Final Technical Report:

Investigating double break (or stacked rotation) options

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Abstract

In Western Australia, Cereal crops account for 60-70% of paddocks sown in any one year, with the remaining area sown to a range of crop and pasture types including canola, lupin, clover, volunteer pasture, or left as fallow. The Eastern Wheatbelt in particular has limited break crop options and there is the need to investigate the better use of break crop options to improve the profitability of wheat. A replicated trial site was established in 2016 near Merredin in the Eastern Wheatbelt region of WA, with four satellite demonstration sites located across the Eastern and Central Wheatbelt. The crop types evaluated were: lupin, chickpea, lentil, field pea, pasture legumes, canola, and fallow. The success of break crops to increase wheat grain yield is dependent on firstly addressing any physical and chemical soil constraints to crop production to allow the successful growing of a wide range of break-crops. The use of chemical fallow as the first break-crop allowed for the successful growing of lupin, chickpea, lentil and field pea that yielded 0.97-1.42 t/ha 0.67-1.1 t/ha, 0.3-0.97 t/ha, and 1.2 t/ha respectively in a below average season. The yield of wheat following legume break crops tended to be higher than either canola or wheat planted in the remaining paddock area. The profitability of double break-crop sequences was negative in many of the sequences evaluated in this study compared to a positive profit for continuous wheat. The profitability of double break-crop sequences can be improved by the inclusion of high value legumes as the second break-crop, but further work is required to lower the risk of growing these species of crops.

Executive Summary

In Western Australia, break crop options are currently limited and there is a high proportion of wheat and barley grown in rotation. Cereal crops account for 60-70% of paddocks sown in any one year, with the remaining area sown to a range of crop and pasture types including canola, lupin, clover, volunteer pasture, or left as fallow. In addition, there is an interest in chickpea and lentil to add a high value legume to the crop rotation. The application of these break crops is dependent on the grain price per tonne and on the level of severity of biological constraints present that lead to a reduction in grain yield and which varies from paddock to paddock. The use of a single break crop in rotation has been shown to be an effective tool in managing both weed and diseases that affect wheat production to remove biological constraints to crop production and allow the sustained production of cereal crops. However, with a change in resistance status of many common weeds and diseases, and a change in soilborne pathogens, a single break crop applied to a cropping system that is largely based on cereals has limited effect in reducing the biological constraints, with the longevity of the break crop benefit being reduced. Recent studies into the break crop benefits for highly herbicide resistant weed populations has found that a break of at least two years was needed to prevent grass seed set and substantially reduce grass seedbank numbers.

Considering the high percentage of cereal crops grown in Western Australia, there is the need to evaluate the use of double break crop sequences to improve wheat grain yield and profitability. In particular, the Eastern Wheatbelt region has very limited break crop options, and there is the need to investigate the better use of tools such as fallow periods to improve break crop outcomes.

A replicated trial site was established in 2016 near Merredin the Eastern Wheatbelt region of WA that contained a high population of annual ryegrass. The crop types evaluated in this project include lupin, chickpea, lentil, pasture legumes, canola, and fallow. These were grown in the 2016 and 2017 seasons and the effect on grain yield and profitability of wheat evaluated in the 2018 season. The average annual and growing season rainfall for each site can be described as average, below average, and average for the 2016, 2017, and 2018 seasons (respectively). The grain yield of wheat in 2018 was greatest following fallow/canola or fallow/balansa clover compared to all other break crop rotations. In contrast, grain yield was lowest following fallow/chickpea, fallow/lentil, and fallow/fallow. The grain yield of wheat grown after wheat/wheat was not significantly different to the lowest yielding nor the highest yielding treatments in 2018. Grain protein was significantly influenced by break crop rotation, with the lowest protein occurring following fallow/oats and fallow/chickpea. In general, grain protein was improved following treatments that had canola as the second break crop preceding wheat in 2018.

The number of ryegrass panicles (heads) were counted prior to maturity for each break crop sequence, with ryegrass numbers being significantly higher for fallow/chickpea and fallow/lentil compared to all other treatments (which had similar numbers of ryegrass panicles). The population of annual ryegrass at the site was reduced significantly where canola was used in crop rotation, but the double break had no effect where chickpea or lentil were grown. The type of fallow used was a spray topped pasture, and this was not effective in reducing the ryegrass population.

Four demonstration sites were established across the central and eastern wheatbelt to further assess the use of double break-crop rotations. These sites contained either chemical fallow or spray topped pasture as the first break-crop in 2016, with the grain yield of break crops in 2017 at the demonstration sites being highest for lupin and varied in a range of 0.97 t/ha to 1.42 t/ha, while chickpea, lentil and field pea yielded 0.67-1.1 t/ha, 0.3-0.97 t/ha, and 1.2 t/ha respectively. The yield of wheat at the demonstration sites following legume break crops tended to be higher than either canola or wheat planted in the remaining paddock area.

The grain yield benefit to wheat and profitability of a break crop rotation was dependent on identifying the biological limitation for crop growth and designing an effective crop rotation to

achieve this. This approach assumes that the physical (soil compaction) and chemical (soil acidity, salinity) constraints have been addressed as a priority. The consequences of poor break-crop performance were not only reduced profitability of the break-crop but also a reduction in the N fixation for legumes, an increase in weed population due to poor crop competition, and lower wheat grain yield in the following (and subsequent) years.

The driver of increased grain yield of wheat following legume breaks appeared to be the fixation of N rather than the reduction in root disease levels. Each legume crop had a different influence on the profile of soil diseases, and this was dependent on the disease susceptibility of each species. The prevalence of P.neglectus and the susceptibility of chickpea to P.neglectus is an issue that will need to be managed in the future as growers look to introduce a high value legume species into their crop rotation to improve profitability. A thorough evaluation by growers of break crop species will be important in the future to ensure effective control of paddock specific root diseases.

The effectiveness of a break-crop rotation at increasing wheat grain yield was dependent on how well each crop was used and managed in the rotation. The use of a fallow was an effective method of increasing soil moisture to benefit the growth of chickpea and lentil in what was considered a dry year. A fallow is most effective when kept clean of weeds during the fallow period so that rainfall can be stored in the soil, and also allow for an accumulation of nutrients through mineralization processes.

Where the fallow period was ineffective at controlling weeds, it was difficult to achieve adequate weed control in the legume break crop prior to growing wheat. This was most evident for hard to control weeds such as annual ryegrass and wild radish. In this instance, canola was the most effective second break crop as there are robust weed control options that can be used to reduce weed populations. Chickpea and lentil are less competitive early in the growing season and have less options for weed control, and this compromised the grain yield and profitability of these crops and the following wheat crop.

The profitability of double break-crop rotations was not higher than a continuous wheat sequence and in many cases for the Eastern Wheatbelt gave a negative Gross Margin over a three or five year period. For the Central Wheatbelt, most break-crop sequences tested were able to return a positive Gross Margin but this was still lower than a cereal dominant crop sequence. These break-crops were effective at reducing weed and disease populations, but the challenge is to further improve the profitability of break-crop sequences. The inclusion of high value legumes such as chickpea and lentil as the second break-crop following fallow gives promise for improved profitability, but further evaluation is required to sufficiently de-risk this crop option for the Eastern and Central Wheatbelt.

The use of a double break crop rotation where two break crops are grown successively has the potential to increase wheat production in the Eastern Wheatbelt if the physical and chemical soil constraints have been addressed and where the first crop is a chemical fallow. It is critical to manage this fallow period effectively to ensure that rainfall is captured and stored in the soil and that weed populations are reduced. This situation allows for a wide range of break crop options to be grown that target control of the biological constraint that is present in the paddock.

Further research to de-risk the adoption of high value legumes such as chickpea and lentil will give growers a greater chance of implementing a profitable and effective break-crop rotation. This includes demonstration of the equipment modifications needed to successfully harvest these crops to reduce harvest losses and maximise grower returns.

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Background

The inclusion of break crops into rotations with cereals can influence the nitrogen (N) dynamics of cropping systems (Peoples et al. 2001) and assist in the management of weeds whilst reducing disease incidence in crop rotations (Kirkegaard et al. 2008). However, the adoption of break crop rotations in WA by grain growers is low due to the low perceived profitability of these crops. This is influenced by high input costs for canola, and fluctuating grain prices of pulses (Seymour et al. 2012).

A review in 2009 was conducted using forty years of crop sequencing trials by the Department of Primary Industries and Regional Development (DPIRD) WA to give Western Australian grain growers an insight into the rotational benefits of break crops. Approximately 160 crop sequence experiments were analysed, and the data clearly demonstrated that continuous wheat was rarely as productive or economically viable as rotations that included either a pasture or break crop, regardless of how much nitrogen fertiliser was applied. It also points to the difficulty of achieving yields higher than 2.5t/ha when wheat is sown after wheat. Overall, wheat sown after lupins out yielded wheat sown after wheat.

