins in either the intercrops or the sole crops. The costs of the fungicide inputs in the FFD and FF treatments, of \$USD19.95 ha^{-1} and \$USD33.95 ha^{-1}, respectively, were different ($p<0.05$) to the \$USD0 spray cost of the nil treatment. The discrepancy between input costs and the lack of overall gross margin difference could be explained by the large variation in gross margins within and across treatments, meaning that there was no fungicide treatment pattern. It could also be explained by the light disease pressure at H2019 and H2020, where the drier conditions were not conducive to disease. Perhaps in a wetter year disease pressure would have been higher, impacting yield, and the fungicide treatment would have been significant. Further work will likely be required to understand the impact of disease incidence on the relative impact of intercropping on disease suppression.

Intercropping can also be a risk minimising strategy, by reducing the likelihood of total crop failure due to drought or frost (Fulwood, 2020; Weih et al., 2021). In Experiment 1, the intercrop provided gross margin stability across the different environments. While the intercrop never returned the highest gross margin, it was often comparable to the highest earning sole crop, and provided the most consistently high gross margin across site-years, a pattern which held across the different scenarios in the sensitivity analysis. On the one hand, at site-years with more rainfall (K2020 and I2020), the intercrop was able to take advantage of the higher linseed yield and market price (US\$690 t^{-1} and US\$379.50 t^{-1} for linseed and chickpea, respectively; (M. Nagorcka, pers. comm., 2021; PIRSA, 2021), boosting profits above that of the sole chickpea. On the other hand, at site-years with less rainfall, and lower yields (P2019), the chickpea component of the intercrop was able to recoup some of the losses of the sole linseed, which has more expensive seed than chickpea (US\$1.93 kg^{-1} and US\$0.41 kg^{-1}, respectively; M. Nagorcka, pers. comm., 2021; PIRSA, 2021). With weather patterns becoming increasingly unpredictable (Crane et al., 2011; Leriorato & Nakamura, 2019), intercropping may allow growers to ‘hedge their bets’ in this way. Indeed, in Canada, one of the primary motivators for growers to adopt intercropping is the associated reduced risk (Fulwood, 2020).

Additionally, in Experiment 2, intercropping appeared to be a risk minimising strategy in terms of oilseed production. Averaged across fungicide treatments, the linseed-chickpea intercrop was as profitable as the sole linseed at both H2019 and H2020, while the canola-chickpea intercrop at H2020 was more profitable than the sole canola. Intercropping improved the earnings of the oilseed component; intercrop linseed earnings were similar to that of the sole linseed and, most notably, the gross margin of the intercrop canola was larger than that of the sole canola. Further, the total gross margin of the linseed-chickpea intercrop was similar to that of the sole linseed at both H2019 and H2020, while the total gross margin of the canola-chickpea intercrop was larger than that of the sole canola. Where the sole oilseed grossed poorly, such as the sole linseed at H2019 and the sole canola at H2020, intercropping with the chickpea improved overall profit. Conversely, where the sole oilseed earnings were sufficient, such as the sole linseed at H2020, intercropping did not reduce profits.

Intercropping an oilseed and a legume can also reduce risk by providing a high-quality hay or grazing option in years of poor grain yield. Mixed crop-livestock farming systems are a major element of the world's land use and of its agricultural production (Bell & Moore, 2012), and the high biomass production of intercropping systems can take advantage of this in years where grain yield is poor. Mixed feed is associated with higher N and crude protein content and greater digestibility (Anil et al., 1998; Kaiser et al., 2007; Mikić et al., 2015; Berti et al., 2021), and typically fetches a higher market price. Although chickpea is not commonly cut for hay or silage, other legumes are widely used as feed or grazing pasture for ruminant livestock (Bruno-Soares et al., 2000; Bampidis et al., 2011; Serrapica et al., 2021), as are oilseeds like canola (Bennet, 2015). In both Experiments 1 and 2, the aboveground biomass overyielded (LER >1) more often and more significantly than their respective grain yields. Similarly, legume-oilseed intercrops utilising different combinations of pea, vetch and grass pea with canola and white mustard demonstrated biomass LER values higher than 1 (Ćupina et al., 2013). In this way, if grain yield is low due to frost or drought, intercrops still provide an option for cutting high quality silage or for grazing, reducing loss and risk, compared with the sole crops.

Conclusion

Oilseed-legume intercropping appears well suited as a low-input system in broadacre cropping in Mediterranean environments. Intercropping chickpea with the oilseed species linseed and canola resulted in yield maintenance, and in some cases improved yield, relative to respective sole crops, and significantly reduced fertiliser and fungicide inputs. In the low fertiliser input scenario, chickpea-linseed intercropping resulted in yield and economic stability and reduced risk. In the low fungicide input scenario, chickpea-canola intercropping, while not as economically successful as the sole chickpea, appeared to improve yield efficiency relative to the sole crops by reducing disease pressure. The comparatively close LERs but highly disparate gross margins of the 0N0P and 50N20P treatments at RW2019 highlight that productivity does not necessarily equate to profitability, reinforcing the suitability of intercropping in a low input scenario. Intercropping with oilseed-legume is demonstrated here to be a risk mitigation strategy and a profitable alternative to traditional high input monocultures in a global environment of rising synthetic input costs.

Acknowledgements

This work would not have been possible without the financial support of the Australian Government Research Training Program scholarship, the Tim Healy Memorial Trust Scholarship, the South Australian Research and Development Institute (SARDI), and the Grains Research and Development Corporation through research funding DAV00150. I acknowledge the support of the technical and research teams at SARDI Clare, and the grower collaborators.

Supplementary Information

Table S1. Itemised 2021 static input costs (US$ ha-^{1}) for all treatments in Experiment 1

	Fertiliser Treatment					
	0N0P	**0N20P**	**25N0P**	**25N20P**	**50N0P**	**50N20P**
Herbicide	26.80	26.80	26.80	26.80	26.80	26.80
Pesticide	13.95	13.95	13.95	13.95	13.95	13.95
Fungicide	36.15	36.15	36.15	36.15	36.15	36.15
Desiccant	24.85	24.85	24.85	24.85	24.85	24.85
Chickpea seed + inoculant (sole crop)	21.60	21.60	21.60	21.60	21.60	21.60
Chickpea seed + inoculant (inter crop)	10.80	10.80	10.80	10.80	10.80	10.80
Linseed seed (sole crop)	78.40	78.40	78.40	78.40	78.40	78.40
Linseed seed (intercrop)	39.20	39.20	39.20	39.20	39.20	39.20
Operations (sole crop)	22.15	22.15	22.15	22.15	22.15	22.15
Operations (intercrop)	36.15	36.15	36.15	36.15	36.15	36.15

Table S2. Itemised 2021 static input costs (US$ ha-^{1}) for all treatments in Experiment 2,

	Fungicide Treatment		
	Nil	**FF**	**FFD**
Herbicide	26.80	26.80	26.80
Pesticide	13.95	13.95	13.95
Chickpea seed + inoculant (sole crop)	21.60	21.60	21.60
Chickpea seed + inoculant (inter crop)	10.80	10.80	10.80
Linseed seed (sole crop)	78.40	78.40	78.40
Linseed seed (intercrop)	39.20	39.20	39.20
Canola seed (sole crop)	19.60	19.60	19.60
Canola seed (intercrop)	9.80	9.80	9.80
MAP fertiliser	25.20	25.20	25.20
Operations (sole crop)	22.15	22.15	22.15
Operations (intercrop)	36.15	36.15	36.15

References

Alcon, F., Marín-Miñano, C., Zabala, J.A., de-Miguel, M-D., Martínez-Paz, J.M. 2020. Valuing diversification benefits through intercropping in Mediterranean agroecosystems: A choice experiment approach. Ecol. Econ. 171:106593. https://doi.org/10.1016/j.ecolecon.2020.106593.

Andersen, S.N., Dresbøll, D.B., Thorup-Kristensen, K. 2014. Root interactions between intercrop legumes and non-legumes – a competition study of red clover and red beet at different nitrogen legumes. Plant Soil. 378, 59-72. https://doi.org/10.1007/s11104-013-2014-4

Anil, L., Park, J., Phipps, R.H., Miller, F.A., 1998. Temperate intercropping of cereals for forage: a review of the potential for growth and utilization with particular reference to the UK. Grass Forage Sci. 53, 301–317. https://doi.org/10.1046/j.1365-2494.1998.00144.x

Bampidis, V.A., Christodoulou, V. 2011. Chickpeas (Cicer arietinum L.) in animal nutrition: A review. Anim. Feed Sci. Technol. 168(1-2), 1-20. https://doi.org/10.1016/j.anifeedsci.2011.04.098

Banik, P., Sasmal, T., Ghosal, P.K., Bagchi, D.K. 2000. Evaluation of Mustard (*Brassica compestris* Var. Toria) and Legume Intercropping under 1:1 and 2:1 Row-Replacement Series Systems. J. Agron. Crop Sci. 185, 9-14.

Bedoussac, L., Journet, E.P., Hauggaard-Nielsen, H., Naudin, C., Corre-Hellou, G., Jensen, E.S., Prieur, L., Justes, E., 2015. Ecological principles underlying the increase of productivity achieved by cereal-grain legume intercrops in organic farming. A review. Agron. Sustain. Dev. 35, 911–935. https://doi.org/10.1007/s13593-014-0277-7

Bell, L.W., Moore, A.D. 2012. Integrated crop-livestock systems in Australian agriculture: Trends, drivers and implications. Ag. Syst. 111, 1-12. http://dx.doi.org/10.1016/j.agsy.2012.04.003

Berti, M.T., Lukaschewsky, J., Samarappuli, D.P. 2021. Intercropping Alfalfa into Silage Maize Can Be More Profitable Than Maize Silage Followed by Spring-Seeded Alfalfa. Agron. 11, 1196. https://doi.org/ 10.3390/agronomy11061196

Bertness, M.D., Callaway R. 1994. Positive Interaction in Communities. Trends Ecol. Evol. 9(5), 191-193. https://doi.org/10.1016/0169-5347(94)90088-4

Bethlenfalvay, G.J., Reyes-Solis, M.G., Camel, S.B., Ferrera-Cerrato, R., 1991. Nutrient transfer between root zones of soybean and maize plants connected by a common mycorrhizal mycelium. Physiol. Planta. 82, 423–432. https://doi.org/10.1034/j.1399-3054.1991.820315.x

Bruno-Soares, A.M., Abreu, J.M.F., Guedes, C.V.M, Dias-da-Silva, A.A. 2000. Chemical Composition, DM and NDF degradation kinetics in rumen of secen legume straws. Anim. Feed Sci Technol. 83(1), 75-80. https://doi.org/10.1016/S0377-8401(99)00113-3

Chalk, P.M, Peoples, M.B., McNeill, A.M., Boddey, R.M., Unkovich, M.J., Gardener, M.J., Silva, C.F., Chen,

D. 2014. Methodologies for estimating nitrogen transfer between legumes and companion species in agro-ecosystems: A review of ^{15}N-enriched techniques. Soil Biol. Biochem. 73, 10-21. https://doi.org/10.1016/j.soilbio.2014.02.005

Chalmers, S., 2017. Responses of pea and canola intercrops to nitrogen and phosphorus applications. Westman Agricultural Diversification Organization 2017 Annual Report. Westman Agricultural Diversification Organization, Manitoba, pp. 127–136.

Couëdel, A., Alletto, L., Kirkegaard, J., Justes, E., 2018. Crucifer glucosinolate production in legume-crucifer cover crop mixtures. Eur. J. Agron. 96, 22–33. https://doi.org/10.1016/j.eja.2018.02.007

Couëdel, A., Kirkegaard, J., Alletto, L., Justes, E., 2019. Crucifer-legume cover crop mixtures for biocontrol: Toward a new multi-service paradigm. Adv. Agron. 157, 55–139. https://doi.org/10.1016/bs.agron.2019.05.003

Crane, T.A., Roncoli, C., Hoogenboom, G. 2011. Adaptation to climate change and climate variability: The importance of understanding agriculture as performance. Wageningen. J. Life Sci. 57, 179-185. doi:10.1016/j njas.2010.11.002

Ćupina, B., Mikić, A., Marjanović-Jeromela, A., Krstić, D., Antanasović, S., Erić, P., Vasiljević, S., Mihailović, V. 2013. Intercropping autumn-grown brassicas with legumes for forage production. Crucif. Newsl. 32, 17-19.

Denton, M.D., Sasse, C., Tibbett, M., Ryan, M.H., 2006. Root distributions of Australian herbaceous perennial legumes in response to phosphorus placement. Funct. Plant Biol. 33, 1091–1102. https://doi.org/10.1071/FP06176

Dowling, A., Sadras, V.O., Roberts, P., Doolette, A., Zhou, Y., Denton, M.D. 2021. Legume-oilseed intercropping in mechanised broadacre agriculture – a review. Field Crops Res. 260:107980. https://doi.org/10.1016/j.fcr.2020.107980

Fernández-Aparicio, M., Emeran, A.A., Rubiales, D., 2010. Inter-cropping with berseem clover (*Trifolium alexandrinum*) reduces infection by *Orobanche crenata* in legumes. Crop Protection 29, 867–871. https://doi.org/10.1016/j.cropro.2010.03.004

Fletcher, A.L., Kirkegaard, J.A., Peoples, M.B., Robertson, M.J., Whish, J., Swan., A.D. 2016. Prospects to utilise intercrops and crop variety mixtures in mechanised, rain-fed, temperate cropping systems. Crop Pasture Sci. 67(12), 1252-1267. https://doi.org/10.1071/CP16211

Fletcher, A., Kirkegaard, J., Condon, G., Swan, T., Greer, K., Bremer, E., Holding, J. 26 Feb 2020, “The potential role of companion and intercropping systems in Australian grain farming. Should we be considering them?”. GRDC update papers, accessed 10/12/21 < https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2020/02/the-potential-role-of-companion-and-intercropping-systems-in-australian-grain-farming.-should-we-be-considering-them >

Fulwood, J., 20 Jun 2020, “Intercropping study demonstrates potential yield and economic upside”. GroundCover, 147, accessed 10 Dec 2021 <https://groundcover.grdc.com.au/innovation/industry-insights/profitable-intercrops-give-growers-optioins >

Fustec, J., Lesuffleur, F., Mahieu, S., Cliquet, J.-B., 2010. Nitrogen rhizodeposition of legumes: A review. Agron. Sustain. Dev. 30, 57–66. https://doi.org/10.1051/agro/2009003

Génard, T., Etienne, P., Diquélou, Yvin, J.-C., Revellin, C., Laîné P., 2017. Rapeseed- legume intercrops: plant growth and nitrogen balance in early stages of growth and development. Plant Biol. 3, 2–20. https://doi.org/10.1016/j.heliyon.2017.e00261

Génard, T., Etienne, P., Laîné, P., Yvin, J.-C., Diquélou, S., 2016. Nitrogen transfer from Lupinus albus L., Trifolium incarnatum L. and Vicia sativa L. contribute differently to rapeseed (Brassica napus L.) nitrogen nutrition. Plant Biol. 2, 2–15. https://doi.org/10.1016/j heliyon.2016.e00150