The use of a single break crop in rotation has been shown to be an effective tool in managing both weed and diseases that affect wheat production. Two GRDC funded trials in paddocks with herbicide-resistant annual ryegrass at Eurongilly, NSW (near Junee) in 2012 and 2013 found weeds had a significant impact on wheat production. Both trials demonstrated that clean fallow or break crop can deliver cheaper, more effective ryegrass control compared with in-crop grass management options in wheat. However, despite the effectiveness of break crops in reducing ryegrass seedbanks (from 5500 to between 114 and 500 seeds per square metre), a single year of weed control was insufficient to prevent yield reductions in the following wheat crop, even with additional in-crop control measures. It was concluded that a break of at least two years was needed to prevent grass seed set and substantially reduce grass seedbank numbers (Peoples 2013)

The use of two successive break crops has led to large increase in cereal yields in the low rainfall zone of South Australia. Intensive field trials of 40 different break sequences have been investigated, including pastures and break crops - such as pulses, canola, brown manure vetch and oaten hay, and have been grown for up to two seasons. Despite very strong wheat yields in the first two years of the trial, disease and grassy weeds are now starting to reduce performance of continuous wheat. However, wheat following two-year breaks are now producing gross margins several hundreds of dollars per hectare higher than continuous wheat that has no major yield constraints present. One-year breaks have improved the following wheat performance, but weeds and diseases are still present.

There has been little work conducted in Western Australia to evaluate the use of successive break crops on the grain yield of wheat. Through the use of economic simulations using the model 'LUSO', the following scenarios have been investigated. Under high wheat prices, in 3 years, continuous wheat was the most profitable. When the rotation was extended to 5 years, including 1 canola break crop gave the highest economic return. When the rotation length was extended to 10 years, 2 green manure pasture breaks increased the economic return. At low wheat prices: adding 1 canola crop in a 3 year rotation, 2 canola crops in a 5 year rotation, and 2 canola crops and 2 green manure pastures in a 10 year rotation, all led to the highest economic return. The size of the weed seedbank required to justify growing a break crop declined as the planning horizon increased and the commodity price of wheat decreased (Lawes, Zee 2015)

Project objectives

This project investigates the use of double break crops to increase the yield of subsequent wheat crops in the Kwinana East and West port zones of the WA grain growing region through the use of field experimentation.

The main objective of this project is to quantify the rotational benefits of broadleaf crops or pastures for cereals – looking at 1 or 2-year break, and to:

- identify whether profitable broadleaf cropping sequence are available as alternatives to continuous cereals for low, medium and high rainfall zones
- provide guidelines for grain-growers and their advisers when and where to include a double break crop to achieve the best outcome.

Methodology

This project is based in the Kwinana East and West port zones of the GRDC Western Region that represent the Central and Eastern Wheatbelt of Western Australia.

A replicated field site was established 12 km north of Merredin in the Eastern Wheatbelt of WA (Table 3) on a grower paddock that had a high background population of hard to control annual ryegrass (Lolium rigidum). The site had been previously cropped to wheat in 2015. Twelve double break rotations were established in 2016 in a randomized block design experiment with 4 replicates (Table 1) under consultation with Dr S Diffey (Apex Biometry). This site was managed by Kalyx Agriculture on behalf of the West Midlands Group. The site was sown using a knifepoint seeder with press wheels on 24cm spacing, and mechanically harvested with a plot harvester.

Table 1. List of treatments for the Merredin trial site for the period 2016-18. Wh = wheat, Ba = barley, TTca= Triazine Tolerant Canola, HYca = Hybrid Canola, Lu = lupin, Ch = chickpea, Fa = fallow, Pa = spray-topped pasture.

Treatment	Treatment Designation	2016 Crop	2017 Crop	2018 Crop
1	Ve/Ca	Vetch	Canola	Wheat
2	Lu/Ca	Lupin	Canola	Wheat
3	Ba/Ca	Balansa	Canola	Wheat
4	Fa/Fa	Fallow	Fallow	Wheat
5	Fa/Ch	Fallow	Chickpea	Wheat
6	Fa/Le	Fallow	Lentil	Wheat
7	Fa/Ca	Fallow	Canola	Wheat
8	Su/Ca	Sub-clover	Canola	Wheat
9	Fa/Ba	Fallow	Balansa	Wheat
10	Fa/Fi	Fallow	Field pea	Wheat
11	Fa/Oa	Fallow	Oats	Wheat
12	Wh/Wh	Wheat	Wheat	Wheat

In addition, four demonstration sites were established in 2016 near Bencubbin, Corrigin, Miling, and Goomalling. The Goomalling site was abandoned in 2017 and replaced with the Calingiri site due to the site not being available. These sites were established in paddocks that had a suspected history of root diseases or weed populations that a single break crop could not address, and which were being sown to a break crop, pasture, or fallow in 2016. In 2017, plots of up to 2 hectares in size were established using grower equipment for a range of break crop options that the grower identified as options to integrate into their farming system. The break crop species evaluated are outlined in Table 2. The remaining area of the paddock was sown to either wheat or canola depending on growers paddock plan.

Table 2. Double break crop sequences evaluated at the four demonstration sites. The Miling site was sown to oats but grazed and not harvested in 2018.

Site	2016 crop	2017 crop	2018 Crop
Bencubbin	Fallow	Canola Lentil Lupin Kabuli Chickpea Desi Chickpea	Wheat
Calingiri	Canola	Lentil Lupin Wheat	Wheat
Corrigin	Fallow	Albus lupin Chickpea Field peas Lentil Wheat	Wheat
Miling	Pasture	Lupin Lentil Chickpea	Grazing oats

In the 2017 and 2018 season, measurements were conducted on the demonstration plots to gauge the establishment, growth and grain yield of each break crop species. Plant counts were conducted 6 weeks after seeding or the break of the season, whichever was the latter. Biomass production was measured at the start of flowering for legume crops in 2017, and at the end of tillering (GS.30) and Anthesis (GS.65) for wheat in 2018. Final harvest yield was measured at maturity by conducting hand harvest cuts. These measurements were completed by counting the number of plants along either side of a 50 cm ruler (equivalent to 1 metre of crop row) in three replicate locations for each break crop and converting to plants/m^2 using a factor of 4 for 24 cm spacing or 3.3 for 30 cm spacing.

In each season, the collection of crop input data allows for the calculation of gross margin return for each break crop sequence to be evaluated. Gross Margin is calculated as the income received from the yield of grain per hectare based and current commodity prices, minus the variable costs associated with the growing of the crop and including allocations for machinery use at a contract rate.

The Gross Margin for each crop was calculated by multiplying the grain yield and average value of each crop and subtracting the cost of seed, fertiliser, herbicide, and fungicide applied to each break-crop in each year. The Net Margin was calculated by further subtracting the cost of machinery at contract rates and an allocation of $150/ha per year for overheads. The Cumulative Gross Margin was calculated as the sum of the Gross Margin for each year and adjusted to present day value by applying a discount of 5%. The Cumulative Net Margin is the sum of the Net Margin for each year adjusted to present day value by applying a discount of 5%.

The Land Use Sequence Optimiser (LUSO) model was calibrated and used as a tool to compare the effectiveness of varying break-crop rotations on weed and disease populations over a longer time horizon. A full list of parameters for this model is included in Appendix A based on the observed crop sequence effects on weed and disease populations in this study. The comparison of various break-crop sequences was evaluated against the effects of a continuous cereal sequence of five years. The change in weed population was evaluated for two scenarios: when the starting weed population was low (50 seeds/m^2) and high (500 seeds/m^2). The Cumulative Profit for the period represents the net margin of each crop in present day value using a discount of 5%. Cumulative Profit is calculated as the yield x value of each crop minus seed, fertiliser, chemical, and fungicide costs as well as an allowance for machinery at contract rates and an allocation of $150/ha for overhead costs.

Location

Table 3. Location of Replicated and demonstration trial sites in the project.

	Latitude (decimal degrees)	Longitude (decimal degrees)
Replicated Trial site	-31.373366°	118.284986°
Nearest Town:	Merredin	
Demonstration site #1	-30.676845°	117.894662°
Nearest Town	Bencubbin	
Demonstration Site #2	-31.114606°	116.597467°
Nearest Town	Calingiri	
Demonstration Site #3	-32.322497°	118.084961°
Nearest Town	Corrigin	
Demonstration Site #4	-31.262740°	116.934221°
Nearest Town	Goomalling	
Demonstration Site #5	-30.489398°	116.244139°
Nearest Town	Miling	

If the research results are applicable to a specific GRDC region/s (e.g. North/South/West) or Agro - Ecological Zone/s please indicate which in the table below:

Research	Benefiting GRDC Region (can select up to three regions)	Benefiting GRDC Agro-Ecological Zone (see link: http://www.grdc.com.au/About-Us/GRDC-Agroecological-Zones) for guidance about AE-Zone locations	
Experiment Title	Choose an item. Choose an item. Western Region	☐ Qld Central ☐ NSW NE/Qld SE ☐ NSW Vic Slopes ☐ Tas Grain ☐ SA Midnorth-Lower Yorke Eyre ☐ WA Northern ☒ WA Eastern ☐ WA Mallee	☐ NSW Central ☐ NSW NW/Qld SW ☐ Vic High Rainfall ☐ SA Vic Mallee ☐ SA Vic Bordertown-Wimmera ☐ WA Central ☐ WA Sandplain

Results

Merredin replicated field site

Rainfall

Table 4. Rainfall for the 2016 to 2018 seasons for the Merredin site. Growing Season Rainfall ('GSR') is the total rainfall for the period April to October (inclusive), while 'Total' rainfall is the total for the year. Mean represents the long term mean rainfall for the period 1904 to 2018. Data collected from Climate Data Online (BOM, 2018, Station ID 010092).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	GSR	Total
2016	41	12	76	55	42	43	39	42	21	11	2	22	253	407
2017	32	53	21	5	28	5	36	48	48	26	11	6	195	318
2018	23	11	9	1	11	39	52	62	3	44	18	24	212	297
Mean	15	15	21	23	40	49	50	39	26	19	15	14	245	326

The main trial site at Merredin was established in June of 2016 and was followed by near average growing season rainfall (Table 4). Most of the treatments in this year were 'fallow' treatments that mimic district practice of leaving a paddock out from crop for the season and then being spray topped at the flowering stage of ryegrass. It is likely that this approach meant that little moisture was carried forward from fallow in 2016 to the 2017 season. There were many severe frosts that occurred during spring in 2016 that had an impact on the yield of crops harvested in 2016. The 2017 season started with above average rainfall during the summer period followed by below average rainfall in autumn. Winter and spring rainfall were below average in the months of June and July which restricted crop growth, but good rainfall in August, September, and October relative to the mean allowed for crops to produce some crop growth and grain yield despite the dry start to 2017. The break crops evaluated in 2017 were short in height and were not easily harvested by mechanical harvester. The canola shed seed very early in the season and was not harvestable. In 2018 the site was sown to wheat for all treatments and received just below average total and growing season rainfall. Despite a dry September period and low rainfall during the summer and autumn period, good rainfall in July, August, and September allowed for good crop growth and grain yield.

Break crop performance

Table 5. Break-crop yield for the 2016 and 2017 season prior to wheat being grown in 2018 at the Merredin site. nd= not determined as some plots could not be mechanically harvested in each season.

		2016		2017	
Treatment	Crop rotation	Crop	Yield (t/ha)	Crop	Yield (t/ha)
1	Ve/Ca	Vetch	0.18	Canola	nd
2	Lu/Ca	Lupin	1.38	Canola	nd
3	Ba/Ca	Balansa	nd	Canola	nd
4	Fa/Fa	Fallow	-	Fallow	-

5	Fa/Ch	Fallow	-	Chickpea	nd
6	Fa/Le	Fallow	-	Lentil	nd
7	Fa/Ca	Fallow	-	Canola	nd
8	Su/Ca	Sub-clover	nd	Canola	nd
9	Fa/Ba	Fallow	-	Balansa	nd
10	Fa/Fi	Fallow	-	Field pea	0.78
11	Fa/Oa	Fallow	-	Oats	2.76
12	Wh/Wh	Wheat	1.13	Wheat	2.72

The grain yield of crops harvested in 2016 were severely affected by frost, with wheat on wheat yielding 1.13 t/ha (Table 5). The only two grain legume crops planted in 2016 were lupin and vetch which yielded 1.38 t/ha 0.18 t/ha respectively. The remaining treatments were either fallow or pasture legumes of balansa clover or sub clover. Grain yield was difficult to measure in 2017 due to dry seasonal conditions and the inability of mechanical harvesting equipment to be able to harvest the short lentil and chickpea crops. It was estimated that a low grain yield of less than 300 kg/ha was achieved in these plots as biomass production was also low (based on visual assessment). The canola matured very early in the season and shed its seed from the pod and meant that harvest was not completed. Field peas, oats, and wheat were able to be harvested and yielded 0.78 t/ha, 2.76 t/ha, and 2.72 t/ha respectively.

Wheat grown after a two-year break crop

Table 6. Soil test values taken following varying two-year break crop rotations prior to wheat being grown in 2018 at the Merredin site. Samples taken on the 1st June 2018. Values are presented for each crop rotation in the 0-10cm soil depth, and 10-50cm for the wheat/wheat treatment only.

Rotation		Depth	Ammonium-N	Nitrate-N	Phosphorus	Potassium	Sulfur	pH
		cm	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	$CaCl_2$
1	Ve/Ca	0-10	17	41	22	54	27.9	4.7
2	Lu/Ca	0-10	19	44	24	68	42.4	4.9
3	Ba/Ca	0-10	16	31	24	66	27.1	4.8
4	Fa/Fa	0-10	6	35	23	52	13.9	4.8
5	Fa/Ch	0-10	10	41	24	81	20.5	4.9
6	Fa/Le	0-10	12	59	23	73	18.9	4.8
7	Fa/Ca	0-10	15	40	20	66	37.1	4.9
8	Su/Ca	0-10	18	41	24	71	37.7	4.8
9	Fa/Ba	0-10	15	64	25	84	24.6	4.9
10	Fa/Fi	0-10	11	44	23	69	20.9	4.8
11	Fa/Oa	0-10	17	42	23	61	46.3	4.8
12	Wh/Wh	0-10	22	46	26	66	53.9	4.8
12	Wh/Wh	10-20	2	6	19	36	25.5	4.6

12	Wh/Wh	20-30	< 1	3	7	30	16.5	5.6
12	Wh/Wh	30-40	< 1	2	3	26	11.6	6
12	Wh/Wh	40-50	< 1	3	< 2	47	19.9	6.2

Following the two successive break-crops for treatments 1 to 11, there were similar levels of nitrogen in the 0-10 cm soil depth compared to wheat/wheat (treatment 12) for both ammonium and nitrate-based N (Table 6). Potassium varied between treatments from 52 mg/kg in the fallow/fallow treatment to 84 mg/kg following balansa clover. Sulfur levels varied between treatments and this may be a reflection of the fertiliser strategies and crop nutritional requirements in each season. Soil pH varied between 4.7 and 4.9 in the 0-10 cm soil depth across the site and down to 4.6 in the 10-20 cm soil depth, and gives an indication that soil acidity may have limited the growth of susceptible species (chickpea, lentil).

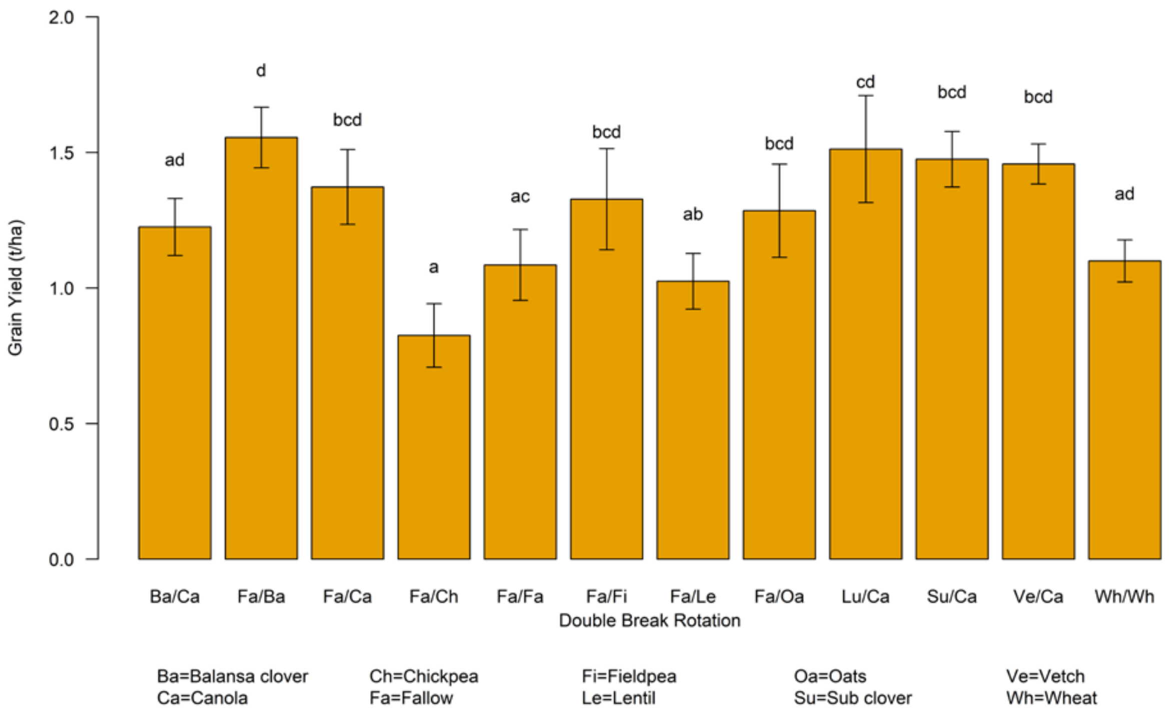

Figure 1. Grain yield of wheat grown after a series of double break crop rotations at the Merredin site in 2018. Error bars denote standard error of treatment mean, lower case letters denote a significant difference (P<0.05).

The grain yield of wheat in 2018 was greatest following fallow/canola or fallow/balansa clover compared to all other break crop rotations (Figure 1). In contrast, grain yield was lowest following fallow/chickpea, fallow/lentil, and fallow/fallow. The grain yield of wheat grown after wheat/wheat was not significantly different to the lowest yielding nor the highest yielding treatments in 2018. Grain protein was significantly influenced by break crop rotation, with the lowest protein occurring following fallow/oats and fallow/chickpea (Table 7). In general, grain protein was improved following treatments that had canola as the second break crop preceding wheat in 2018. Grain weight (hectolitre weight) was greatest for wheat following fallow/canola and fallow/balansa and lowest for fallow/chickpea, fallow/oats, and wheat/wheat. Screenings followed the inverse trend for the same treatments, with screenings being lower where hectolitre weight was relatively high.

The number of ryegrass panicles (heads) were counted prior to maturity for each treatment on the 31st of October 2018. Ryegrass numbers were significantly higher for fallow/chickpea and fallow/lentil compared to all other treatments (which had similar numbers of ryegrass panicles) (Figure 2).