Goulding, K.W.T. 2016. Soil acidification and the importance of liming agricultural soils with particular reference to the United Kingdom. Soil Use Manag. 32, 390-399. https://doi.org/10.1111/sum.12270

GRDC GrowNotes™, 2017, Chickpea – Southern Region. https://grdc.com.au/resources-and-publications/grownotes/crop-agronomy/chickpea-southern-region-grownotes

Hamel, C., Furlan, V., Smith, D.L., 1992. Mycorrhizal effects on interspecific plant competition and nitrogen transfer in legume-grass mixtures. Crop Sci. 32, 991–996. https://doi.org/10.2135/cropsci1992.0011183X003200040032x

Hinsinger, P., Betencourt, E., Bernard, L., Brauman, A., Plassard, C., Shen, J., Tang, C., Zhang, F., 2011. P for two, sharing a scarce resource: soil phosphorus acquisition in the rhizosphere of intercropped species. Plant Physiol. 156, 1078–1086. https://doi.org/10.1104/pp.111.175331

Homulle, Z., George, T.S., Karley, A.J. 2022. Root traits with team benefits: understanding belowground interactions in intercropping systems. Plant Soil. 471, 1-26. https://doi.org/10.1007/s11104-021-05165-8

Jensen, E.S., Carlsson, G., Hauggaard-Nielsen, H. 2020. Intercropping of grain legumes and cereals improves the use of soil N resources and reduces the requirement for synthetic fertiliser N: a global-scale analysis. Agron. Sustain, Dev. 40(5), 9pp. https://doi.org/10.1007/s13593-020-0607-x

Jiao, N., Wang, J., Ma, C., Zhang, C., Guo, D., Zhang, F., Jensen, E.K. 2021. The importance of aboveground and belowground interspecific interactions in determining crop growth and advantages of peanut/maize intercropping. Crop J. 9(6), 1460-1469. https://doi.org/10.1016/j.cj.2020.12.004

Kakoti, P., Gogoi, P., Yadav, A., Singh, B.P., Saikia, R. 2020. Foliar Fungal Diseases in Pulses: Review and Management. In Singh, B.P., Singh, G., Kumar, K., Nayak, S.C., Srinivasa, N. (Eds.), *Management of Fungal Pathogens in Pulses, Current Status and Future Challenges*. Springer. https://doi.org/10.1007/978-3-030-359478-8.

Kaiser, A.G., Dear, B.S., Morris, S.G. 2007. An evaluation of the yield and quality of oat-legume and ryegrass-legume mixtures and legume monocultures harvested at three stages of growth for silage. Aus. J. Exp. Agric. 47(1), 25-38. https://doi.org/10.1071/EA05221

Khanal, U. Scott, K.J., Armstrong, R., Nuttall, J.G., Henry, F., Christy, B.P., Mitchell, M., Riffkin, P.A., Wallace, A.J., McCaskill, M., Thayalakumaran, T., O'Leary, G.J. 2021. Intercropping – Evaluating the Advantages to Broadacre Systems. Agric. 11, 453. https://doi.org/10.3390/agriculture11050453

Kirkegaard, J., Christen, O., Krupinsky, J., Layzell, D. 2008. Break crop benefits in temperate wheat production. Field Crop Res. 107, 185-195. https://doi.org/10.1016/j.fcr.2008.02.010

Kirkegaard, J., Condon, G. 2019. Companion cropping – should we be considering it? GRDC update papers, accessed 12 April 2022, <https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2019/02/companion-cropping-should-we-be-considering-it >

Leriorato, J.C., Nakamura, Y. 2019. Unpredictable extreme cold events: a threat to range-shifting tropical reef fishes in temperate waters. Mar. Biol. 166:110. https://doi.org/10.1007/s00227-019-3557-6

Maestre, F.T., Callaway, R.M., Valladares, F., Lortie, C.J. 2009. Refining the stress-gradient hypothesis for competition and facilitation in plant communities. J. Ecol. 97, 199-205. https://doi.org/10.1111/j.1365-2745.2008.01476.x

Mikić, A., Ćupina, B., Rubiales, D., Mihailović, V., Šarūnaitė, L., Fustec, J., Antanasović, S., Krstić, D., Bedoussac, L., Zorić, L., Dordević, V., Perić, V., Srebrić, M. 2015. Models, developments, and perspectives of mutual legume intercropping. Adv. Agron., 130, 337-419. https://doi.org/10.1016/bs.agron.2014.10.004

Montesinos-Navarro, A., Verdo, M., Querejeta, J.I., Valiente-Banuet, A., 2017. Nurse plants transfer more nitrogen to distantly related species. Ecol. 98, 1300–1310. https://doi.org/10.1002/ecy.1771

Orton, T.G., Mallawaarachchi, T., Pringle, M.J., Menzies, N.W., Dalal, R.C., Kopittke, P.M., Searle, R., Hochman, Z., Dang, Y.P. 2018. Quantifying the economic impact of soil constraints on Australia agriculture: A case-study of wheat. Land Degrad. Dev. 29, 3866-3875. https://doi.org/10.1002/ldr.3130

Oyejola, B.A., Mead, R. 1982. Statistical assessment of different ways of calculating land equivalent ratios (LER). Exp. Agric. 18, 125-138. https://doi.org/10.1017/S0014479700013600

Department of Primary Industries and Regions South Australia (PIRSA), 2021. Gross Margin and Enterprise Planning Guide. Government of South Australia, Adelaide.

RStudio Team. 2020. RStudio: Integrated Development for R. RStudio, PBC, Boston, MA < http://www rstudio.com/ >

Serrapica, F., Masucci, F., De Rosa, G., Calabrò, S., Lambiase, C., Di Francia, A. 2021. Chickpea Can Be a Valuable Local Produced Protein Feed for Organically Reared, Native Bulls. Animals. 11(8), 2353. https://doi.org/10.3390/ani11082353

Siddique, K. H. M., Brinsmead, R. B., Knight, R., Knights, E. J., Paull, J. G., & Rose, I. A. 2000. Adaptation of chickpea (*Cicer arietinum* L.) and faba bean (Vicia faba L.) to Australia. In Linking research and marketing opportunities for pulses in the 21st century, 289-303. Springer Netherlands.

South East Research Farm (SERF), 2015. Intercropping chickpea and flax (Agri-Arm Research Update). Saskatchewan Ministry of Agriculture, Saskatchewan.

Szumigalski, A.R., Van Acker, R.C., 2006. Nitrogen yield and land use efficiency in annual sole crops and intercrops. Agron. J. 98, 1030–1040. https://doi.org/10.2134/agronj2005.0277

Tosti, G., Thorup-Kristensen, K. 2010. Using coloured roots to study root interaction and competition in intercropped legumes and non-legumes. J. Plant. Ecol. 3(3), 191-199. https://doi.org/10.1093/jpe/rtq014

USDA, 2022. USDA Agricultural Projections to 2031. World Agricultural Outlook Board, United States Department of Agriculture. Access 23 June 2022 < https://www.usda.gov/sites/default/files/documents/USDA-Agricultural-Projections-to-2031.pdf >

VanKoughnet, B., 2016. On-farm evaluation of peaola intercropping – an intercrop of peas and canola. Agri Skills Inc., Manitoba Pulse and Soybean Growers, Manitoba.

Westman Agricultural Diversification Organization (WADO), 2018. Effect of fungicide and alfalfa understory with pea-canola intercrop production. Westman Agricultural Diversification Organization 2018 Annual Report. Westman Agricultural Diversification Organization, Manitoba, pp. 74–81.

Wei, T., Simko, V., Levy, M., Xie, Y., Jin, Y., Zemla, J., Freidank, M., Cai, J., Prtoivinsky, T. 2018. 'corrplot'. Visualization of a Correlation Matrix. < https://github.com/taiyun/corrplot >

Weih, M., Karley, A., Newton, A.C., Kiær, L.P., Scherber, C., Rubiales, D., Adam, E., Ajal, J., Brandmeier, J., Pappagallo, S., Villegas-Fernández, A., Reckling, M., Tavoletti, S. 2021. Grain Yield Stability of Cereal-Legume Intercrops Is Greater Than Sole Crops in More Productive Conditions. Agric. 11, 225. https://doi.org/10.3390/agri

CHAPTER 5: Mycorrhizal colonisation has a limited effect on crop growth and phosphorus nutrition in legume-oilseed intercrops.

Alyce Dowling, Penny Roberts, Yi Zhou, Matthew D Denton

School of Agriculture, Food and Wine, University of Adelaide, Urrbrae, South Australia, 5064, Australia

Plant and Soil

Submitted manuscript

Statement of Authorship

Title of Paper	Mycorrhizal colonisation has a limited effect on crop growth and phosphorus nutrition in legume-oilseed intercrops.
Publication Status	☐ Published ☐ Accepted for Publication ☒ Submitted for Publication ☐ Unpublished and Unsubmitted work written in manuscript style
Publication Details	submitted manuscript to Plant and Soil

Principal Author

Name of Principal Author (Candidate)	Alyce Dowling		
Contribution to the Paper	Planned the study, conducted glasshouse experiment and sampled field experiment, analysed and interpreted all data, wrote the manuscript		
Overall percentage (%)	85%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	02/09/2022

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate to include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Penny Roberts		
Contribution to the Paper	Conducted the field experiment that was sampled, helped with interpretation, edited the manuscript.		
Signature		Date	27/09/2022

Name of Co-Author	Yi Zhou		
Contribution to the Paper	Supervised development of work, helped with data analysis.		
Signature		Date	9/9/2022

Name of Co-Author	Matthew D Denton
Contribution to the Paper	Supervised development of work, edited the manuscript.

Signature	[redacted]	Date	21/09/2022

Mycorrhizal colonisation has a limited effect on crop growth and phosphorus nutrition in legume-oilseed intercrops.

Alyce Dowling[a*], Penny Roberts[ab], Yi Zhou[a], Matt Denton[a]

[a]School of Agriclture, Food, and Wine, The University of Adelaide, Waite Campus, Urrbrae, SA 5064, Australia

[b]South Australian Research and Development Institute, Clare, SA 5453, Australia

*Corresponding author: Alyce Dowling alyce.dowling@adelaide.edu.au

Keywords

Lentil, chickpea, canola, linseed, mycorrhizal symbiosis

Abstract

Background and Aims

Legume-oilseed intercrops are increasingly grown in mechanised agricultural systems for their improved nutrient use efficiency. However, the mechanisms that underpin this advantage are not well known. This study aimed to investigate the effect of intercropping sowing arrangement and species combination on the arbuscular mycorrhizal fungi (AMF) colonisation of oilseed and legume crops, and subsequent effects on crop growth and phosphorus nutrition.

Methods

I sampled legume-oilseed intercrops in field experiments with differing sowing arrangements and measured the level of AMF root colonisation and shoot phosphorus. Additionally, I grew legume-oilseed intercrops in the glasshouse using AMF-inoculated (*Rhizophagus irregularis*) and mock-inoculated (control) treatments. Measurements included mycorrhizal colonisation, root and shoot biomass, and shoot phosphorus.

Results

Mycorrhizal colonisation and the subsequent effect on phosphorus nutrition was host plant dependent. Lentil was the most mycorrhizal plant, followed by linseed, chickpea, and then canola. Only in lentil in the glasshouse was there a correlation between mycorrhizal colonisation and shoot phosphorus ($R = 0.79$, $p<0.001$). Intercropping reduced mycorrhizal colonisation of lentil in the glasshouse but not in the field; intercropping did not affect AMF colonisation in any other species. The interaction between intercropping and AMF had a limited effect on crop growth and shoot phosphorus, while intercropping alone increased canola shoot phosphorus. Sowing arrangement did not affect mycorrhizal colonisation. Canola had increased phosphorus concentration in the alternate row compared with the mixed row, while the other three species were unaffected.

Conclusion

The role of AMF in the growth and phosphorus nutrition of legume-oilseed intercropping systems appears host specific and lacks a “one size fits all” explanation. Research should be directed towards host plant-AMF specificity, and field studies using diverse soil P profiles.

Abbreviations:

AMF – Arbuscular Mycorrhizal Fungi; AM – Arbuscular Mycorrhiza

Introduction

In the face of rising production costs (USDA, 2022) and a changing climate (Crane et al., 2011; Leriorato & Nakamura, 2019), farmers are seeking alternative systems of farming that improve resource use efficiency and reduce costs without sacrificing yield (Fletcher et al, 2020; Khanal et al., 2021). One approach, that embraces principles of agroecology and conservation agriculture, focuses on the sustainable intensification of agriculture through the utilisation of naturally occurring interspecies interactions and ecosystem services (Andres & Bhullar, 2016; Rillig et al., 2016; Duchene et al., 2017). The practice of intercropping, wherein multiple crop species are grown together in the same area for a sustained period of time, is central to this approach (Betencourt et al., 2012; Dowling et al., 2021). Intercropping increases species diversity, and is thought to improve the overall nutrient use efficiency of the system through improved utilisation of soil phosphorus (Latati et al., 2016; Zhang et al., 2019) and nitrogen (Andersen et al., 2004; Cadoux et al., 2015; Génard et al., 2017). There are a number of different types of intercropping, differing in layout and the ecosystem services they provide (Verret et al., 2020). Sowing arrangement is a key differentiating feature between the types of intercropping, and common arrangements include mixed rows, wherein species are mixed within a row, and alternate rows, wherein species are grown in alternating rows (Dowling et al., 2021).

The agroecological and conservation approach also focuses on the symbiosis between plants and arbuscular mycorrhizal fungi (AMF) to increase plant phosphorus supply (Hontoria et al. 2019; Guzman et al., 2021). Symbiosis with mycorrhizas is correlated with increased early phosphorus nutrition (Miller et al., 1995; Gavito & Miller, 1998) and increased plant growth and yield (Thingstrup et al., 1998; Smith & Smith, 2011; Zhang et al., 2016). Few studies have investigated the intersection of intercropping and AMF, and the interaction with crop yield and nutrient efficiency (Guzman et al., 2021; Rezaei-Chiyaneh et al., 2021). While the extensive work on monocrops can be extrapolated to intercropping systems, there are many interspecies interactions that may generate an outcome different to the sum of their parts.