Table 7. Grain quality characteristics of wheat following varying break crop rotation combinations at the Merredin site in 2018. There were no significant differences in grain yield attributes (P<0.05)

Break-crop sequence	Protein %	Moisture %	Hectolitre Weight kg/HL	Screenings %
Ba/Ca	10.0	9.2	78.1	2.3
Fa/Ba	9.6	9.2	77.2	2.3
Fa/Ca	9.1	9.1	76.9	2.7
Fa/Ch	8.9	9.2	73.2	4.3
Fa/Fa	9.4	9.2	77.0	3.0
Fa/Fi	9.4	9.2	76.0	2.8
Fa/Le	9.7	9.2	76.1	2.9
Fa/Oa	8.7	9.1	73.4	2.9
Lu/Ca	10.1	9.2	77.5	2.5
Su/Ca	9.7	9.3	76.5	2.7
Ve/Ca	9.8	9.2	76.6	2.8
Wh/Wh	9.6	9.2	75.8	3.4
P-value	*0.2*	*0.2*	*0.09*	*0.08*

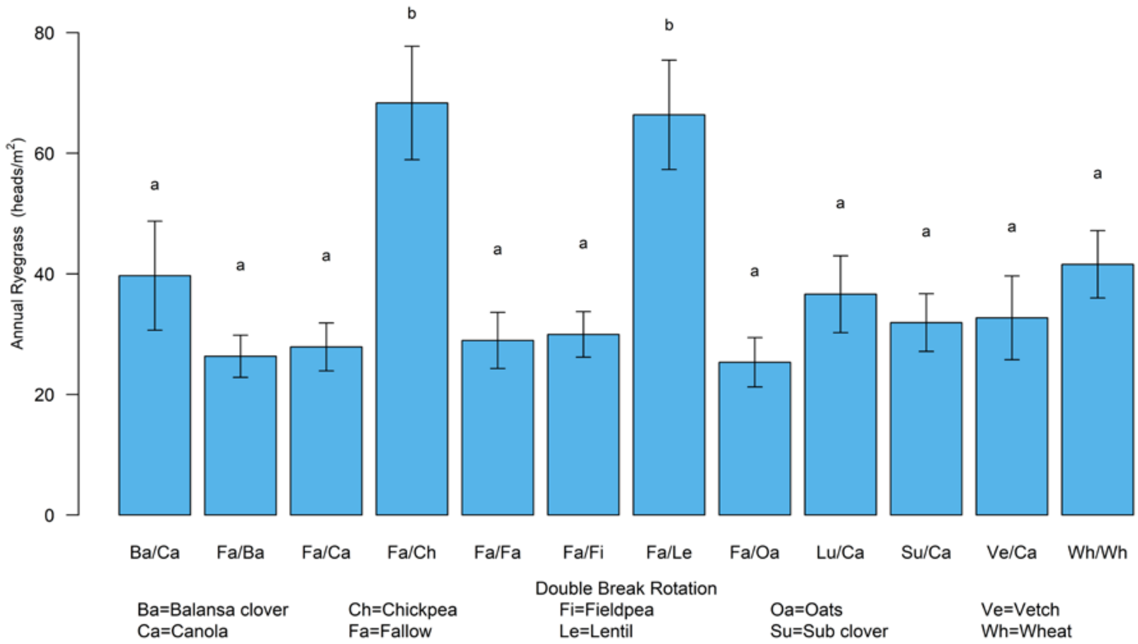

Figure 2. The number of ryegrass panicles (heads) present in each treatment measured on 31/10/18. Error bars denote standard error of treatment mean, lower case letters denote significant differences between treatments (P<0.05).

Demonstration site results

Table 8. Annual and growing season rainfall (GSR) for the 2017 and 2018 seasons at the double break demonstration sites (BOM, 2018). Data for the Miling site not included for 2018 as no crop was harvested at this site.

	Miling		Calingiri		Bencubbin		Corrigin	
	2017	2018	2017	2018	2017	2018	2017	2018
Jan	93		72	57	52	45	48	43
Feb	36		61	34	49	7	122	31
Mar	31		27	0	22	8	40	3
Apr	0		1	2	4	0	6	9
May	8.5		16	31	7	21	14	15
Jun	7		29	60	3	37	27	31
Jul	44		78	111	31	42	47	60
Aug	59		7	106	53	42	60	55
Sep	28		41	8	30	9	36	4
Oct	10.5		13	42	17	28	39	30
Nov	9.5		14	4	10	12	13	7
Dec	7		11	3	5	43	16	1
Total (mm)	333		437	457	283	293	468	289
GSR (mm	157		252	357	146	179	229	195

Annual and growing season rainfall (GSR) for the 2017 and 2018 seasons for the Miling, Calingiri, Bencubbin, and Corrigin sites is presented in Table 8. The large amount of summer rainfall at most sites in 2017 would have led to an increase in stored soil water available for crops during the growing season. This stored soil water would have been in addition to the treatments that were based on a fallow in 2016. Growing season rainfall in April and May of 2017 was very low at all sites and was a restriction for early establishment and crop growth of the break crops. Most sites received adequate rainfall during spring (along with cooler temperatures) to allow the legume crops to adequately flower and fill grain. Plant height was restricted by the later season break and low growing season rainfall, resulting in the Miling, Calingiri and the Bencubbin sites being hand harvested to estimate grain yield.

Grain Yield

Table 9. Grain yield of wheat in 2018 at each demonstration site following various break crops and their grain yield in 2017. nd = not determined.

Site	2016 crop	2017 crop	2017 yield	2018 Wheat yield
Bencubbin	Fallow	Canola	0.6	2.1
		Lentil	0.6	2.8
		Lupin	1.42	2.6
		Kabuli Chickpea	0.6	2.8
		Desi Chickpea	1.1	3.4
Calingiri	Wheat	Lentil	0.36	6.2
		Lupin	0.97	5.7
		Canola	nd	5.6
Corrigin	Fallow	Albus lupin	0.8	3.9

		Chickpea	0.9	4.0
		Field peas	1.2	4.1
		Lentil	0.3	4.1
		Wheat	2.4	3.8
Miling	Pasture	Lupin	0.97	nd
		Lentil	0.82	nd
		Chickpea	0.67	nd

The grain yield of the break crops in 2017 at each demonstration site is summarised in Table 9. Lupins are a common legume break crop in Western Australia, and lupin yield will be compared with the yield of the alternate high value legumes. At all sites, Jurien lupins had a higher grain yield compared to all other legumes and varied in a range of 0.97 t/ha to 1.42 t/ha. Desi chickpeas yielded closest to lupins at the Bencubbin site, achieving 75% of lupin yield, while at the Miling site, Hurricane lentils achieved 85% of lupin yield. However, Hurricane lentils only achieved 42% of lupin yield at Bencubbin, and 37% of lupin yield at Calingiri, while Kabuli chickpea only achieved 42% of lupin yield at Bencubbin. At the Corrigin site, Desi chickpeas and field peas were the best performing legumes, although lupins were not included as a comparison at this site. Hurricane lentils at the Corrigin site yielded only 0.29 t/ha and were not able to be mechanically harvested.

The yield of wheat in 2018 following legume break crops tended to be higher than the crop planted in the rest of the paddock (Table 10). At the Bencubbin site, canola was sown in the remaining area of paddock and led to a wheat yield of 2.1 t/ha, while grain yield was increased to 3.4 t/ha following chickpea. Wheat following lentil and lupin also yielded higher than canola. At the Calingiri site, there was a more modest increase in wheat yield, from 5.6 t/ha following lupin to 6.2 t/ha following lentil. Wheat at the Corrigin site was increased to 4.1 t/ha following field pea and lentil compared to following wheat at 3.8 t/ha. Oats were planted at the Miling site in 2018 and were grazed by livestock during the season and so no grain yield data was available.

Grain quality was measured at the Corrigin site in 2018 to evaluate the effect of the presence of weeds at the site. Capeweed was not effectively controlled in the chickpea and lentil crops in 2017 and this led to high numbers of this weed in wheat in 2018 (visual observation). Grain protein tended to be lower for wheat following chickpea and wheat following wheat.

Table 10. Grain quality attributes of wheat grown following a range of break-crop rotations at the Corrigin site in 2018. No data available for Bencubbin or Calingiri sites.

Break Crop Sequence	Protein %	Moisture %	Hectolitre weight (Kg/HL)	Screenings %
Fa/Fi	10.9	10.5	81.9	4.0
Fa/Lu	10.4	10.3	82.4	3.3
Fa/Le	10.1	10.4	83.4	2.7
Fa/Ch	9.6	10.4	83.5	3.4
Fa/Wh	9.9	10.5	82.6	5.0

Effect of double break crops on root disease levels

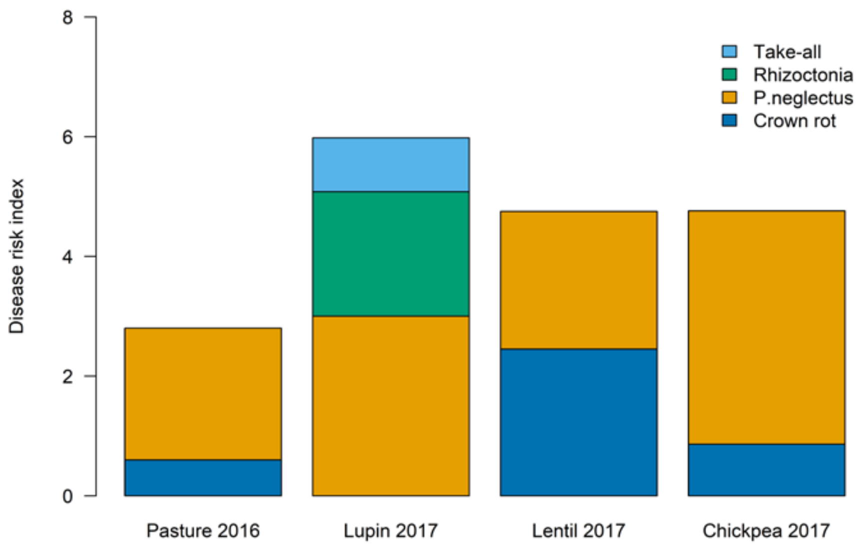

Figure 3. Root disease risk increased following a range of legume crops grown at the Miling site in 2017. PredictaB sampling was conducted at the start of the 2017 and 2018 seasons following volunteer pasture in 2016 and legume crops in 2017.

The dominant root disease constraint at the Miling site was ***Pratylenchus neglectus*** (*P.neglectus*, Figure 3), with a low amount of Crown rot present following a volunteer pasture in 2016. The levels of these diseases increased following growing lupin, lentil, and chickpea in 2017. Lupin was effective at reducing Crown rot compared to lentil and chickpea, however, there was a large increase in Rhizoctonia and Take-all. While an increase in Rhizoctonia under lupin is a common occurrence, this site appears to not have been an effective double break due to the volunteer pasture in 2016 potentially containing grasses and cereals that are susceptible to Crown rot and *P.neglectus*. It is also important to note that chickpea is susceptible and lentil are moderate hosts to *P.neglectus*, and this would be a large reason why the increase in *P.neglectus* was highest under chickpea, and lower under lentil. It is not clear why *P.neglectus* increased under lupin, which is considered a resistant crop, but may be due to a presence of increased inoculum from the volunteer pasture. *P.neglectus* continues to be a yield constraint at this site for the 2018 season.

The demonstration site at Bencubbin was a chemical fallow in 2016 prior to being sown to a range of legumes in 2017 (Figure 4). The dominant root disease constraint at this site were *P.neglectus* and Crown rot. Inoculum levels of these diseases were high following the fallow in 2016, as Crown rot was most likely harboured in the retained crop stubble on the soil surface. The dry season in 2017 would allow for carryover of this inoculum into 2017 as there would have been little stubble breakdown during the season. This site highlights that lentil, chickpea, and canola are all classified as susceptible to moderate hosts of *P.neglectus* that have maintained or increased the levels of this nematode in the soil. At this site, the resistance of lupins to *P.neglectus* can be clearly seen to reduce the numbers of nematodes in the soil compared to the other legume and canola crops. There may be a trend in this data that canola and chickpea were better at reducing the levels of Crown rot at this site.

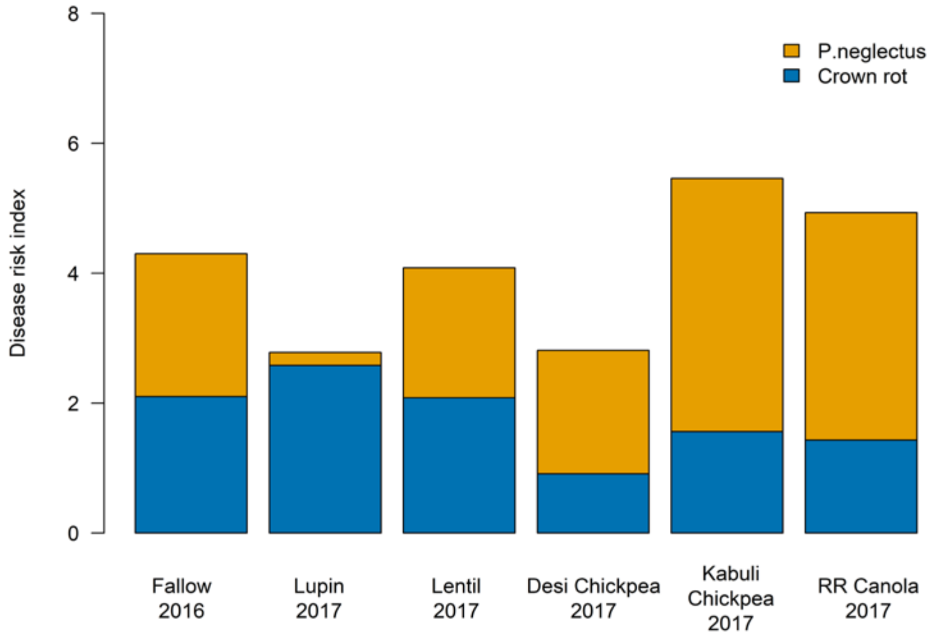

Figure 4. The change in disease risk following a range of legume crops grown at the Bencubbin site in 2017. PredictaB sampling was conducted at the start of the 2017 and 2018 seasons following each respective crop. Roundup Ready canola (RR Canola) was grown in the paddock around the demo sites and is included as a comparison.

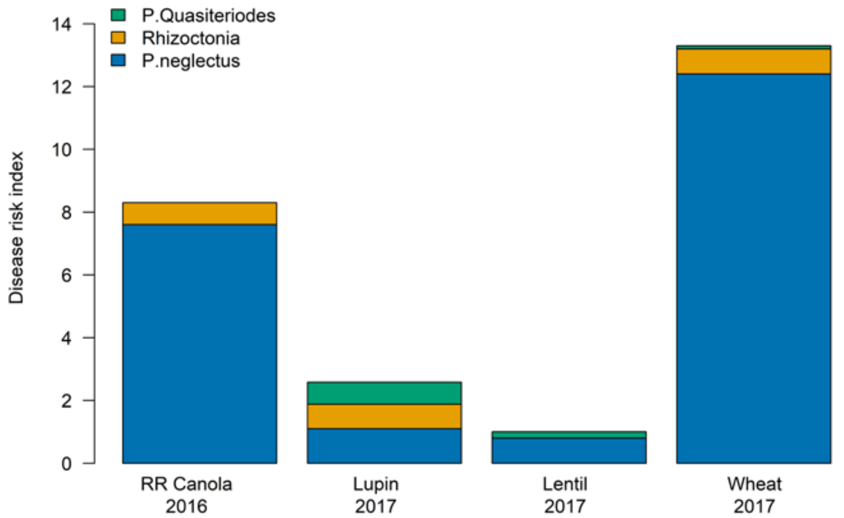

Figure 5. The change in disease risk following a range of legume crops following at the Calingiri site in 2017 following canola in 2016. PredictaB sampling was conducted at the start of the 2017 and 2018 seasons following each respective crop. Wheat was grown in the paddock around the demo site in 2017 and is included as a comparison.

The site at Calingiri was sown to Canola (RR Canola) in 2016 prior to the demonstration site being established in 2017 (Figure 5). Lentil and lupin treatment strips were established in the paddock while the remaining area of paddock was sown to Wheat. The dominant root disease constraint at this site was *P. neglectus* following canola in 2016. This was decreased by growing lupin and lentil, and increased by growing wheat in 2017. Lupins slightly increased the level of Rhizoctonia and *Pratylenchus quasiteriodes* at this site, which is consistent for Rhizoctonia under lupin for other demonstration sites in this project. The use of a double break rotation at the Calingiri site was an effective method of reducing the nematode constraint to grain yield.

The levels of root disease present at the Corrigin site at the start of the 2017 season following a chemical fallow was low compared to other sites in this study (Figure 6).

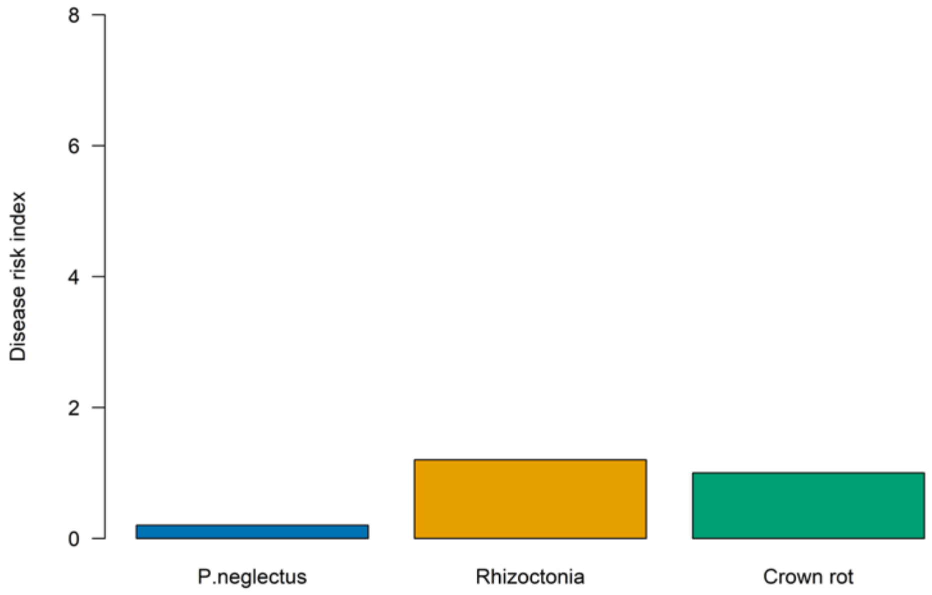

Figure 6. Root disease levels at the Corrigin site in 2017 following chemical fallow and before legume break-crops were planted.