Some studies suggest that AMF are important in intercropping systems, providing both a phosphorus mining function and a network where resources can flow between species (Bethlenfalvay et al., 1991; Eason et al, 1991; He et al., 2003, 2009; Simard et al., 2012; Walder et al., 2012; Nie et al., 2016). However, more research is needed, particularly in the context of legume-oilseed intercrops. Further, canola is often used as the oilseed component of legume-oilseed intercrops (e.g. field pea-canola, Madsen et al., 2022; faba bean-canola, Suraweera et al., 2022; lentil-canola, Roberts et al., 2019) due to its high market relevance, yet it is a non-mycorrhizal crop (Fester & Sawers, 2011; French, 2017; Floc'h et al., 2022). Does the canola component of a legume-canola intercrop affect the extent or quality of the AMF symbiosis with the mycorrhizal legume, and how does this impact phosphorus dynamics within the system? Crop rotation studies have shown reduced mycorrhizal colonisation and yield reductions in mycorrhizal crops planted in rotation following canola (Grant et al., 2009; McGonigle et al., 2011; Bakhshandeh et al., 2017; Higo et al., 2017), but little is known about its effect in an intercrop. Further, the effect of intercrop sowing arrangement (e.g. mixed rows, alternate rows etc.) on mycorrhizal colonisation and phosphorus acquisition is little studied, but is of great importance given the extra complexity associated with sowing alternating rows compared with mixed rows (Fletcher et al., 2016; Dowling et al., 2021).

As such, this study aimed to investigate the interaction between intercropping and AM colonisation, and the subsequent effect plant growth phosphorus acquisition. The study comprised two field experiments and one pot experiment in a glasshouse. The field experiments examined the effect of different intercrop sowing arrangements and species combinations at the large scale, while the glasshouse experiment examined the effect of intercrop species combinations at the small scale. In the field experiments, I hypothesised that i) intercrop sowing arrangement would affect mycorrhizal root colonisation and phosphorus nutrition and ii) that the direction of this effect would be dependent on intercrop species combination. In the glasshouse experiment I hypothesised iii) that mycorrhizal colonisation of roots would improve plant growth and phosphorus acquisition, iv) that intercropping would affect mycorrhizal colonisation and subsequent phosphorus acquisition, and v) that the direction of this effect would be dependent on intercrop species combination.

Materials and Methods

2.1 Study location and trial design and management

Field Experiments

A total of two legume-oilseed intercropping field experiments located at Hart, South Australia (33°45'34.1"S 138°24'49.7"E), were sampled in 2020 and 2021. The experiment sampled in 2020 is referred to as Experiment 1, and the experiment sampled in 2021 is referred to as Experiment 2 (Table 1). Experiment 1 had a mixed sowing arrangement, with legume and oilseeds sown together in the same row. Experiment 2 had a 2:2 alternate row arrangement, with alternating 2:2 legume:oilseed rows.

Table 1. Environmental variables at the two experimental sites.

	Experiment 1	**Experiment 2**
Pre-season rainfall (mm)	211	54.8
Sowing to sampling rainfall (mm)	56.8	157.2
Background soil nitrate 0-10cm (mg kg^{-1})	10	11
Background soil Colwell phosphorus 0-10cm (mg kg^{-1})	35	10
Soil pH (H2O) 0 to 10cm	8.5	8.2
Soil organic C 0 to 10cm (%)	1.37	0.97
EC 0 to 10cm (dS m^{-1})	0.179	0.177

In the year before Experiment 1 and Experiment 2 were carried out, oat hay (*Avena sativa*, cv Mulgara) was grown.

Prior to sowing, Experiments 1 and 2 were treated with pre-seeding herbicides (Round Up (active ingredient glyphosate) at 1.5 L ha^{-1}, Hammer 400EC (active ingredient 400 g L^{-1} carfentrazone-ethyl) at 0.03 L ha^{-1}, and Trifluralin 480 g L^{-1} at 1.4 kg ha^{-1}). Subsequent control of weeds was achieved through a mixture of hand weeding and controlled application of glyphosate using a hand-held brush. 80kg ha^{-1} of monoammonium phosphate (MAP) was applied at sowing. Insecticide (Chlorpyrifos 500 g L^{-1} at 0.9 L ha^{-1}, Bifenthrin 100 g L^{-1} at 0.2 L ha^{-1}) and fungicide (Chlorothalonil 2 L ha^{-1}) was applied one week after sowing. The pre-harvest desiccant used was Spray Seed 250 (active ingredients 135g L^{-1} paraquat dichloride and 115g L^{-1} diquat dibromide) applied at 2 L ha^{-1} (as per regional guidelines for southern Australia; GRDC GrowNotes, 2017).

Chickpea (*Cicer arietinum* L., cv. ‘Genesis 090’) and lentil (*Lens culinaris* L. cv. ‘Hurricane’) were the legume species used in the study, with mycorrhizal linseed (*Linum usitatissimum* L. cv. ‘Croxton’) and non-mycorrhizal canola (*Brassica napus* L., cv. ‘Thumper’) being the oilseed species used. Sole chickpea, sole lentil, and sole linseed were sown at 35, 40, and 40 plants m^{-2}, while sole canola was sown at 1.5 kg ha^{-1}. Intercrops were sown at half the sole crop densities over the same area.

In Experiment 1 chickpea-linseed and chickpea-canola plots were sampled, plus corresponding sole crop stands. There were three replicates of each plot, totalling 15 plots sampled in Experiment 1. In Experiment 2, chickpea-linseed, chickpea-canola, and lentil-canola intercrop plots were sampled, plus all corresponding sole crop stands. There were three replicates of each plot, totalling 21 plots sampled in Experiment 2.

Glasshouse Experiment

Plants were grown in pots in a glasshouse at the Waite campus of the University of Adelaide from late June to August 2021.

The soil used was a mixture of 85% sand (2 mm) and 15% field soil (Tosti & Thorup-Kristensen, 2010), collected from the Kingsford Field Research site, Kingsford, South Australia. The field soil is a hard-setting red-brown clay loam with a H_2O pH of 7.3, and KCl extractable concentrations of nitrate and ammonium N of 21 mg kg^{-1} and 3.1 mg kg^{-1}, respectively. The field soil had a plant available (Colwell) P concentration of 63.5 mg P kg^{-1} and a plant available (Colwell) K concentration of 783 mg K kg^{-1}. The soil contained 2% organic carbon. The soil was sieved to 2 mm to remove any debris, autoclaved and oven dried at 60°C before being mixed with the sand. Autoclaving did not completely sterilise soil, but did reduce the level of background microorganisms, including mycorrhizal spores. The final sand:soil mixture contained 14.5 mg P kg^{-1} of plant-available (Colwell) P.

All pots were filled with 900mL of the sand:soil mixture. To half the pots (28 pots) an AMF inoculum (*Rhizophagus irregularis* WFVAM10) was added at 10% total pot volume (100mL). The inoculum was made up of dried soil, hyphae and a small amount of root material from colonised (>80%) Marigold (*Tagetes patula*). To the other half of the pots (28 pots), a mock inoculum was added, composed of the same materials as the inoculum (excluding mycorrhizal hyphae) but from non-colonised Marigold plants (see Watts-Williams & Gilbert, 2020 for details). The pots with the mock inoculum formed the control treatment.

Species and cultivars used were the same as in the field. Seeds were germinated in the soil:sand mixture, with staggered sowing dates to ensure all plants were at the same growth stage for transplanting. When all plants had germinated and were showing two true leaves, seedlings were transplanted into pots in a sole crop 4:0 ratio and an intercrop 2:2 ratio (total four plants per pot). There were four replicates. The pots were arranged randomly on the glasshouse bench and were rearranged weekly. Plants were watered three times a week with RO water to 10% of the soil weight (Tran et al., 2019).

Over the course of the experiment, the glasshouse had an average maximum temperature of 27.6°C and an average minimum of 18.3°C, with supplemental lighting in a 9:15 day:night photoperiod and average of 20428 lux.

2.2 Plant harvest and sample analysis

Field Experiments

The same sampling methods were followed in Experiments 1 and 2. At chickpea growth stage ~V5 (leaf attached to the 5th node is fully expanded; GRDC GrowNotes, 2017) 10 plants per species per plot (i.e. 10 plants per sole crop plot and 20 plants per intercrop plot) were randomly selected and carefully extracted, keeping roots as intact as possible. Plants were harvested at this stage because of the importance of phosphorus uptake at the vegetative stage in determining overall plant yield. Shoots were cut from the roots at the soil level. A subsample of finely ground shoot was then digested in a 4:1 (v/v) mix of nitric acid and hydrogen peroxide (Miller, 1998), and total P concentration (mg g^{-1}) determined using inductively-coupled plasma atomic emission spectroscopy (ICP-AES). After legume plants had been given a nodule score, roots were cut into ~10mm pieces and placed in 50% ethanol for storage. The fresh root samples fixed in ethanol were then rinsed using RO water, and cleared in 10% KOH at room temperature for 7 days. Cleared roots were rinsed and then stained in 5% Sheaffer Black Ink in vinegar (Modified from Vierheilig et al., 1998) at 60 °C for 10 minutes, before being destained in acidified water (1:20 white vinegar:water) for 12 hours. Roots were then washed and moved to RO water for storage. Mycorrhizal colonisation was determined on stained root samples according to the gridline intersect method (Giovannetti & Mosse, 1980).

Glasshouse Experiment

At 39 days after transplant (when ~15 % of plants were in flower), all plants were destructively harvested as follows. Plants were removed from the pot. Plant shoots were cut at soil level and the roots gently washed in water. Root and shoot fresh weight (g per plant) were then taken. A subsample of fresh root (~0.25 - 0.8 g) was placed into 50% ethanol for storage. The DW of the remaining root biomass and total shoot biomass was determined after oven drying at 60 °C for 120 hours. Shoot biomass was ground finely, and the total P concentration (mg g^{-1}) was determined using the same method as for the field sample shoots. The subsamples of fresh root fixed in ethanol were rinsed using RO water, and the subject to the same methods as the field roots (above) to determine mycorrhizal colonization (%).

2.3 Statistical analysis and calculations

Prior to analysis, all data were tested for normality via the Shapiro-Wilk test, and were log-transformed if required.

Field Experiments

Data were initially analysed using ASReml-R in the statistical program R (Rstudio Team, 2020). To investigate the effect of sowing arrangement, data were combined across sites. A separate linear mixed model was built for the mycorrhizal root colonisation and shoot phosphorus. The model specified experiment × treatment (intercropping × legume species × oilseed species) as the fixed effects and replicate × experiment as the random effects. The residual errors for each site were modelled using spatial methods. To investigate the effect of treatment (intercropping × legume species × oilseed species) on mycorrhizal root colonisation and shoot phosphorus within each experiment, the same approach as above was used, but experiment was removed as a fixed effect. In both the across and within experiment analysis, Tukey’s HSD test was used for post-hoc analysis. The correlation between intercropping, intercropping companion, shoot phosphorus, and root mycorrhizal colonisation was explored through Pearson correlation using the corrplot package (Wei et al., 2018) in R.

Glasshouse Experiment

Data were initially analysed using ASReml-R in the statistical program R (Rstudio Team, 2020). A separate linear mixed model was built for each mycorrhizal root colonisation, shoot and root dry weight, and shoot phosphorus. The model specified intercropping × legume species × oilseed species as the fixed effects and replicate as the random effects. Tukey's HSD test was used for post-hoc analysis. The correlation between intercropping, intercropping companion, shoot phosphorus, root mycorrhizal colonisation and root dry weight was explored through Pearson correlation using the corrplot package (Wei et al., 2018) in R.

Results

3.1 Mycorrhizal colonisation

Field Experiments

There was no difference in mycorrhizal colonisation of either legume or oilseed roots between Experiment 1 (mixed rows) and Experiment 2 (alternate 2:2 rows).

Mycorrhizal colonisation of both legume and oilseed roots did not differ between sole and intercrop treatments in either Experiment 1 (Fig 1) or Experiment 2 (Fig 2). In both experiments linseed had greater colonisation than the canola ($p<0.001$; Figs 1b, 2b). In Experiment 2, there was no difference in colonisation between lentil and chickpea (Fig 2a).

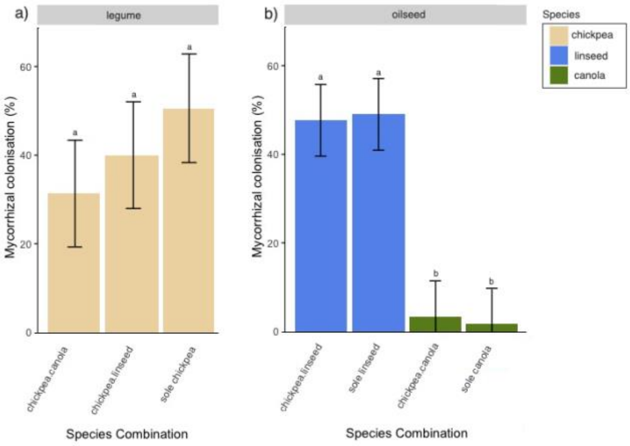

Figure 1. a) chickpea and b) linseed and canola root mycorrhizal colonisation (%) in intercrop and as sole crops in Experiment 1. Error bars indicate ± 95% confidence interval. Different letters indicate significant difference at $p<0.05$.

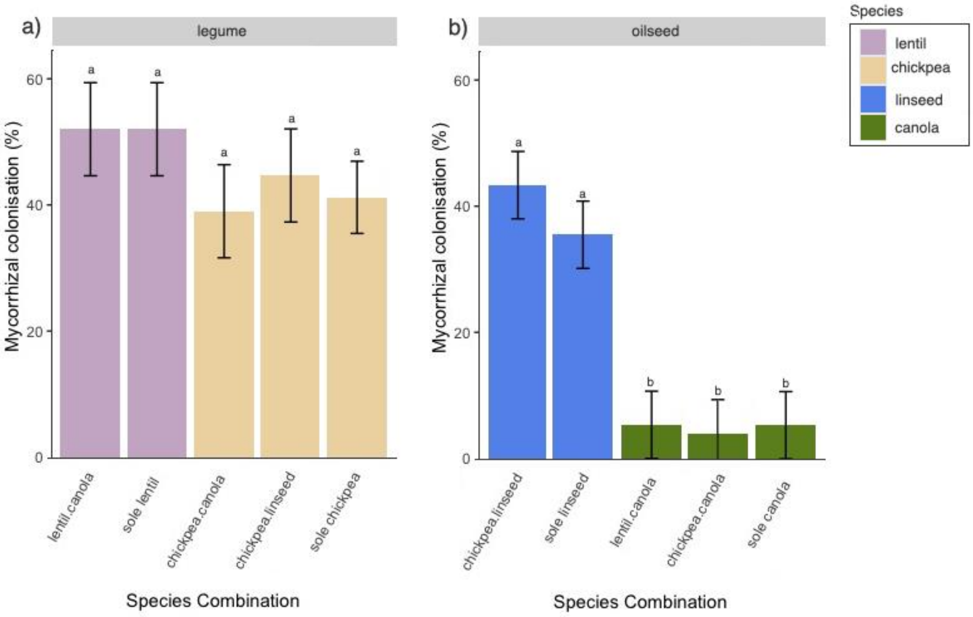

Figure 2. a) Lentil and chickpea and b) linseed and canola root mycorrhizal colonisation (%) in intercrop and as sole crops in Experiment 2. Error bars indicate ± 95% confidence interval. Different letters indicate significant difference at $p<0.05$.