Table 11. Soil pathogen levels following a range of two-year break crop rotations prior to wheat being grown in 2018 at the Merredin site. Samples were collected just prior to the season break. Values have been log transformed prior to risk level assessment; orange shading denotes medium level of risk and all other values assessed as low root pathogen risk (SARDI PredictaB research assessment guide, version: Nov 2018).

Root pathogen		Take all	Rhizoctonia	Crown rot	Yellow leaf spot	Bipolaris	Pythium	White grain disorder	Pratylenchus	Charcoal rot
Scientific name/family		Gaeumannomyces graminis	R.solani AG8	Fusarium spp.	Pyrenophora tritici-repentis	Bipolaris sorokiniana	Pythium clade F	Eutiarosporella spp.	P. Neglectus	Macrophomina phaseolina
Crop rotation		pgDNA/g Sample	pgDNA/g Sample	pgDNA/g Sample	pgDNA/g Sample	pgDNA/g Sample	pgDNA/g Sample	kDNA copies/g Sample	nematodes /g soil	kDNA copies/g Sample
1	Vetch/Canola	0	0	0	0	0	1.51	0	1	1.43
2	Lupins/Canola	0	0	0	0	0	1.48	0	0	1.73
3	Balansa/Canola	0.30	0	0	0	0	1.49	0	0	1.73
4	Fallow/Fallow	0	0	0	0.30	0	1.53	0	1	1.52
5	Fallow/Chickpea	0	0	0	0	0	1.54	0	1	1.63
6	Fallow/Lentil	0	0	0	0	0.85	1.56	0	3	1.62
7	Falow/Canola	0.30	0	0	0	0	1.48	0	2	1.78
8	Sub-clover/Canola	0.30	0	0	0.30	0	1.48	0	0	1.92
9	Fallow/Balansa	0	0	0	0	0	1.46	0	1	2.45
10	Fallow/Fieldpea	0	0	0	0	0	1.61	0.30	0	1.66
11	Fallow/Oats	1.40	0	2.41	0.60	0.48	1.59	0	1	2.68
12	Wheat/Wheat	1.30	0	2.90	2.11	0.48	1.23	0	1	2.00

The following root pathogens were below the limit of detection: CCN, Stem nematode, Gaeumannomyces graminis spp., Eutiarosporella spp., Eyespot, P. thornei, P.penetrans, P.quasi., Phytophthora medicaginis, Phoma spp.

Table 12.Summary of root disease levels found at each demonstration site prior to wheat being grown in 2018. Samples were collected just prior to the season break. Values have been log transformed prior to risk level assessment; red shading denotes high risk level, orange shading denotes medium risk level, and all other values assessed as low root pathogen risk (SARDI PredictaB research assessment guide, version: Nov 2018).

	Root pathogen	Take all	Rhizoc-tonia	Crown rot	Yellow leaf spot	Bipolaris	Pythium	White grain disorder	P. neglectus	P. quasi	Char coal rot	Black spot
Site	Crop rotation	pgDNA/g	pgDNA/g	pgDNA/g	pgDNA/g	pgDNA/g	pgDNA/g	kDNA copies/g	nematodes /g		kDNA copies/g	
Corrigin	Wheat		1.21	1.98	3.07			3.17	2.3		1.06	
	Chickpea				0.36		1.08		0.9		3.75	2.82
	Lentil	0.88			1.53	0.64	1.54		0.6		2.18	3.29
	Albus lupin	1.49			0.69		1.08		0.1		2.87	3.13
	Field pea		1.04				1.64	1.49	0.2		0.91	4.9
Bencubbin	Kabuli Chickpea			1.56	0	1.16	0		3.9		1.14	
	Lupin			2.59	0.32	1.76	1.17		0.2		1.68	
	Desi Chickpea			0.91	0	1.15	0		1.9		1.62	
	Lentil			2.08	0	1.48	1.27		2		1.42	
	Canola			1.43	0	2.37	0		3.5		1.54	
Calingiri	Lentil		0	0	1.49	0	1.88		0.8	0.2	2.26	
	Lupin		0.78	0	1.26	0	1.68		1.1	0.7	1.91	
	Wheat		0.8	0	2.63		1.1		12.4	0.1	1.56	
Miling	Chickpea	0	0	0.86	0	1.61	0		3.9	0	1.99	
	Lentil	0	0	2.45	0	2.25	0		2.3	0	1.69	
	Lupin	0.9	2.08	0	0	1.86	0		3	0	1.9	

Economic analysis of break crop rotations for Central and Eastern Wheatbelt of WA

The Gross Margin of each crop was influenced by seasonal conditions during the 2016 to 2018 period. There were sever frost events in 2016 that reduced the grain yield of harvested crops, while in 2017 dry seasonal conditions reduced the growth, yield, and harvestability of many of the break-crops at all sites. This had a strong effect on the yield of each crop in each of the 2016 and 2017 seasons. Fallow in 2016 in many treatments resulted in a small loss for the Gross Margin, but a significant loss when machinery and overhead costs were included in the Net Profit (Table 13). Of the break crops grown in 2016, lupins were the only crop to achieve a positive Gross Margin following severe frosting of the wheat. In 2017, low yields of canola meant that the Gross Margin was roughly break even, while field pea, oats and wheat achieved positive Gross Margins due to better harvestability. Wheat grown across all sites in 2018 achieved a positive Gross Margin which varied from $90/ha following chickpea to $309/ha for wheat following balansa clover. The cumulative Gross Margin (expressed in present day value) for each crop sequence was positive for all crop sequences but varied from $25/ha for Fa/Ch/Wh to $532/ha for the highest break-crop rotation (Lu/Ca/Wh). Wheat monoculture achieved the highest cumulative Gross Margin of $826/ha while Fa/Oa/Wh was second highest at $694/ha. However, when comparing the Net Margin (in present day value) that includes machinery and overhead costs, all break crop sequences returned a negative return over the three-year period.

Table 13. Gross Margin and Net Present Value (NPV) of double break-crop rotations at the Merredin site across the 2016 to 2018 seasons. Gross Margin is calculated as gross income minus variable costs, while Net Margin includes cost allocations for machinery use at contract rates and an overhead cost allowance of $150/ha. NPV gives the discounted value of the future gross margin in today's value at the 5% rate.

	2016		2017		2018		Cumulative	
Crop sequence	Gross Margin	Net Margin	Gross Margin	Net Margin	Gross Margin	Net Margin	Gross Margin NPV	Net Margin NPV
Ve/Ca/Wh	-$20	-$296	$2	-$274	$282	$6	$226	-$525
Lu/Ca/Wh	$287	$11	$2	-$274	$297	$21	$532	-$220
Ba/Ca/Wh	-$78	-$354	$2	-$274	$213	-$63	$112	-$640
Fa/Fa/Wh	-$14	-$172	-$18	-$176	$168	-$108	$116	-$416
Fa/Ch/Wh	-$14	-$172	-$44	-$320	$90	-$186	$25	-$614
Fa/Le/Wh	-$14	-$172	-$33	-$309	$153	-$123	$88	-$551
Fa/Ca/Wh	-$14	-$172	$2	-$274	$255	-$21	$209	-$430
Su/Ca/Wh	-$96	-$372	$2	-$274	$285	$9	$157	-$595
Fa/Ba/Wh	-$14	-$172	-$101	-$259	$309	$33	$162	-$370
Fa/Fi/Wh	-$24	-$182	$99	-$177	$243	-$33	$277	-$362
Fa/Oa/Wh	-$36	-$194	$583	$307	$231	-$45	$694	$55
Wh/Wh/Wh	$129	-$147	$609	$333	$174	-$102	$826	$74

The Gross Margin for was also calculated for each crop sequence at the Bencubbin and Corrigin demonstration sites (Table 14). Similar to the Merredin site, there was a low Gross Margin cost for the fallow treatment in the first year. While conditions were dry in 2017, all break crops at the Bencubbin site achieved a positive Gross Margin due to an effective fallow in 2016 providing excellent weed control and moisture conservation. At the Corrigin site in 2017, chickpea and lentil were the only break-crop to not achieve a positive Gross Margin and there were issues with the harvestability of these crops due to reduced crop growth in the dry season (in comparison to the Bencubbin site where the site was hand harvested for accurate yield determination). The Gross Margin for wheat in 2018 at both sites ranged between $515/ha for Fa/Ca/Wh at Bencubbin to $1110/ha for Fa/Albus Lupin/Wh at Corrigin. The Net Margin was positive for all crop sequences except those with canola, lentil, and Kabuli chickpea at Bencubbin.

Table 14. Gross Margin and Net Present Value (NPV) of double break-crop rotations at the Bencubbin (Eastern) and Corrigin (Central Wheatbelt) demonstration sites across the 2016 to 2018 seasons. Gross Margin is calculated as gross income minus variable costs, while Net Margin includes cost allocations for machinery use at contract rates and an overhead cost allowance of $150/ha. NPV gives the discounted value of the future gross margin in today's value at the 5% rate.