Glasshouse Experiment

All four species were colonized by *R. irregularis* in the inoculated treatments (Fig 3). For lentil and linseed, mycorrhizal root colonisation was greater in the inoculated treatment than in the control treatment ($p<0.05$), while there was no inoculation effect on the chickpea or canola (Fig 3). In the inoculated treatment, lentil had the greatest mycorrhizal colonisation, followed by linseed, chickpea and then canola (Fig 3). Lentil had greater mycorrhizal colonisation in the sole crop than the intercrop ($p<0.05$), while intercropping had no effect on chickpea mycorrhizal colonisation (Fig 3a). Intercropping did not affect mycorrhizal colonisation in either of the oilseed species (Fig 3b).

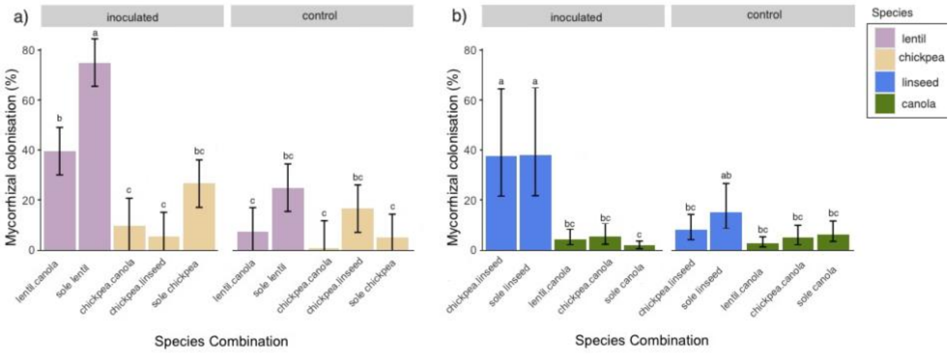

Figure 3. a) Lentil (purple) and chickpea (beige), and b) linseed (blue) and canola (green) root mycorrhizal colonisation (%) in intercrop and as sole crops in the inoculated and control treatments. Error bars indicate ± 95% confidence interval. Different letters indicate significant difference at $p<0.05$.

3.2 Biomass

Glasshouse Experiment

Inoculation alone did not affect root or shoot dry weight of either the legumes or the oilseeds ($p>0.05$; Fig 4). Shoot dry weight of all crop species was greater in the sole crop compared with the intercrop ($p<0.001$; Fig 4). For chickpea and linseed, root dry weight was greater in the sole crop than the intercrop ($p<0.05$; Fig 4b, c), while for lentil and canola there was no difference in root dry weight between the sole and intercrop treatments (Fig 4a, d).

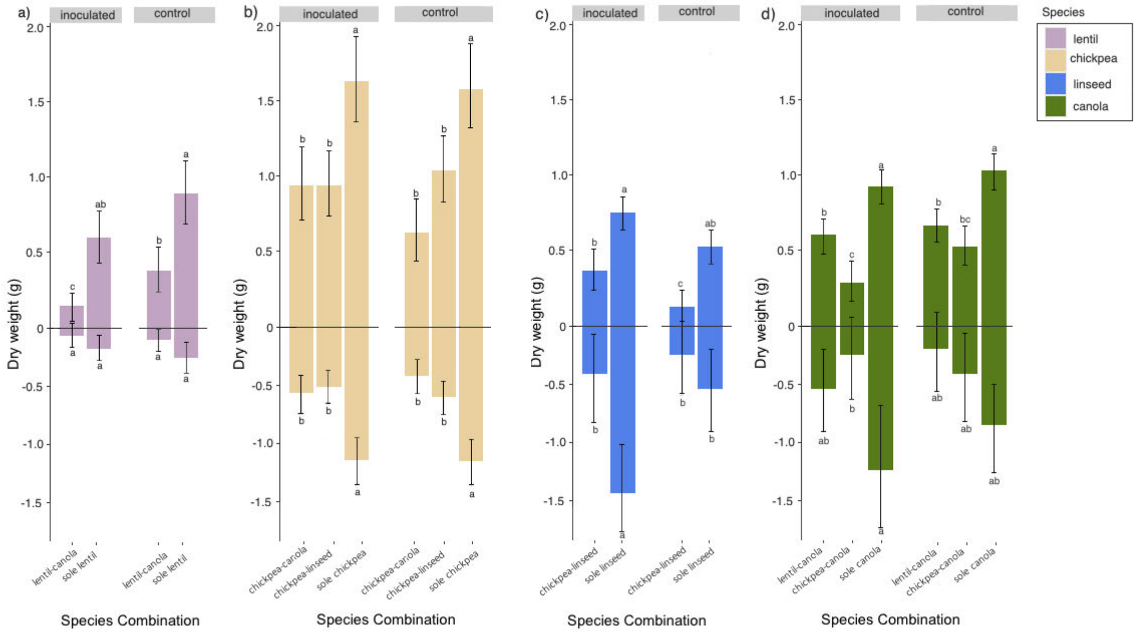

Figure 4. Mean dry weight per plant (DW, g) at harvest of shoot (above x-axis) and root (below x-axis) of a) lentil, b) chickpea, c) linseed, and d) canola in intercrop and as sole crops in the inoculated and control treatments. Error bars indicate ± 95% confidence interval. Different letters indicate significant difference at $p<0.05$.

3.3 Shoot phosphorus

Field Experiments

There was no difference in shoot phosphorus concentration (mg g^{-1}) between Experiment 1 and Experiment 2 for lentil, chickpea, or linseed. Canola shoot phosphorus concentration, however, was greater in Experiment 2 than in Experiment 1 ($p<0.05$).

There was no difference in shoot phosphorus concentration between intercrops and sole crops of the same species in either Experiment 1 (Fig 5) or Experiment 2 (Fig 6). In Experiment 2, shoot phosphorus concentration was different between species of the same crop type (p<0.001), with greater phosphorus concentration in the lentil than in the chickpea (Fig 6a), and greater phosphorus concentration in the canola than in the linseed (Fig 6b).

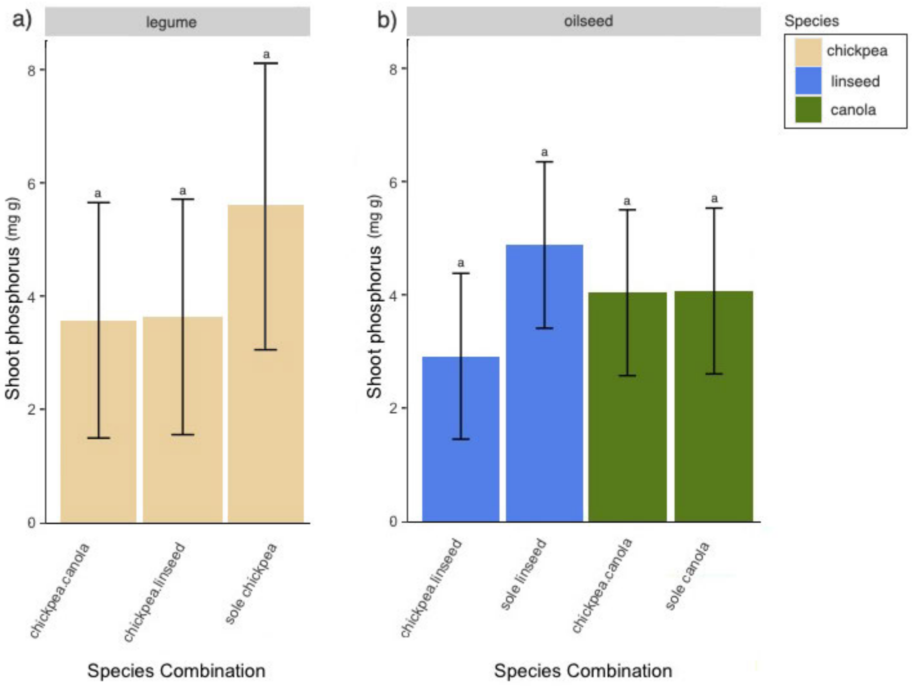

Figure 5. Shoot phosphorus concentration (mg g^{-1}) of a) chickpea and b) linseed and canola in intercrop and as sole crops in Experiment 1. Error bars indicate ± 95% confidence interval. Different letters indicate significant difference at p<0.05.

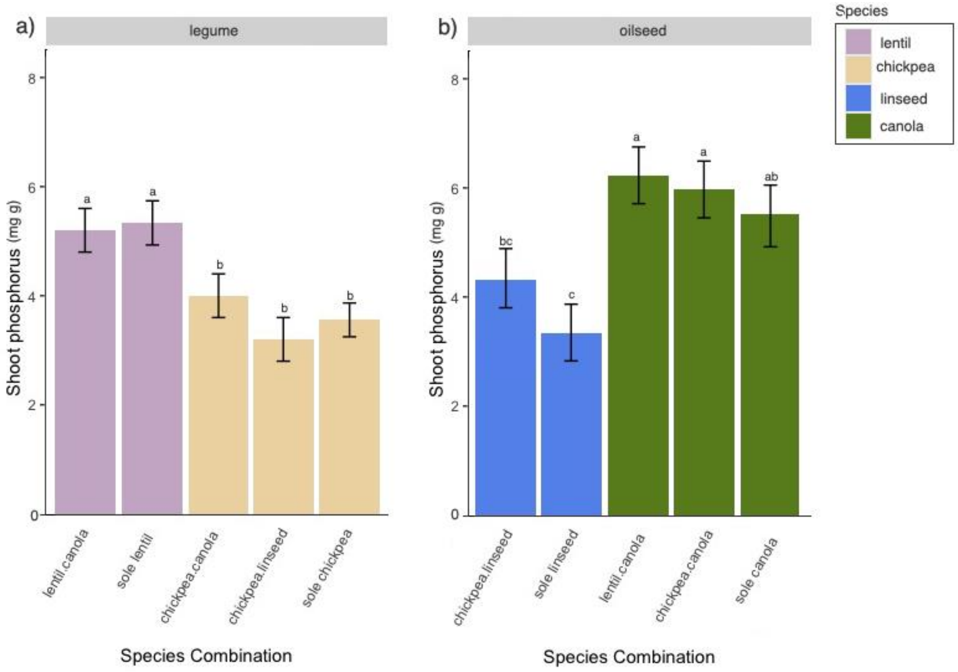

Figure 6. Shoot phosphorus concentration (mg g^{-1}) of a) lentil and chickpea and b) linseed and canola in intercrop and as sole crops in Experiment 2. Error bars indicate ± 95% confidence interval. Different letters indicate significant difference at $p<0.05$.

Glasshouse Experiment

Shoot phosphorus concentration was lower in the glasshouse than in the field experiments. In the glasshouse, the shoot phosphorus concentration of the legumes was affected by the inoculation × species interaction ($p<0.001$). Inoculation increased shoot phosphorus concentration in both the sole and intercropped lentil but not in the chickpea (Fig 7a). The inoculation × intercropping interaction also affected legume species differently ($p<0.01$). While there was no difference between sole and intercropped lentil in the control treatment, sole lentil had a greater shoot phosphorus concentration than the intercrop in the inoculated treatment ($p<0.05$; Fig 7a). Conversely, chickpea was not affected and had the same shoot phosphorus concentration across intercropping and inoculation treatments (Fig 7a). Oilseed species shoot phosphorus concentration was not affected by inoculation alone, but was affected by the inoculation × intercropping × species interaction ($p<0.01$). Canola shoot phosphorus concentration was similar across species combinations in the inoculated treatment, but in the control treatment canola intercropped with chickpea had a greater shoot phosphorus concentration ($p<0.05$, Fig 7b). Linseed shoot phosphorus concentration was affected by neither inoculation nor intercropping (Fig 7b).

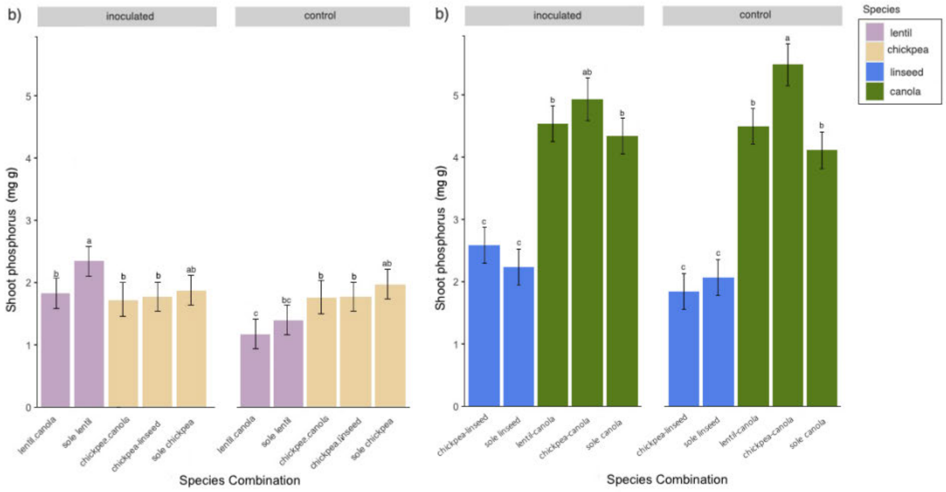

Figure 7. Shoot phosphorus concentration (mg g^{-1}) of a) lentil and chickpea and b) linseed and canola in intercrop and as sole crops in the inoculated and control treatments. Error bars indicate ± 95% confidence interval. Different letters indicate significant difference at $p<0.05$.

The Pearson correlation analysis revealed that canola shoot phosphorus concentration was highly positively correlated with chickpea intercropping ($R = 0.71$, $p<0.001$), but was unaffected by intercropping with lentil ($R = -0.12$, $p>0.05$). Shoot phosphorus concentration in the linseed and legume species was unaffected by intercropping ($p>0.05$).

3.4 Mycorrhizal colonisation and shoot phosphorus

In Experiments 1 and 2 (data combined from both field experiments), there was no correlation between shoot phosphorus concentration and mycorrhizal root colonization for either the legumes or linseed (Fig 8a-c). Canola data has been omitted from this analysis, as it is a non-mycorrhizal species.

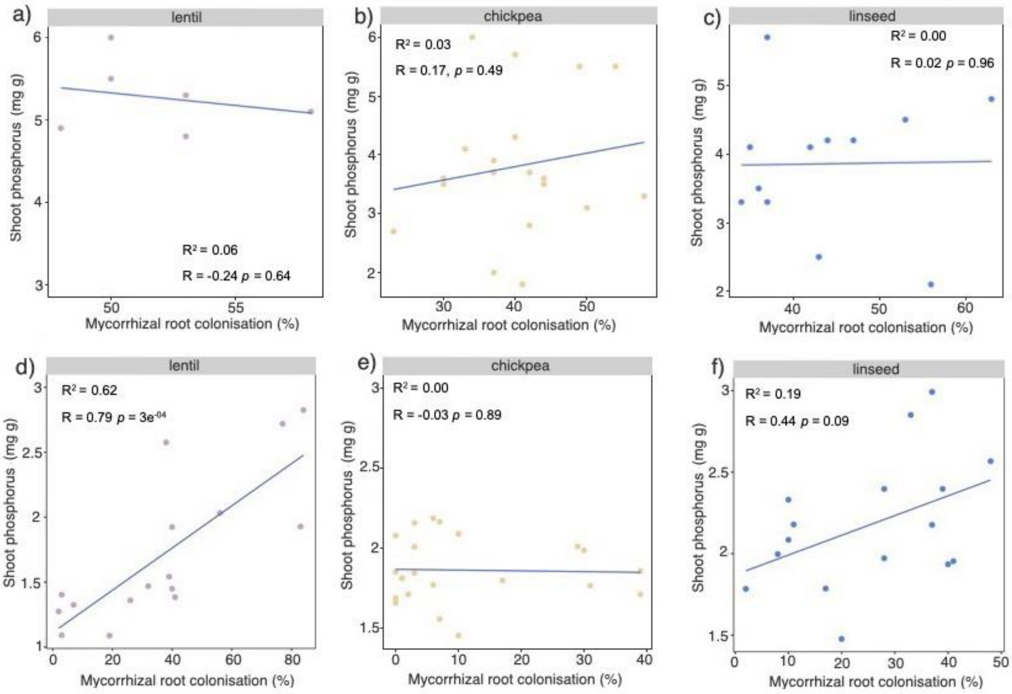

Figure 8. Regression of shoot phosphorus (mg g^{-1}) by mycorrhizal root colonisation (%) of both sole crops and intercrops in Experiments 1 and 2 (combined field data) (a-c) and the glasshouse experiment (d-f) for lentil, chickpea, and linseed. Correlation between the two variables is shown by R, fit of the line by R^2.

In the glasshouse, a correlation between mycorrhizal root colonisation and shoot phosphorus concentration was only observed in lentil ($p<0.001$); as root colonisation increased shoot phosphorus concentration (mg g^{-1}) also increased (Fig 8d). While there was a weak positive correlation between the root colonisation and shoot phosphorus concentration in the linseed, the relationship was not significant due to scatter around the regression line (Fig 8f).

Discussion

In the present study, I investigated the effect of intercropping species combination and sowing arrangement on mycorrhizal root colonisation and plant shoot phosphorus. Importantly, intercrop species combination and sowing arrangement had a minimal effect on mycorrhizal root colonisation. Further, the role of AMF in plant growth and phosphorus nutrition appears host-plant specific. Outside of the interaction with AMF, intercropping alone affected plant growth and phosphorus nutrition.

Contrary to our hypothesis, mycorrhizal colonisation of plant roots was not affected by either intercropping sowing arrangement or species combination. The one exception to this was the lentil in the glasshouse experiment, which had decreased colonisation in the intercrop compared with the sole crop. Most surprisingly, being intercropped with the non-mycorrhizal canola did not affect lentil or chickpea root colonisation (excepting lentil in the glasshouse) relative to the sole crop or being intercropped with the highly mycorrhizal linseed. Sowing arrangement also had no effect, despite greater sharing of the rhizosphere in the mixed rows compared with the alternate rows. This is unexpected, as canola is known to release glucosinolates (Gimsing & Kirkegaard, 2009; Couëdel et al., 2019) that are toxic to fungi and are thought to contribute to the plant's non-mycorrhizal status (Floc'h et al., 2022). Indeed, mycorrhizal plants, such as maize and linseed, had reduced mycorrhizal colonisation and yield in years where they follow canola in crop rotation, compared with another mycorrhizal crop (McGonigle et al., 2011; Higo et al., 2017). It is important to note that the small amount of AM colonisation in the canola (<5%) is superficial, occurring only on the epidermis and outer cells of the root, and is not sufficient to sustain a functional mycorrhizal symbiosis (Floc'h et al., 2022).

Trenbath (1993) and Boudreau (2013) suggest that sowing brassica species with a companion legume may negate any negative effects on soil biota, and it is possible this was the case with the mycorrhiza in our lentil-canola and chickpea-canola intercrops. Alternatively, it is possible that I harvested the plants before the canola could exude sufficient amounts of glucosinolates to affect the mycorrhizal colonisation of its companion, and that it would have released potentially more toxic levels when more established. Glucosinolate content in canola is reported to increase up until budding (~100 DAS, growth stage 2.2; Berkenkamp, 1973), with the majority of total glucosinolate content at this time in the plant roots (40-86 %) (Clossais-Besnard & Larher, 1991; Sarwar & Kirkegaard, 1998). Further research involving whole-season experiments, with sampling at multiple growth stages (such as early flowering, podding and maturity) is needed to establish the longer-terms effects of intercropping with canola. An important aspect of this is break crop rotation research. If the yield of mycorrhizal cereal crops such as wheat is worse following canola, as much of the literature suggests (Owen et al., 2010; Bakhshandeh et al., 2017), could legume-canola intercrops take the place of sole canola? This would maintain the break crop and market-relevance benefits, whilst also providing continuation of the mycorrhizal community for the following cereal crop.

Root mycorrhizal colonisation was only correlated with shoot phosphorus in the lentil in the glasshouse experiment, contrary to our hypothesis. While a lack of correlation between mycorrhizal root colonisation and shoot phosphorus is to be expected for non-mycorrhizal canola (Fester & Sawers, 2011; French, 2017), it is especially surprising for linseed, which is known to be highly mycorrhizal (Thingstrup et al., 1998; McGonigle et al., 2011; Rahimzadeh & Pirzad, 2019). As in the literature, I also found high levels of mycorrhizal root colonisation in linseed in both the field and glasshouse experiments. In Experiment 1, the lack of correlation between mycorrhizal colonisation and shoot phosphorus could be explained by the adequate supply of background soil phosphorus (Table 1). The most significant benefits from AMF have been reported under phosphorus limitation, with adequate N, light, and water supply (Thingstrup et al., 1998; Smith & Smith; 2011; Ryan & Graham, 2018; Tran et al., 2019). The background Colwell-P value of the soil in Experiment 1 was well above the critical range for most oilseeds (16-19 mg kg^{-1}) and legumes (20-29 mg kg^{-1}) in low to mid rainfall environments (Bell et al., 2013). Given ample phosphorus supply, plants would not have had to rely heavily on the AMF symbiosis to fulfil their growth requirements. In Experiment 2 and in the glasshouse experiment, however, the soil did not have sufficient Colwell P (10 mg kg^{-1} and 14.5 mg kg^{-1}, respectively). In these scenarios, the lack of correlation between shoot phosphorus and colonisation could be due to the short duration of the experiment. Perhaps P limitation at later growth stages would have necessitated greater reliance on the AMF symbiosis to provide phosphorus as plant phosphorus demands change over time (Veneklaas et al., 2012). Field studies of longer duration and on P-limited soils are needed to investigate the role of AMF in intercrop phosphorus nutrition.

Comparison of root colonisation in the field and glasshouse experiments suggests some level of host plant preference for specific AMF species, and vice versa. Chickpea had ~ 40-60 % root colonisation in the field (depending on intercropping treatment), while in the glasshouse colonisation of chickpea roots was significantly less (~ 10-30 %). While plant-AM specificity was previously thought to be low (Mosse, 1975; Brundrett, 2009), a meta-analysis by Van Geel et al. (2016) found that symbiosis with different AM species produces different growth and nutrition responses in a given plant. Similarly, Xavier & Germida (2002) report that plant response to inoculation with AMF varies significantly depending on the AMF species. In our study, the field soil would have harboured a number of different mycorrhiza species (Ványi et al., 2016; Guzman et al., 2021) while the inoculum in the glasshouse experiment contained only *Rhizophagus irregularis* spores. The low colonisation of chickpea roots in the glasshouse but high colonisation in the field suggests that chickpea prefers to associate with AMF species other than *R. irregularis*, while lentil freely associates with *R. irregularis* and potentially other species. The literature reports colonisation of chickpea roots of ~60 % by AMF species *Funneliformis mosseae* and *Glomus intraradices* (Tavasolee et al., 2011; Li et al., 2022), a similar level of colonisation to the chickpea in the field, supporting the notion of host-AMF species specificity.

Our study found lentil to be highly mycorrhizal, which is consistent with many previous studies (Khan et al., 1988; Amirnia et al., 2019). As discussion of sustainable farming practices gains momentum, farmers are increasingly focussing more attention on enhancing and maintaining abundant communities of mycorrhiza in the soil (Ryan & Graham, 2018; Kirkegaard & Condon, 2019). Although linseed is a highly mycorrhizal crop (Grant et al., 2009), it has a relatively small global market (FAOSTAT, 2022). By using lentil as their ‘mycorrhizal’ crop, farmers could ensure the maintenance of soil mycorrhizal populations with a species that has high market relevance. In Australia, for example, lentil has the third largest planted area of the pulse crops (ABARES, 2022), and is already included as break crops in cereal dominant rotations (GRDC GrowNotes, 2018).

In contrast to mycorrhizal colonisation, intercropping did affect shoot phosphorus. This is in line with the literature, which suggests that intercrop component interactions alter P availability in the rhizosphere (Costa et al., 2014; Nie et al., 2016). In the glasshouse experiment, canola shoot phosphorus was highly and positively correlated with chickpea intercropping, and was greater in the intercrop with chickpea than in either the sole crop or when intercropped with lentil. This suggests a phosphorus benefit of intercropping with some species combinations and not others. Enhanced resource acquisition in an intercrop can be explained by positive interspecific interactions such as resource partitioning or facilitation (Hinsinger et al., 2011; Li et al., 2018), or by competitive dominance wherein one crop component increases resource acquisition at the expense of the other (Loreau & Hector, 2001; Li et al., 2018). In the case of the chickpea-canola intercrop, the increased canola shoot phosphorus but similar chickpea shoot phosphorus relative to their respective sole crops suggests that the chickpea facilitates increased uptake in the canola, rather than the canola outcompeting the chickpea. Chickpea, along with field pea and faba bean, has been shown to have a superior ability to mobilise soil phosphorus compared with other legumes (Miheguli et al., 2018). It exudes large amounts of acid phosphates that hydrolyse organic phosphorus into plant available inorganic forms (Li et al., 2003; Liao et al., 2020). More research is needed to test compatible legume-oilseed intercrop combinations with regards to phosphorus acquisition. Research should focus on investigating the mechanisms behind the intercrop benefit, with selection for complementary and facilitative interactions that enhance the nutrient dynamics of the whole system, over competitive dominance, which enhances one crop at the expense of the other.

In contrast to the positive effect of intercropping on canola phosphorus, intercropping negatively affected shoot dry weight in both the inoculated and control treatments in the glasshouse eperiment. It is possible that the species used are ill-suited as intercrop companions, but as many field trials with similar species combinations have found increased intercrop biomass (Ćupina et al., 2013; Jeromela et al., 2017), it is likely that another mechanism is at play. It is interesting that in the lentil and the canola there was no difference in root dry weight between the intercrop and the sole crop treatments. It is possible that in an intercrop the close proximity of another species may promote early investment in root growth at the expense of shoot growth, in order to ensure greater competitive ability to access resources later on. This potential variation in resource investment could account for the reduced shoot biomass in the intercrops compared with the sole crops. More research is needed.

Conclusion

In line with much of the literature on AMF in monocultures, our study found that root colonisation by the AMF species *Rhizophagus irregularis,* and the subsequent effect on plant phosphorus nutrition in the early stages of growth, was largely host plant species dependent. Intercropping species combination and sowing arrangement had a minimal effect on mycorrhizal root colonisation. In turn, mycorrhizal colonisation had a limited effect on crop growth and shoot phosphorus concentration. The exception to this was lentil, which had the highest mycorrhizal colonisation of the four study species, and was the only species to have a positive correlation between colonisation and shoot phosphorus. Outside of the interaction with AMF, intercropping increased canola shoot phosphorus, but did not affect shoot phosphorus of the other three species. Similarly, canola was the only crop to be affected by intercropping sowing arrangement, having higher shoot phosphorus concentration in the alternate 2:2 rows than the mixed rows. The intersection of intercropping and AMF poses a complex and multi-faceted situation that lacks a “one-size fits all” explanation (Rillig et al., 2016). More research into host plant-AMF specificity is needed, as are intercropping field studies of longer duration and with various soil P profiles, with information gathered at different plant growth stages up until harvest.

Acknowledgements
This work would not have been possible without the financial support of the Australian Government Research Training Program scholarship, the Tim Healy Memorial Trust Scholarship, the South Australian Research and Development Institute (SARDI), and the Grains Research and Development Corporation through research funding DAV00150. I acknowledge the support of the technical and research teams at SARDI Clare and Hart Field Site. I extend my deepest gratitude to Dr Judith Rathjen for reviewing the manuscript prior to submission.

References

ABARES (2021). Agricultural commodities: December quarter 2021 – Statistical tables – data tables XLS. https://www.agriculture.gov.au/abares/research-topics/agricultural-outlook/data#agricultural-commodities. Accessed February 10, 2022.

Amirnia, R., Ghiyasi, M.m Moghaddam, S.S., Rahimi, A., Damalas, C.A., Heydarzadeh, S. 2019. Nitrogen-Fixing Soil Bacteria Plus Mycorrhizal Fungi Improve Seed Yield and Quality Traits of Lentil (*Lens culinaris* Medik). J. Soil Sci. Plant Nutri. 19, 592-602. https://doi.org/10.1007/s42729-019-00058-3.

Andersen, M.K., Hauggaard-Nielsen, H., Ambus, P., Jensen, E.S., 2004. Biomass production, symbiotic nitrogen fixation and inorganic N use in dual and tri- component annual intercrops. Plant Soil 266, 273–287.

Andres, C., Bhullar, G. S. (2016). Sustainable intensification of tropical agro-ecosystems: need and potentials. Front. Environ. Sci. 4:5. doi: 10.3389/fenvs.2016.00005

Bakhshandeh,S., Corneo, P.E., Mariotte, P., Kertesz, M.A., Dijkstra, F.A. 2017. Effect of crop rotation on mycorrhizal colonization and wheat yield under different fertilizer treatments. Agric. Ecosystm. Environ. 247, 130-136. http://dx.doi.org/10.1016/j.agee.2017.06.027

Begum, N., Qin, C., Ahanger, M.A., Raza, S., Khan, M.I., Ashraf, M., Ahmed, N., Zhang, L. 2019. Role of Arbuscular Mycorrhizal Fungi in Plant Growth Regulation: Implications in Abiotic Stress Tolerance. Front. Plant Sci. 10, 1068, doi: 10.3389/fpls.2019.01068

Bell, M.J., Moody, P.W., Anderson, G.C., Strong, W. 2013. Soil phosphorus – crop response calibration relationships and criteria for oilseeds grain legumes and summer cereal crops grown in Australia. Crop Pasture Sci. 64, 499-513. doi: 10.1071/CP12428

Berkenkamp, B. 1973. A Growth-Stage Key for Rape. Can. J. Plant. Sci. 53, 413.

Betencourt, E., Duputel, M., Colomb, B., Desclauz, D., Hinsinger, P. 2012. Intercropping promotes the ability of durum wheat and chickpea to increase rhizosphere phosphorus availability in a low P soil. Soil Biolg. Biochem. 46, 181-190.