	2016		2017		2018		Cumulative	
Crop sequence	Gross Margin	Net Margin	Gross Margin	Net Margin	Gross Margin	Net Margin	Gross Margin NPV	Net Margin NPV
Bencubbin								
Fa/Ca/Wh	-$30	-$204	$189	-$87	$431	$154	$515	-$141
Fa/Le/Wh	-$30	-$204	$117	-$160	$641	$363	$631	-$26
Fa/Lu/Wh	-$30	-$204	$299	$21	$581	$302	$745	$86
Fa/Kabuli Ch/Wh	-$30	-$204	$137	-$143	$641	$361	$649	-$12
Fa/Desi Ch/Wh	-$30	-$204	$437	$157	$821	$540	$1,077	$414
Corrigin								
Fa/Albus Lu/Wh	$285	$111	$0	-$282	$971	$688	$1,110	$444
Fa/Ch/Wh	-$30	-$204	-$20	-$303	$1,001	$717	$818	$150
Fa/Fi/Wh	-$30	-$204	$106	-$178	$1,031	$746	$958	$289
Fa/Le/Wh	-$30	-$204	-$22	-$307	$1,031	$745	$842	$171
Fa/Wh/Wh	-$30	-$204	$607	$321	$941	$654	$1,335	$661

Validation of LUSO model for the Eastern Wheatbelt of WA

The Land Use Sequence Optimiser (LUSO) (Lawes et.al, 2010) provides a framework to evaluate various crop rotations on the basis of an individual crop species influence on disease, weeds, and nitrogen. The model provides for a discounted cumulative profit to show the present-day value of a crop sequence based on grain yield, price per tonne, variable costs of growing the crop, and includes an allowance of $150/ha for fixed overhead costs as outlined in Appendix A.

The parameters for each crop type evaluated in Table 15 were adapted based on the results of this project to determine the suitability of LUSO to reflect the weed and disease dynamics found a the Merredin trial site and various demonstration sites. LUSO was then used to determine the profitability and effect on the weed seed bank of varying double-break crop rotations across a sequence of 5 crops relative to standard practice of either cereal monoculture or single break crop followed by 4 cereal crops. The attributes of each break crop for use in LUSO have been parameterized from the results of this project and in discussion with local grower representatives (Table. 16).

Table 15. Relative characterisation and parameterisation of break-crop types used in LUSO based on data from Merredin, Bencubbin, and Corrigin sites. Parameter values are more favourable when higher for weed competitiveness and lower for Disease effect, weed survival, and weed seeds returned. A full list of parameters in included in Appendix A.

Crop type	Grain yield	$ /tonne	Input cost $/ha	Disease effect (0-1)	N fixed /tonne grain	Weed survival	Weed competit -iveness	Weed seeds returned
Wheat	2.2	350	250	0.7	0	0.05	0.091	1
Sprayed pasture	3	0	80	0.5	25	0.03	0.08	0.5
TT canola	0.8	600	250	0	0	0.005	0.08	0.5
Barley	2.5	300	200	0.7	0	0.04	0.095	1
Fallow	1	0	80	0	10	0.001	0.08	1
Lupin	1	300	200	0	50	0.001	0.08	0.5
Chickpea	0.8	700	250	0	16	0.005	0.08	1
Hybrid Canola	1.2	600	300	0	0	0.001	0.08	1

Table 16. The effect of various five-year sequences of monoculture, single, or double-break crop rotation on cumulative profit per hectare and disease presence, weed penalty, and weed seed bank levels. Wh = wheat, Ba = barley, TTca= Triazine Tolerant Canola, HYca = Hybrid Canola, Lu = lupin, Ch = chickpea, Fa = fallow, Pa = spray-topped pasture. Cumulative profit represents the discounted cash return per hectare for the five-year crop rotation.

Rotation	Starting	End of rotation (year 5)			
	Weed burden (pl/m^2)	Disease presence (Scale: 0-1)	Weed penalty (Scale: 0-1)	Weed seed bank (pl/m^2)	Cumulative Profit (NPV) ($/ha)
Wh/Wh/Wh/Ba/Ba	50	0.31	0.09	707	$114
	500	0.31	0.20	5090	-$90
TTca/Wh/Wh/Wh/Ba	50	0.29	0.07	158	-$87
	500	0.29	0.11	1462	-$138
Pa/Lu/Wh/Wh/Ba	50	0.25	0.07	109	-$178
	500	0.25	0.10	1000	-$209
Fa/Lu/Wh/Wh/Ba	50	0.25	0.07	20	-$146
	500	0.25	0.08	196	-$152
Pa/TTca/Wh/Wh/Ba	50	0.25	0.07	141	-$227
	500	0.25	0.10	1274	-$272
Fa/TTca/Wh/Wh/Ba	50	0.25	0.07	26	-$142
	500	0.25	0.08	254	-$150
Lu/TTCa/Wh/Wh/Ba	50	0.25	0.07	22	-$150
	500	0.25	0.08	221	-$158
Lu/HYca/Wh/Wh/Ba	50	0.25	0.07	17	-$52
	500	0.25	0.07	168	-$58
Fa/Ch/Wh/Wh/Ba	50	0.25	0.07	59	$95
	500	0.25	0.09	576	$76
Ch/HYca/Wh/Wh/Ba	50	0.25	0.07	51	$41
	500	0.31	0.20	5090	-$90
Fa/HYca/Wh/Wh/Ba	50	0.25	0.07	16	$36
	500	0.25	0.07	163	$31

The output from LUSO reflects the Net Margin achieved for break-crops at the Merredin site, with most commonly used crop sequences having a negative Cumulative Profit (Table 16). The Cumulative Profit in the LUSO output was lower than the outcomes of the Merredin site as the time horizon is longer and includes three more profitable cereal crops following the break crop sequence. Continuous wheat sequence was the most profitable sequence, with a Cumulative Profit of $114/ha, but at the cost of increasing the weed seed bank from 50 to 707 and 500 to 5090 seeds/m^2 during this period. Break-crops that were effective in their weed control by having a relatively a low weed survival (more effective control strategies) and weeds seeds returned rating (Table 15) were effective in a double break-crop rotation (eg. Lupins, TT canola, fallow) compared to less effective options (eg. Spray topped pasture, chickpea). In contrast, a positive Cumulative Profit was achieved where the grain value or the grain yield of the break-crop could be increased (Table 16). The inclusion of chickpea with a higher grain value ($700/tonne in this scenario) following a fallow achieved a Cumulative Profit of $95/ha where there was a low weed population and $76/ha where there was a high weed population. Hybrid canola that could potentially give a yield advantage over TT canola (1.2 t/ha versus 0.8 t/ha in this example) gave a positive Cumulative Profit but was lower than chickpea due to the increased cost of access to this technology.

The size of the initial weed population influenced the effectiveness of break-crop sequence to control the weed population. Where the initial weed population was 50 seeds/m^2, break-crop rotations were effective at maintaining low weed populations compared to continuous wheat where the population increased to 707 seeds/m^2. At a higher initial weed population of 500 seeds/m2, final weed populations all increased, and the less effective break-crops were above a grower threshold of 500 seeds/m^2 that is considered the trigger point for a change in paddock management.

Discussion of Results

The objective of this project was to investigate the profitability of break crop rotations in the Eastern and Central Wheatbelt region of WA to guide growers and advisors on profitable cropping sequences as alternatives to monoculture wheat. Due to seasonal conditions, this project has evaluated a range of break crop rotations grown in years with average or below annual and growing season rainfall. These results should be considered in the context of these generally dry years and that above average seasonal conditions could possibly provide for improved break-crop outcomes. When considering the potential effects of climate change on decreasing annual rainfall in the eastern wheatbelt, this project is relevant to the current and future challenges of growers in the region.

The effectiveness of a break crop rotation at overcoming biological constraints was dependent on identifying the biological limitation for crop growth and designing an effective crop rotation to achieve this. This approach assumes that the physical (soil compaction) and chemical (soil acidity, salinity) constraints have been addressed as a priority. For example, a soil pH of 4.6 in the 10-20 cm soil depth at the Merredin site may have posed a significant limitation to the growth, yield, and N fixation of sensitive chickpea and lentil species. In contrast, chickpea and lentil were able to increase the following yield of wheat at the Bencubbin site due to the absence of soil constraints and effective storage of soil water from the previous summer and fallow in 2016. The consequences of poor break crop growth are not only reduced profitability of the crop due to decreased grain yield, but also a reduction in the fixation of N for legumes due to lower biomass production, and an increase in weeds due to poor crop competition. The effectiveness of current rhizobium species for many legumes is also reduced in acidic soils, further compounding the effect of this chemical constraint. When considering the yield of wheat following an ineffective break crop rotation, both grain yield and grain quality can be reduced and lead to a less profitable rotation compared to monoculture wheat.

The fixation of N associated with legume break crops rather than the reduction in root disease level was more likely to be the driver of increased grain yield of wheat following these crops. Each legume crop had a different influence on the level of root disease in the soil, and this was dependent on the disease susceptibility of each species. The prevalence of P.neglectus and the susceptibility of chickpea to P.neglectus is an issue that will need to be managed into the future as growers look to introduce a high value legume species into their crop rotation to improve profitability. The presence of Pythium and charcoal rot at most sites was identified and did not seem to be influenced by break crop rotation. The test procedure for charcoal rot is undergoing evaluation at present to determine the threshold levels for crop damage. The use of disease testing services and tools by growers to identify individual paddock disease issues to evaluate each break crop species will be important in the future to ensure that break crops are effective in controlling paddock specific root diseases.