Bethlenfalvay, G.J., Reyes-Solis, M.G., Camel, S.B., Ferrera-Cerrato, R., 1991. Nutrient transfer between root zones of soybean and maize plants connected by a common mycorrhizal mycelium. Physiol. Planta. 82, 423–432.

Boudreau, M.A., 2013. Diseases in intercropping systems. Annu. Rev. Phytopathol. 51, 499–519.

Brundrett, M.C. 2009. Mycorrhizal associations and other means of nutrition of vascular plants: understanding the global diversity of host plants by resolving conflicting information and developing reliable means of diagnosis. Plant Soil. 320, 37–77. doi:10.1007/s11104-008- 9877-9

Cadoux, S., Sauzet, G., Valantin-Morison, M., Pontet, C., Champolivier, L., Robert, C., Lieven, J., Fl´enet, F., Mangenot, O., Fauvin, P., Landed, N., 2015. Intercropping frost sensitive legume crops with winter oilseed rape reduces weed competition, insect damage, and improves nitrogen use efficiency. OCL 22, D302.

Clossais-Besnard, N., Larher, F. 1991. Physiological Role of Glucosinolates in *Brassica napus*. Concentration and Distribution Pattern of Glucosinolates among Plant Organs during a Complete Life Cycle. J. Sci. Food. Agric. 56, 25-38.

Costa, S.E.V.G.A., Souza, E.D., Anghinoni, I., Carvalho, P.C.F., Martins, A.P., Kunrath, T. R., Cecagno, D., Balerini, F., 2014. Impact of an integrated no-till crop-livestock system on phosphorus distribution, availability and stock. Agric. Ecosyst. Environ. 190, 43–51.

Couëdel, A., Kirkegaard, J., Alletto, L., Justes, E., 2019. Crucifer-legume cover crop mixtures for biocontrol: Toward a new multi-service paradigm. Adv. Agron. 157, 55–139.

Crane, T.A., Roncoli, C., Hoogenboom, G. 2011. Adaptation to climate change and climate variability: The importance of understanding agriculture as performance. Wageningen. J. Life Sci. 57, 179-185. doi:10.1016/j njas.2010.11.002

Ćupina, B., Mikić, A., Marjanović-Jeromela, A., Krstić, D., Antanasović, S., Erić, P., Vasiljević, S., Mihailović, V. 2013. Intercropping autumn-grown brassicas with legumes for forage production. Crucif. Newsl. 32, 17-19.

Dowling, A., Roberts, P., Doolette, A., Zhou, Y., Denton, MD. 2023. Oilseed-legume intercropping is productive and profitable in low input scenarios. Agric. Syst. 204, 103551. doi: 10.1016/j.agsy.2022.103551

Duchene, O., Vian, J-F., Celette, F. 2017. Intercropping with legume for agroecological cropping systems: Complementarity and facilitation processes and the importance of soil microorganisms. A review. Agric. Ecosyst. Environ. 240, 148-161. http://dx.doi.org/10.1016/j.agee.2017.02.019

Eason, W.R., Newman, E.I., Chiba, P.N., 1991. Specificity of interplant cycling of phosphorus: the role of mycorrhizas. Plant Soil. 137, 267–274.

FAOSTAT (2021). Crops and livestock products. https://www.fao.org/faostat/en/#data/QCL. Accessed July 29, 2022.

Fester, T., and Sawers, R. (2011). Progress and challenges in agricultural applications of arbuscular mycorrhizal fungi. *Crit. Rev. Plant Sci.* 30, 459–470. doi: 10.1080/07352689.2011.605741

Fletcher, A., Kirkegaard, J., Condon, G., Swan, T., Greer, K., Bremer, E., Holding, J. 26 Feb 2020, “The potential role of companion and intercropping systems in Australian grain farming. Should we be considering them?”. GRDC update papers, accessed 10/12/21 < https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2020/02/the-potential-role-of-companion-and-intercropping-systems-in-australian-grain-farming.-should-we-be-considering-them >

Floc'h, J-B, Hamel, C., Laterriére, M., Tidemann, B., St-Arnaud, M., Hijri, M. 2022. Arbuscular Mycorrhizal Fungi in the Rhizosphere and Bulk Soils of Non-host *Brassica napus* and Their Networks of Co-occurring Microbes. Front. Plant Sci. 13:828145. doi: 10.3389/fpls.2022.828145

French, K. 2017. Engineering Mycorrhizal Symbioses to Alter Plant Metabolism and Improve Crop Health. Front. Microbiol. 8, 1403, doi: 10.3389/fmicb.2017.01403

Gavito, M.E., Miller, M.H. 1998. Early phosphorus nutrition, mycorrhizae development, dry matter partitioning and yield of maize. Plant Soil. 199, 177-186.

Génard, T., Etienne, P., Diquélou, Yvin, J.-C., Revellin, C., Laîné, P., 2017. Rapeseed- legume intercrops: plant growth and nitrogen balance in early stages of growth and development. Plant Biol. 3, 2–20.

Gimsing, A., Kirkegaard, J.A., 2009. Glucosinolates and biofumigation: fate of glucosinolates and their hydrolysis products in soil. Phytochem. Rev. 8, 299–310.

Giovannetti, M., Mosse, B. 1980. An evaluation of techniques for measuring vesicular arbuscular mycorrhizal infection in roots. New Phytol. 84, 489-500.

Grant, C.A., Monreal, M.A., Irvine, R.B., Mohr, R.M., McLaren, D.L., Khakbazan, M. 2009. Crop response to current and previous season applications of phosphorus as affected by crop sequence and tillage. Can. J. Plant. Sci. 89, 49-66.

GRDC GrowNotes (2017) Chickpea – Southern Region. https://grdc.com.au/resources-and-publications/grownotes/crop-agronomy/chickpea-southern-region-grownotes. Accessed August 5, 2022.
GRDC GrowNotes (2018) Lentil – Southern Region. https://grdc.com.au/resources-and-publications/grownotes/crop-agronomy/lentil-southern-region-grownotes. Accessed August 5, 2022.

Guzman, A. Montes, M., Hutchins, L., DeLaCerda, G., Yang, P., Kakouridis, A., Dahlquist-Willard, R.M., Firestone, M.K., Bowles, T., Kremen, C. 2021. Crop diversity enriches arbuscular mycorrhizal funglas communities in an intensive agricultural landscape. New Phyto. 231, 447-459. doi: 10.1111/nph.17306

He, X., Xu, M., Qiu, G.Y., Zhou, J., 2009. Use of ^{15}N stable isotope to quantify nitrogen transfer between mycorrhizal plants. J. Plant Ecol. 2, 107–118.

He, X.H., Critchley, C., Bledsoe, C., 2003. Nitrogen transfer within and between plants through common mycorrhizal networks (CMNs). Crit. Rev. Plant. Sci. 22, 531–567.

Higo, M., Takahashi, Y., Gunji, K., Isobe, K. 2017. How are arbuscular mycorrhizal associations related to maize growth performance during short-term cover crop rotation? J. Sci. Food. Agric. 98, 1388-1396. DOI 10.1002/jsfa.8606

Hinsinger, P., Betencourt, E., Bernard, L., Brauman, A., Plassard, C., Shen, J., Tang, C., Zhang, F., 2011. P for two, sharing a scarce resource: soil phosphorus acquisition in the rhizosphere of intercropped species. Plant Physiol. 156, 1078–1086.

Hontoria, C., García-González, I., Quemada, M., Roldán, A., Alguacil, M.M. 2019. The cover crop determines the AMF community composition in soil and in roots of maize after a ten-year continuous crop rotation. Sci. Tot. Environ. 660, 913-922. https://doi.org/10.1002/ppp3.10090

Jeromela, A.M., Mikić, A.M., Vujić, S., Ćupina, B., Krstić, D., Dimitrijević, A., Vasiljević, S., Mihailović, V., Cvejić, S., Miladinović, D. 2017. Potetnail of Legume-Brassica Intercrops for Forage Porudction and Green Manure: Encouragements from a Temperate Southeast European Environment. Front. Plant Sci. 8:312. doi: 10.3389/fpls/2017.00312.

Khan, A.H., Islam, A., Islam, R., Begum, S., Hug, S.M.I. 1988. Effect of Indigenous VA-Mycorrhizal Fungi on Nodulation, Growth and Nutrition of Lentil (*Lens culinaris* L.) and Blackgram (*Vigna mungo* L.). J. Plant Physiol. 133, 84-88.

Khanal, U. Scott, K.J., Armstrong, R., Nuttall, J.G., Henry, F., Christy, B.P., Mitchell, M., Riffkin, P.A., Wallace, A.J., McCaskill, M., Thayalakumaran, T., O'Leary, G.J. 2021. Intercropping – Evaluating the Advantages to Broadacre Systems. Agric. 11, 453. https://doi.org/10.3390/agriculture11050453

Kirkegaard, J. Condon, G. 19 Feb 2019, "Companion cropping – should we be considering it?". GRDC update papers, accessed 10/12/21 < https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2019/02/companion-cropping-should-we-be-considering-it >

Latati, M., Bargaz, A., Belarbi, B., Lazali, M., Benlahrech, S., Tellah, S., Kaci, G., Drevon, J.J., Ounane, S.M. 2016. The intercropping common bean with maize improves rhizobial efficiency, resource use and grain yield under low phosphorus availability. Europ. J. Agronomy. 72, 80-90. DOI: 0.1016/j.eja.2015.09.015

Leriorato, J.C., Nakamura, Y. 2019. Unpredictable extreme cold events: a threat to range-shifting tropical reef fishes in temperate waters. Mar. Biol. 166:110. https://doi.org/10.1007/s00227-019-3557-6

Li, C., Li, H., Hoffland, E., Zhang, F., Zhang, J., Kuyper, T.W. 2022. Common mycorrhizal networks asymmetrically improve chickpea N and P acquisition and cause overyielding by a millet/chickpea mixture. Plant Soil. 472, 279-293. https://doi.org/10.1007/s11104-021-05232-0.

Li, L., Tang, C.X., Rengel, Z., Zhang, F.S. 2003. Chickpea facilitates phosphorus uptake by intercropped wheat from an organic phosphorus source. Plant Soil 248, 297-303.

Li, X-F., Wang, C-B., Zhang, W-P., Wang, L-H., Tian, X-L., Yang, S-C., Jiang, W-L., van Ruijven, J., Li, L. 2018. The role of complementarity and selection effects in P acquisition of intercropping systems. Plant Soil. 422(1/2), 479-493.

Liao, D., Zhang, C., Li, H., Lambers, H. 2020. Changes in soil phosphorus fractions following sole cropped and intercropped maize and faba bean grown on calcareous soil. Plant Soil. 448, 587-601. https://doi.org/10.1007/s/11104-020-04460-0.

Loreau, M., Hector, A. 2001. Partitioning selection and complementarity in biodiversity experiments. Nature. 412, 72-76.

Madsen, I.J., Parks, J.M., Friesen, M.L., Clark, R.E. 2022. Increasing Biodiversity and Land-Use Efficiency Through Pea (*Pisum aestivum*)-Canola (*Brassica napus*) Intercropping (Peaola). Front. Soil. Sci. 2:818862. DOI: 10.3389/fsoil.2022.818862.

McGonigle, T.P., Hutton, M., Greenley, A., Karamanos, R. 2011. Role of Mycorrhiza in a Wheat-Flax versus Canola-Flax Rotation: A Case Study. Commun. Soil Sci. Plant. Anal. 42(17), 2134-2142. DOI: 10.1080/00103624.2011.596242

Miheguli, R., Schoenau, J.J., Jefferson, P.G. 2018. Yield and Uptake of Phosphorus by Wheat and Canola Grown after Two Years of Forage Legume and Annual Crops. 2018. Am. J. Plant Sci. 9, 1807-1825. https://doi.org/10.4236/ajps.2018.99132.

Miller, M.H., McGonigle, T.P., Addy, H. 1995. Functional ecology of vesicular-arbuscular mycorrhizas as influenced by phosphate fertilization and tillage in an agricultural ecosystem. Crit. Rev. Biotechnol. 15, 241-255.

Miller, R.O. 1998. Microwave digestion of plant tissue in a closed vessel. In ‘Handbook and reference methods for plant analysis’. (Ed. YP Kalra) pp. 53–56. (CRC Press: New York)

Mosse, B. 1975. Specificity in VA mycorrhizas. In: Endomycorrhizas. Academic Press, London, UK, pp 469–484.

Nie, Z., McLean, T., Clough, A., Tocker, J., Christy, B., Harris, R., Riffkin, P., McCaskill, M., 2016. Benefits, challenges and opportunities of integrated crop- livestock systems and their potential application in the high rainfall zone of southern Australia: A review. Agric. Ecosyst. Environ. 235, 17–31.

Owen, K.J., Clewett, T.G., Thompson, J.P. 2010. Pre-cropping with canola decreased *Pratylenchus thornei* populations, arbuscular mycorrhizal fungi, and yield of wheat. Crop Pasture. 61, 399-410. 10.1071/CP09345

Rahimzadeh, S. Pirzad, A. 2019. *Pseudomonas* and mycorrhizal fungi co-inoculation alter seed quality of flax under various water supply conditions. Ind. Crop Prod. 129, 518-524. https://doi.org/10.1016/j.indcrop.2018.12.038

Rezaei-Chiyaneh, E., Jalilian, J., Seyyedi, S.M., Barin, M., Ebrahimian, El., Afshar, R.K. 2021. Isabgol

(*Plantago ovata*) and lentil (*Lens culinaris*) intercrop responses to arbuscular mycorrhizal fungi inoculation. Biol. Agric. Hortic. 37(2), 125-140. DOI: 10.1080/01448765.2021.1903556

Rillig, M.C., Sosa-Hernández, M.A., Roy, J., Aguilar-Trigueros, C.A., Vályi, K., Lehman, A. 2016. Towards an Integrated Mycorrhizal Technology: Harnessing Mycorrhiza for Sustainable Intensification in Agriculture. Front. Plant Sci. 7:1625. *doi: 10.3389/fpls.2016.01625*

Roberts, P., Moodie, M., Wilhelm, N., 2019. Intercropping increases productivity in the South Australian Mallee. In: Proceedings of the 2019 Agronomy Australia Conference. 25-29 August 2019, Wagga Wagga, Australia.

RStudio Team. 2020. RStudio: Integrated Development for R. RStudio, PBC, Boston, MA. http://www rstudio.com/.

Ryan, M.H., Graham, J.H., 2018. Little evidence that farmers should consider abundance or diversity of arbuscular mycorrhizal fungi when managing crops. New Phytol. 220, 1092–1107.

Sarwar, M., Kirkegaard, J.A. 1998. Biofumigation potential of brassicas: II. Effect of environment and ontogeny on glucosinolate production and implications for screening. Plant Soil. 201(1), 91-101.