The effectiveness of a break crop rotation at increasing wheat grain yield was dependent on how well each break-crop was used and managed in the rotation. The use of a fallow can be an effective method of managing weeds while increasing soil moisture on soil types with good waterholding capacity to benefit the subsequent crop. Where this was used effectively, high value legumes such as chickpea and lentil were able to be grown to achieve a yield of 0.6-0.9 t/ha and provide a profitable break-crop sequence outcome. This was achieved at the Bencubbin site in 2017 – a year regarded as a dry year. The subsequent yield of wheat following the break crop was also higher compared to where wheat followed canola in the same paddock.

In contrast, an ineffective fallow period places a large amount of pressure on the following break crops, particularly the high value legumes such as chickpea and lentil that are poor early season weed competitors. Inadequate weed control during the fallow phase did not provide a high level of ryegrass control as one spray at the end of the season was used at the Merredin site. In this instance, the fallow could more accurately be described as a spray topped volunteer pasture where timing is critical to effective weed control. A fallow is most effective when kept clean of weeds during the fallow period so that any rainfall can be stored in the soil, and also allow for an accumulation of nutrients through mineralization processes. The presence of weeds during this fallow period utilize this stored moisture and accumulated nutrients to reduce the value of the fallow period.

Where the fallow period was ineffective at controlling weeds, it was difficult to achieve adequate weed control in the succeeding legume break crop prior to growing wheat. This is most evident for hard to control weeds such as annual ryegrass and wild radish. In this instance, canola was the most effective second break crop as there are robust weed control options that can be used to reduce weed populations. Chickpea and lentil are less competitive early in the growing season and have less options for weed control, and as a consequence, compromised the grain yield and profitability of these crops. This effect also followed on to reduce wheat yield in the following year.

In-crop weed control in chickpea, lentil, and field pea was also hard to achieve at many sites where there was a large weed burden present. The presence of capeweed at many sites caused a reduction in the yield of the grain legumes, but due to more robust control options being available in wheat, the yield of the following wheat crop was not affected. The issue of robust weed control options for grain legume crops is an issue going forward that will need to be addressed in order to achieve a broader adoption of these species.

The use of double break crop rotations including high value legumes can be grown across the Eastern and Central Wheatbelt, but there may be limitations in the areas that each particular legume species can be grown. For example, the mid-sized Desi Chickpea may be better adapted to the mid to low rainfall environment, while lentils may be a better option for mid to high rainfall environments. Further evaluation of the suitability of each legume across regions is required as this statement is based on one year of demonstration site data in seasons with below average/average growing season rainfall.

The profitability of growing break-crops was generally not improved by stacking two break-crops in succession. In the lower rainfall Eastern Wheatbelt, the use of a chemical fallow rather than a spray topped pasture shows promise as part of an effective double break-crop sequence. While there is no income associated with a fallow, effective weed control, nutrient mineralisation, and the storage of soil moisture contribute to a higher yielding scenario for a second year break-crop. This can increase the likelihood of growing a profitable second break-crop and succeeding wheat crop. In contrast, a spray-topped pasture may have additional income through grazing with livestock (which was not accounted for in this study) but poor weed and disease control can reduce the growth, grain yield, and overall profitability and effectiveness of the second break-crop and the sequence as a whole.

There are a wide range of profitable double break-crop sequences are available to growers in the medium rainfall zone of the Central Wheatbelt, however, the double break-crop sequences that were evaluated in this study were not as profitable as a single break-crop followed by two wheat crops. The challenge is to identify a second-year break-crop that can further lower weed and disease burdens, while capitalising on the conditions that the previous break-crop has created. In this study, TT canola was an effective break-crop to reduce weed numbers as a first or second break crop option but particularly when the first break-crop was not successful in reducing weed or disease populations. Lupin grown after a fallow generally did not result in an increased Gross Margin as price and yield are not elastic enough to increase the profitability of the break-crop under more favourable conditions.

The inclusion of a high value grain legume as a potential break-crop could increase the profitability of crop sequences across the both the Central and Eastern Wheatbelt. Even though lupins achieved a higher yield compared to chickpea and lentil, the value of chickpea and lentil is normally significantly higher (at least double) compared to lupins. The range in grain price for high value legumes is far greater than which can be achieved with other break-crop options and this can have a significant effect on the profitability of the break-crop sequence. This places high value legumes such as chickpea and lentil in a situation where they can be grown quite profitably even at a low grain yield. The use of high value legumes appears to be best suited as the second crop in the break-crop sequence as weed control options are slightly limited in these crops, and this can be compensated for by a highly effective first break-crop. Where chickpea or lentil were grown as the first break-crop, slow growth and limited weed control options could not satisfactorily control weeds and this compromised the yield of the break-crop. In this scenario, canola as the second break-crop was the only option to reduce weed populations sufficiently prior to a cereal phase to ensure some break-crop benefit was achieved. Therefore, the role of a high value legume as the second crop in a double break-crop sequence is to boost profitability while maintaining a reasonable level of weed control. Where a high value legume is grown following an effective fallow, an increase in stored soil moisture on suitable soil types may lower the risk of growing these crops and this approach requires further evaluation as an effective and profitable break-crop sequence for these zones.

From a practical farmers perspective, the results of this project may not increase their desire to try break crops other than lupins. Lupins are easily harvested in most circumstances with a machine harvester that has minimal modifications required to harvest lupins. The lentils and chickpeas at each site were hand harvested due to the low plant height of these crops, and the inability to harvest with a mechanical plot harvester. This practical harvesting issue does have some possible solutions to allow these crops to be integrated into future farming systems. Harvesting technology is available that uses a flexing harvest front to allow for short crops to be easily harvested, assuming that there is an absence of large rocks and other obstructions in the paddock. The use of inter-row seeding into standing cereal stubble using GPS RTK guidance can increase podding height by up to 38% and increase grain yield by 25% by allowing easier harvestability of the crop. Another common practice method to aid harvestability where there are rocks/stones is to roll the paddock following sowing and prior to the early growth of the legume crop. Further evaluation of these methods may be needed to ensure that offsite impacts of farming such as wind erosion are not increased as a result of adopting high value legumes into the rotation.

Conclusion

The use of a double break crop rotation where two break crops are grown successively can increase the grain yield of subsequent wheat crops while also increasing the profitability of the crop rotation. However, it is critical to select the most appropriate break crops to be grown to achieve this based on the biological constraint to be overcome, and to first ensure that all physical and chemical constraints will not impact on break crop performance. The use of fallow appears to be an effective first year break crop for the eastern wheatbelt that allows for the accumulation of stored soil moisture while also maintaining effective control of weeds. This approach can improve the growth and yield of the second break crop, particularly legume crops. Canola is an effective break-crop whether grown as the first or second crop, while high value legumes such as chickpea and lentil are best placed as the second break-crop in sequence following an effective break-crop. This allows for improved growth and gain yield of the high value legume while maintaining good levels of weed control. High value legume crops such as chickpea and lentil generally yielded less than lupin but were equal or greater in profitability due to the higher value of the grain. Effective weed control during the break crop rotation is important for realizing the benefit of this approach, with chickpea and lentil having slightly less weed control options available. The subsequent yield of wheat was less affected by the presence of weeds if the weeds are easily controlled in the wheat crop. To encourage growers to adopt a wider range of break-crops, including high value legumes, demonstration of the equipment modifications needed to successfully harvest these crops is needed to increase grower confidence in growing high value legumes and allow for a diverse range of break crop rotations to be utilized by growers.

Appendix A.

Parameters used in the LUSO model based on observed data from the Merredin, Bencubbin and Corrigin sites.

Parameter	yield	price	cost	costCont	Nreq	IE prev crop	DE crop	Nboost perTonne	weed survival	comp index	sow density	weed seed return	water mult	extra cost per extra yield
hi wheat	2.2	350	250	250	120	0.7	0.1	0	0.05	0.091	150	1	1	0
sprayed pasture	3	0	80	80	0	0.5	0.1	25	0.03	0.08	50	0.5	1	0
TT canola	0.8	600	250	250	120	0	0	0	0.005	0.08	100	0.5	1	0
hi barley	2.5	300	200	200	140	0.7	0.1	0	0.04	0.095	140	1	1	0
clean fallow	1	0	80	80	0	0	0	10	0.001	0.08	50	1	1.1	0
lupins harvested	1	300	200	200	0	0	0	50	0.001	0.08	40	0.5	1	0
chickpea	0.8	700	250	250	0	0	0	16	0.005	0.08	40	1	1	0
RR canola	1.2	600	300	300	150	0	0	0	0.001	0.08	100	1	1	0
poor chickpea	0.4	700	250	250	0	0	0	6	0.05	0.06	40	1	1	0
poor lupin	0.5	280	200	200	0	0	0	25	0.05	0.06	40	1	1	0
poor fallow	1	0	80	80	0	0	0	0	0.05	0.06	50	0.8	1	0

nyears	seed bank	weed germination	weed compindex	weed maxseedset	Ncost	N0	DI0	DImin	IE prev inc	IE random	DE inc	DE random	fixed costs	cost per weed seed	season
5	50/500	0.8	0.02	30000	2	0.05	0.1	0.1	0.5	0.02	0.5	0.02	150	0.1	1