Simard, S.W., Beiler, K.J., Bingham, M.A., Deslippe, J.R., Philip, L.J., Teste, F.P., 2012. Mycorrhizal networks: mechanisms, ecology and modelling. Fungal Biol. Rev. 26, 39–60.

Smith, S.E., Smith, F.A. 2011. Roles of arbuscular mycorrhizas in plant nutrition and growth: new paradigms from cellular to ecosystem scales. Annu. Rev. Plant Biol. 62, 227–250.

Suraweera, D.D., Riffkin, P.A., Christy, B.P, O'Leary, G.J., McCaskill, M.R., Mitchell, M.L. 2022. *Vegetative competition between crops grown in intercropping systems*. In Proceedings of the 20th Agronomy Australia Conference, Toowoomba, Qld.

Tavasolee, A., Aliasgharzad, N., Salehi, G.R., Mardi, M., Asgharzadeh, A., Akbarivala, S. 2011. Effects of Co-Inoculation with Arbuscular Mycorrhizal Fungi and Rhizobia on Fungal Occupancy in Chickpea Root and Nodule Determined by Real-Time PCR. Curr. Microbiol. 63, 107-114. DOI: 10.1007/s00284-011-9951-z.

Thingstrup, I., Rubæk, G., Sibbesen, E., Jakobsen, I. 1998. Flax (*Linum usitatissimum* L.) depends on arbuscular mycorrhizal fungi for growth and P uptake at intermediate but not high soil P levels in the field. Plant Soil, 203, 37-46.

Tosti, G., Thorup-Kristensen, K. 2010. Using coloured roots to study root interaction and competition in intercropped legumes and non-legumes. J. Plant. Ecol. 3(3), 191-199. doi: 10.1093/jpe/rtq014

Tran, B.T.T., Watts-Williams, S.J., Cavagnaro, T.R. 2019. Impact of an arbuscular mycorrhizal fungus on the growth and nutrition of fifteen crop and pasture plant species. Funct. Plant Biol. 46, 732-742.

https://doi.org/10.1071/FP18327

Trenbath, B.R. 1993. Intercropping for the management of pests and disease. Field Crop. Res. 34, 381-405.

USDA, 2022. USDA Agricultural Projections to 2031. World Agricultural Outlook Board, United States Department of Agriculture. Access 23 June 2022 < https://www.usda.gov/sites/default/files/documents/USDA-Agricultural-Projections-to-2031.pdf >

Vályi, K., Mardhiah, U., Rillig, M.C., Hempel, S. 2016. Community assembly and coexistence in communities of arbuscular mycorrhizal fungi. ISME J. 10: 2341–2351.

Van Geel, M., De Beenhouwer, M., Lievens, B., Honnay, O. 2016. Crop-specific and single-species mycorrhizal inoculation is the best approach tto improve crop growth in controlled environments. Agron. Sustain. Dev. 36:37. DOI: 10.1007/s13593-016-0373-y

Vierheilig H, Coughlan AP, Wyss U, Piché Y (1998) Ink and vinegar, a simple staining technique for arbuscular-mycorrhizal fungi. Appl Environ Microbiol 64:5004–5007.

Walder, F., Niemann, H., Natarajan, M., Lehmann, M.F., Boller, T., Wiemken, A., 2012. Mycorrhizal Networks: Common Goods of Plants Shared under Unequal Terms of Trade. Plant. Physiol. 159, 789-797.

Watts-Williams, S.J., Gilbert, S.E. 2020. Arbuscular mycorrhizal fungi affect the concentration and distribution of nutrients in the grain differently in barley compared with wheat. Plant. People Planet. 3(5), 567-577.

Wei, T., Simko, V., Levy, M., Xie, Y., Jin, Y., Zemla, J., Freidank, M., Cai, J., Prtoivinsky, T. 2018. ‘corrplot’. Visualization of a Correlation Matrix. https://github.com/taiyun/corrplot

Wilkes, T.I. 2021. Arbuscular Mycorrhizal Fungi in Agriculture. Encycl. 1, 1132-1154. https://doi.org/10.3390/encyclopedia1040085

Xavier, L.J.C., Germida, J.J. 2002. Response of lentil under controlled conditions to co-inoculation with arbuscular mycorrhizal fungi and rhizobia varying in efficacy. Soil Biol. Biochem. 43, 181-188.

Zhang, B., Chang, S.X., Anyia, A. 2016. Mycorrhizal inoculation and nitrogen fertilization affect the physiology and growth of spring wheat under two contrasting water regimes. Plant Soil. 398, 47-57. DOI: 10.1007/s11104-015-2635-x

Zhang, D., Li, H., Fu, Z., Cai, S., Xu, S., Zhu, H., Shen, J. 2019. Increased planting density of Chinese milk vetch (*Astragalus sinicus*) weakens phosphorus uptake advantage by rapeseed (*Brassica napus*) in a mixed cropping system. AoB Plant. 11(4), doi:10.1093/aobpla/plz033

CHAPTER 6: General discussion and conclusion

6.1 Introduction

This thesis has investigated the yield, nutrient and economic dynamics of legume-oilseed intercropping in mechanised broadacre systems in a Mediterranean climate. On the basis of this research, legume-oilseed intercropping is well suited to low input scenarios. It provided similar or greater yield and increased land use efficiency relative to the respective sole crops, as well as improved stability of both yield and gross margins across environments. Further, intercropping had limited effects on the plant-AMF symbiosis, even when the non-mycorrhizal canola was used as the oilseed component.

6.2 Yield dynamics

There was no difference between the absolute yield of the combined chickpea-linseed intercrop and that of the highest yielding sole crop at each site-year (Chapter 3). This is in contrast to the literature, which has shown improved intercrop yield relative to the respective sole crops in a range of oilseed-legume pairings including chickpea-linseed (SERF, 2015, Vankoughnet, 2016; WARC, 2016), and pea-canola (Madsen et al., 2022). However, intercropping is utilised for a number of reasons beyond increased yield. In mechanised systems the primary motivation for the recent adoption of intercropping is reduced input costs and reduced risk, with overyielding viewed as a secondary benefit (Kirkegaard & Condon, 2019; Fulwood, 2020). In this way, intercropping systems that improve resource use efficiency and reduce risk relative to the respective sole crops can be viewed as beneficial, even if overyielding doesn’t occur. Thus, while the absolute yield of the chickpea-linseed intercrop was not greater than that of the highest yielding sole crop (Chapter 3), the potential of the system lies in the improved performance relative to the sole crops under low input conditions, as well as grain yield and gross margin stability across environments, which reduces risk.

6.3 Intercropping as a low input system

6.3.1 Improved relative yield under low input scenarios

The chickpea-linseed and chickpea-canola intercrops investigated in Chapter 4 were equally or more productive than the respective sole crops, specifically under the low fertiliser and fungicide regimes. In Experiment 1, the intercrop in the nil fertiliser treatment had the highest LER and was the only LER that out-yielded the sole crops. Similarly, in Experiment 2, grain LERs of both the chickpea-linseed and chickpea-canola intercrops were consistently below the sole crop value of 1 in the foliar fungicide + desiccant treatment, but consistently above 1 in the nil fungicide treatment.

The consistent underperformance of the intercrops in the higher input treatments, and the consistent improved performance of the intercrops in the nil treatments demonstrate the advantage of intercrops in the absence of inputs. Where nutrient availability was increased by the application of fertiliser, or crops were protected from disease by the application of foliar fungicide and dried down with the use of desiccant, intercropping did not confer an advantage. Conversely, in the nil treatments the facilitative and/or complementary interspecies interactions would have reduced environmental stress in the intercrop relative to the sole crops, resulting in the higher LERs of the intercrops in the nil treatments. In this way, legume-oilseed intercropping is demonstrated as a low input system for farmers wanting to decrease input costs without sacrificing yield. This is particularly important in the context of rising nitrogen fertiliser prices (USDA, 2022), greater regulation of pesticide, and increasing consumer demand for reduced pesticide usage (Matthews et al., 2021; Simoglou and

Roditakis, 2022).

6.3.2 Higher gross margins under low input

The highest intercrop gross margin was achieved in the nil (0N0P) or low (0N20P) fertiliser treatment at each site-year, suggesting an optimum balance between input costs and yield outputs when soil background nutrition is adequate (Chapter 4, Experiment 1). By comparison, although intercrops in the higher fertiliser treatments had grain LERs similar to the sole crop, the gross margins were lower because of the high cost of fertiliser. The comparatively close LERs but disparate gross margins of the nil and low, compared with the high fertiliser treatments, highlight that productivity does not necessarily equate to profitability, reinforcing the suitability of intercropping in a low input scenario. If intercropping, which entails more complex management practices, is to be adopted then it needs to be economical (Roberts et al., 2019). The gross margin and sensitivity analysis (Chapter 4) demonstrates that an economic return greater than, or similar to, the sole crop is possible.

6.3.3 Mechanisms of efficiency: nitrogen dynamics

The intercrop showed improved land use efficiency in terms of nitrogen uptake (NLER) relative to the sole crops, and greater or similar absolute N uptake (kg N ha^{-1}) (Chapter 3). The intercrop NLER of 1.27 indicates that to acquire the same amount of nitrogen as the intercrop, the respective sole crops would need 27% more land. Moreover, fertiliser treatments had no effect on NLER, suggesting improved nitrogen uptake efficiency in the intercrop under varying soil nitrogen availabilities.

The improved nitrogen uptake efficiency in the intercrop could be a function of the increased biological nitrogen fixation (BNF) of the chickpea component. The intercrop chickpea had increased %Ndfa compared with the sole chickpea. BNF is inhibited by high levels of soil inorganic nitrogen (Peoples et al., 1995; Génard et al., 2016). In an intercrop, if the non-legume component outcompetes the legume for soil nitrogen, the legume will be forced to fix atmospheric nitrogen, improving the overall nitrogen efficiency of the system. The increased NLER in the intercrop compared with the sole crop suggests just this; the chickpea fixed its own nitrogen while the linseed utilised the soil pool or fixed nitrogen released by the chickpea (Jensen, 1996; Fustec et al., 2010; Chalk et al., 2014; Lorin et al., 2016; Génard et al., 2016, 2017). In utilising these complementary sources of nitrogen, intercropping presents the possibility to reduce nitrogen fertiliser application and, in turn, reduce input costs without a yield penalty. The sensitivity analysis (Chapter 4) highlighted the rapidly increasing price of nitrogen fertiliser, with the 2021 price being the highest in the past five years. In this context, any system that can maintain yield under low nitrogen input, or enhance N fixation is beneficial to farmers.

6.3.4 Mechanisms of efficiency: phosphorus dynamics

In the field, the chickpea-linseed intercrop showed reduced land use efficiency in terms of phosphorus uptake compared with the sole crops, and similar or less absolute P uptake (kg P ha^{-1}) (Chapter 3). Conversely, in the glasshouse shoot phosphorus in canola intercropped with chickpea was greater than in both the sole canola and the canola intercropped with lentil (Chapter 5). This suggests a phosphorus benefit of intercropping with some species combinations and not others. Enhanced resource acquisition in an intercrop can be explained by positive interspecific interactions such as resource partitioning or facilitation (Hinsinger et al., 2011; Li et al., 2018), or by competitive dominance wherein one crop component increases resource acquisition at the expense of the other (Loreau & Hector, 2001; Li et al., 2018). In the case of the chickpea-canola intercrop in the glasshouse, the increased canola shoot phosphorus but similar chickpea shoot phosphorus relative to their respective sole crops suggests that the chickpea is facilitating increased acquisition in the canola, rather than the canola outcompeting the chickpea. Comparatively, in the field, interspecies competition appears to have negatively affected both the chickpea and linseed crop components in terms of phosphorus acquisition. Chickpea and linseed have a similar distribution of roots throughout the soil profile (Gan et al., 2009), making interspecies competition for resources likely. This appears to be the case, given the reduced PLER and absolute P uptake of the intercrop compared with the sole crops. More research is needed to test compatible legume-oilseed intercrop combinations with regards to phosphorus acquisition. Research should focus on investigating the mechanisms behind the intercrop benefit, with selection for complementary and facilitative interactions that enhance the nutrient dynamics of the whole system, over competitive dominance and negative competition effects.

6.4 Intercropping as a risk minimising strategy

6.4.1 Chickpea yield stability across environments

Intercropping appeared to provide yield stability to the chickpea component across environments and varying water availabilities (Chapter 3). The yield of the sole crop chickpea decreased with decreasing rainfall, while the yield of the intercrop chickpea was similar across P2019, K2020, and I2020, despite the latter two site-years having considerably more rainfall during the critical pre-season and flowering to maturity periods. This finding is supported by Wallace et al. (2022), who report that intercrop yield was higher relative to the sole crop yield specifically under drier conditions in field pea-canola and faba bean-canola intercrops. In the context of increasingly unpredictable weather and changing rainfall patterns (Crane et al., 2011; Flohr et al., 2021) intercropping appears to provide a buffer, minimising the risk of crop failure and/or heavily reduced yields in years of lower rainfall.

6.4.2 Gross margin stability across environments

Intercropping provided gross margin stability across the different environments (Experiment 1, Chapter 4). While the intercrop never returned the highest gross margin, it was often comparable to the highest earning sole crop and also provided the most consistently high gross margin across the site-years. This pattern held across the different scenarios in the sensitivity analysis. On the one hand, at site-years where linseed had higher yield as a result of the higher rainfall, intercrop gross margins were higher due to the market price of the linseed, boosting profits above those of the sole chickpea. On the other hand, at site-years with less rainfall and lower yields, the chickpea component of the intercrop was able to recoup some of the losses of the sole linseed, which has a higher seed cost than the chickpea. With changes in rainfall patterns and weather becoming increasingly unpredictable (Crane et al., 2011; Flohr et al., 2021), intercropping may allow growers to 'hedge their bets' in this way.

Additionally, intercropping appears to be a risk minimising strategy in terms of oilseed production (Chapter 4). The linseed-chickpea intercrop was equally or more profitable than the sole linseed across five of the six site-years in Experiments 1 and 2, while the canola-chickpea intercrop was more profitable than the sole canola. Where the sole oilseed grossed poorly, intercropping with the chickpea improved overall profit. Conversely, where the sole oilseed earnings were sufficient, intercropping did not reduce profits. Further, intercropping improved the earnings of the oilseed component in Experiment 2; intercrop linseed earnings were similar to those of the sole linseed, and most notably the gross margin of the intercrop canola was larger than that of the sole canola.

6.5 Mycorrhiza and intercropping

Importantly, mycorrhizal colonisation of plant roots was not affected by intercropping (Chapter 5). The one exception to this was the lentil in the glasshouse experiment, which had increased colonisation in the sole crop compared with the intercrop. Interestingly, being intercropped with the non-mycorrhizal canola did not affect lentil or chickpea root colonisation (excepting lentil in the glasshouse) relative to the sole crop or being intercropped with the highly mycorrhizal linseed. This is unexpected, as canola is known to release glucosinolates into the soil (Gimsing & Kirkegaard, 2009; Couëdel et al., 2019), which are toxic to fungi and are thought to contribute to the plant's non-mycorrhizal status (Floc'h et al., 2022). Indeed, crop rotation studies have shown both reduced mycorrhizal colonisation and yield of mycorrhizal plants, such as maize and linseed, following canola, as opposed to another mycorrhizal crop (McGonigle et al., 2011; Higo et al., 2017). As an explanation of the nil canola effect, Trenbath (1993) and Boudreau (2013) suggest that sowing brassica species with a companion legume may negate any negative effects on soil biota by the brassicas, and it is possible this was the case with the mycorrhiza in our lentil-canola and chickpea-canola intercrops. Alternatively, it is possible that I harvested the plants before the canola could exude sufficient levels of glucosinolates to affect the mycorrhizal colonisation of its companion, and that it would have released potentially more toxic levels when more established. Irrespective, the result suggests that intercrops including popular brassica and legume species, such as lentil-canola (Roberts et al., 2019) or pea-canola (Bennet, 2009; Chalmers, 2017) can be utilised for the multitude of benefits they provide (see Dowling et al., 2021) without damaging mycorrhizal communities and reducing any ecosystem services they may provide.

6.6 Conclusions

The aim of this thesis was to investigate the viability of legume-oilseed intercropping in mechanised broadacre agriculture, with a focus on the productivity and profitability outcomes of legume-oilseed intercrops in a low input system. Importantly, I found legume-oilseed intercropping appears well suited as a low-input system in broadacre cropping in Mediterranean environments. Although the actual yield of the intercrops was similar to the respective sole crops, intercropping chickpea with the oilseed species linseed and canola resulted in improved land use efficiency (LER) relative to sole crops, particularly under reduced fertiliser and fungicide inputs. The intercrops also provided greater gross margins and gross margin stability under low input scenarios. Relative to the sole crops, the intercrops had increased nitrogen uptake efficiency per unit land area (NLER) and similar or greater actual nitrogen uptake (kg N ha^{-1}), but a lower PLER than the sole crops and the same or lower phosphorus uptake (kg P ha^{-1}). Finally, the interaction between intercropping and inoculation with AMF had limited effect on crop growth and shoot phosphorus, and intercropping with non-mycorrhizal canola did not reduce legume colonisation. This result suggests that intercrops, including popular brassica and legume species, such as lentil-canola or pea-canola, can be utilised for the multitude of benefits they provide without damaging the health and performance of mycorrhizal communities. In summary, legume-oilseed intercropping can be utilised as a risk mitigation strategy and a profitable alternative to traditional high input monocultures in a global environment of rising synthetic input costs.

6.7 Limitations of the study and recommendations for future research

I have identified four major areas that future studies should consider:

- A major limitation of the current study was the nutrient rich soils of some of the sites selected. Given that the effect of intercropping on yield under reduced nutrient availability was being tested, this was not ideal. Moving forward, field studies should be implemented at sites with lower background soil nutrient profiles. Firstly, this would allow the effect of intercropping on system nutrient dynamics under varying fertiliser treatments to be properly gauged in a situation where plant growth is not fully supported by background nutrients. Further, field studies on P-limited soils are required to explore the role of AMF in intercropping, particularly as the AMF symbiosis is reduced under high levels of soil phosphate (Thingstrup et al., 1998; Wilkes, 2021). In the context of intercropping, it is important to investigate the reliance of crops on AMF when P is limited, particularly as interspecies interactions are known to alter P availability in the rhizosphere (Costa et al., 2014; Nie et al., 2016). This would entail running trials at the same site over multiple years, as well as at locations with nutrient-limited soils.

- Another limitation of the current study was the limited range of species, and species combinations used. Different oilseed-legume pairings warrant investigation, particularly as linseed has a limited global market. In the Mediterranean cropping region of southern Australian, chickpea-canola and lentil-canola combinations would have merit, given the relative planting areas and market relevance of these crops, particularly as effective disease control options for cereal dominant systems.
- Given the yield stability of the intercrop chickpea across environments that intercropping appeared to provide the chickpea, the effect of water availability on the nutrient dynamics and growth of intercrop compared with sole crop warrants investigation.
- To establish the longer-terms effects of intercropping with canola, whole-season experiments should be carried out, with sampling at multiple growth stages. An important aspect of this is break crop rotation research. If the yield of mycorrhizal

cereal crops such as wheat is worse following canola, as much of the literature suggests (Owen et al., 2010; Bakhshandeh et al., 2017), could legume-canola intercrops take the place of sole canola? This would maintain the break crop and market relevance benefits, whilst providing continuation of the mycorrhizal community for the following cereal crop.

References

Bakhshandeh, S., Corneo, P.E., Mariotte, P., Kertesz, M.A., Dijkstra, F.A. 2017. Effect of crop rotation on mycorrhizal colonization and wheat yield under different fertilizer treatments. Agric. Ecosystm. Environ. 247, 130-136. http://dx.doi.org/10.1016/j.agee.2017.06.027

Bennet, M. 2009. Peola at Minnipa in 2009. In: Scholz, N., Cook, A., Latta, R., Wilhelm, N., Mennet, M., Paterson, C., Brace, D., McNeill, A., Chirgwin, M. (Eds.), Eyre Pensinsula farming systems 2009 summary. South Australiam Research and Development Institute, South Australia. pp.60-62.

Boudreau, M.A., 2013. Diseases in intercropping systems. Annu. Rev. Phytopathol. 51, 499–519.

Chalk, P.M, Peoples, M.B., McNeill, A.M., Boddey, R.M., Unkovich, M.J., Gardener, M.J., Silva, C.F., Chen, D. 2014. Methodologies for estimating nitrogen transfer between legumes and companion species in agro-ecosystems: A review of ^{15}N-enriched techniques. Soil Biol. Biochem. 73, 10-21. https://doi.org/10.1016/j.soilbio.2014.02.005

Chalmers, S., 2017. Responses of pea and canola intercrops to nitrogen and phosphorus applications. Westman Agricultural Diversification Organization 2017 Annual Report. Westman Agricultural Diversification Organization, Manitoba, pp. 127–136.

Costa, S.E.V.G.A., Souza, E.D., Anghinoni, I., Carvalho, P.C.F., Martins, A.P., Kunrath, T. R., Cecagno, D., Balerini, F., 2014. Impact of an integrated no-till crop-livestock system on phosphorus distribution, availability and stock. Agric. Ecosyst. Environ. 190, 43–51.

Couëdel, A., Kirkegaard, J., Alletto, L., Justes, E., 2019. Crucifer-legume cover crop mixtures for biocontrol: Toward a new multi-service paradigm. Adv. Agron. 157, 55–139.

Crane, T.A., Roncoli, C., Hoogenboom, G. 2011. Adaptation to climate change and climate variability: The importance of understanding agriculture as performance. Wageningen. J. Life Sci. 57, 179-185. doi:10.1016/j njas.2010.11.002

Dowling, A., Sadras, V.O., Roberts, P., Doolette, A., Zhou, Y., Denton, M.D. 2021. Legume-oilseed intercropping in mechanised broadacre agriculture – a review. Field Crops Res. 260, 107980, https://doi.org/10.1016/j.fcr.2020.107980

Floc'h, J-B, Hamel, C., Laterriére, M., Tidemann, B., St-Arnaud, M., Hijri, M. 2022. Arbuscular Mycorrhizal Fungi in the Rhizosphere and Bulk Soils of Non-host *Brassica napus* and Their Networks of Co-occurring Microbes. Front. Plant Sci. 13:828145. doi: 10.3389/fpls.2022.828145

Flohr, B.M., Ouzman, J., McBeath, T.M., Rebetzke, G.J., Kirkegaard, J.A., Llewellyn, R.S. 2021. Redefining the link between rainfall and crop establishment in dryland cropping systems. Agric. Syst. 190, 103105. https://doi.org/10.1016/j/agsy.2021.103105

Fulwood, J., 20 Jun 2020, “Intercropping study demonstrates potential yield and economic upside”. GroundCover, 147. https://groundcover.grdc.com.au/innovation/industry-insights/profitable-intercrops-give-growers-optioins. Accessed December 10, 2021.

Fustec, J., Lesuffleur, F., Mahieu, S., Cliquet, J.-B., 2010. Nitrogen rhizodeposition of legumes: A review. Agron. Sustain. Dev. 30, 57–66. https://doi.org/10.1051/agro/2009003

Gan, Y.T., Campbell, C.A., Janzen, H.H., Lemke, R., Liu, L.P., Basnyat, P., McDonald, C.L. 2009. Root mass for oilseed and pulse crops: Growth and distribution in the soil profile. Can. J. Plant. Sci. 89, 883-893. doi: 10.4141/CJPS08154

Génard, T., Etienne, P., Diquélou, Yvin, J.-C., Revellin, C., Laîné, P., 2017. Rapeseed- legume intercrops: plant growth and nitrogen balance in early stages of growth and development. Plant Biol. 3, 2–20.

Génard, T., Etienne, P., Laîné, P., Yvin, J.-C., Diquélou, S., 2016. Nitrogen transfer from Lupinus albus L., Trifolium incarnatum L. and Vicia sativa L. contribute differently to rapeseed (Brassica napus L.) nitrogen nutrition. Plant Biol. 2, 2–15. https://doi.org/10.1016/j heliyon.2016.e00150

Gimsing, A., Kirkegaard, J.A., 2009. Glucosinolates and biofumigation: fate of glucosinolates and their hydrolysis products in soil. Phytochem. Rev. 8, 299–310.

Higo, M., Takahashi, Y., Gunji, K., Isobe, K. 2017. How are arbuscular mycorrhizal associations related to maize growth performance during short-term cover crop rotation? J. Sci. Food. Agric. 98, 1388-1396. DOI 10.1002/jsfa.8606

Hinsinger, P., Betencourt, E., Bernard, L., Brauman, A., Plassard, C., Shen, J., Tang, C., Zhang, F., 2011. P for two, sharing a scarce resource: soil phosphorus acquisition in the rhizosphere of intercropped species. Plant Physiol. 156, 1078–1086.

Jensen, E.S. 1996. Grain yield, symbiotic N_2 fixation and interspecific competition for inorganic N in pea-barley intercrops. Plant Soil. 182, 25-38. doi: 10.1007/BF00010992

Kirkegaard, J., Condon, G. 2019. Companion cropping – should we be considering it? GRDC update papers. https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2019/02/companion-cropping-should-we-be-considering-it. Accessed April 12, 2022.

Li, X-F., Wang, C-B., Zhang, W-P., Wang, L-H., Tian, X-L., Yang, S-C., Jiang, W-L., van Ruijven, J., Li, L. 2018. The role of complementarity and selection effects in P acquisition of intercropping systems. Plant Soil. 422(1/2), 479-493.

Loreau, M., Hector, A. 2001. Partitioning selection and complementarity in biodiversity experiments. Nature. 412, 72-76.

Lorin, M., Jeuffroy, M.-H., Butier, A., Valantin-Morison, M. 2016. Undersowing winter oilseed rape with frost-sensitive legume living mulch: Consequences for cash crop nitrogen nutrition. Field Crops Res. 193, 24-33. http://dx.doi.org/10.1016/j fcr.2016.03.002

Madsen, I.J., Parks, J.M., Friesen, M.L., Clark, R.E. 2022. Increasing Biodiversity and Land-Use Efficiency Through Pea (*Pisum aestivum*)-Canola (*Brassica napus*) Intercropping (Peaola). Front. Soil. Sci. 2:818862. DOI: 10.3389/fsoil.2022.818862.

Matthews, K., Astin, A., Corbett, M., Suann, C. 2021. *Final Report of the Independent Review of the Pesticides and Veterinary Medicines Regulatory System in Australia*. Australian Government, Department of Agriculture, Water and the Environment, Canberra.

McGonigle, T.P., Hutton, M., Greenley, A., Karamanos, R. 2011. Role of Mycorrhiza in a Wheat-Flax versus Canola-Flax Rotation: A Case Study. Commun. Soil Sci. Plant. Anal. 42(17), 2134-2142. DOI: 10.1080/00103624.2011.596242

Nie, Z., McLean, T., Clough, A., Tocker, J., Christy, B., Harris, R., Riffkin, P., McCaskill, M., 2016. Benefits, challenges and opportunities of integrated crop- livestock systems and their potential application in the high rainfall zone of southern Australia: A review. Agric. Ecosyst. Environ. 235, 17–31.

Owen, K.J., Clewett, T.G., Thompson, J.P. 2010. Pre-cropping with canola decreased *Pratylenchus thornei* populations, arbuscular mycorrhizal fungi, and yield of wheat. Crop Pasture. 61, 399-410. 10.1071/CP09345

Peoples, M.B., Herridge, D.F., Ladha, J.K., 1995. Biological nitrogen fixation: An efficient source of nitrogen for sustainable agricultural production? Plant Soil. 174, 3–28. https://doi.org/10.1007/BF00032239

Roberts, P., Moodie, M., Wilhelm, N., 2019. Intercropping increases productivity in the South Australian Mallee. In: Proceedings of the 2019 Agronomy Australia Conference. 25-29 August 2019, Wagga Wagga, Australia.

Simoglou, K.B., Roditakis, E. 2022. Consumers' Benefit – Risk Perception on Pesticides and Food Safety – A Survey in Greece. Agric. 12, 192. https://doi.org/10.3390/agriculture12020192

South East Research Farm (SERF), 2015. Intercropping chickpea and flax (Agri-Arm Research Update). Saskatchewan Ministry of Agriculture, Saskatchewan.

Thingstrup, I., Rubæk, G., Sibbesen, E., Jakobsen, I. 1998. Flax (*Linum usitatissimum* L.) depends on arbuscular mycorrhizal fungi for growth and P uptake at intermediate but not high soil P levels in the field. Plant Soil, 203, 37-46.

Trenbath, B.R. 1993. Intercropping for the management of pests and disease. Field Crop. Res. 34, 381-405.

USDA, 2022. USDA Agricultural Projections to 2031. World Agricultural Outlook Board, United States Department of Agriculture. Access 23 June 2022 < https://www.usda.gov/sites/default/files/documents/USDA-

Agricultural-Projections-to-2031.pdf >

VanKoughnet, B., 2016. On-farm evaluation of peaola intercropping – an intercrop of peas and canola. Agri Skills Inc., Manitoba Pulse and Soybean Growers, Manitoba.

Wallace, A., Christy, B., Mitchell, M., Nuttall, J., O'Leary, G. 2022. *Water use of cereal, oilseed, and grain legume crops within intercropping systems of southern Australia*. In Proceedings of the 20th Agronomy Australia Conference, Toowoomba, Qld.

Western Applied Rsearch Corporation (WARC). 2016. Chickpea flax intercropping: can flax stress chickpea to hasten seed set and maturity and/or act as a barrier to disease spread (Final Report 20130460). Saskatchewan Ministry of Agriculture, Saskatchewan.

Wilkes, T.I. 2021. Arbuscular Mycorrhizal Fungi in Agriculture. Encylo. 1, 1132-1154. https://doi.org/10.3390/encylopedia1040085