Department of
Agriculture and **Food**

Crop sequence experiments conducted in Western Australia

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Executive summary

A database has been collated from all of the available rotation experiments conducted in WA. Over 10,000 records representing the results of over 160 experiments conducted since 1966 appear in the database, allowing for rigorous interrogation of rotation effects over a long period of time. In the experiments conducted to date continuos wheat was rarely as productive or economically viable as any rotation which includes either a pasture or break crop, regardless of nitrogenous fertiliser input.

Indeed, continuous wheat appears to be a yield limiting exercise with few trials on light land where narrow-leafed lupin is grown reporting wheat on wheat (WW /2) yields above 2.5 t/ha.

Wheat following lupin out- yields wheat following wheat in the vast majority of experiments even at high rates of applied nitrogen in the wheat year, however the size of the response and likelihood of the magnitude of the response decreases as nitrogen rate increases. The average response to lupin is 600 kg/ha. The frequency of large responses to lupin increases when wheat on wheat yields less than 1.7 t/ha. This indicates the largest responses to lupin occur when there is some factor9s) limiting wheat on wheat production. Invariably these factors have been identified to be root diseases, in particular take-all, and to a lesser extent weed competition, in particular grass weeds. Where these factors are not issues response to lupin will invariably be smaller.

Whilst on average break crop provide a boost to following wheat crops, in approximately 10% of instances wheat following lupin or field pea is no higher yielding than wheat after wheat. In some instances, this may be due to some management failure in the break crop. Most commonly this is a failure to adequately control weeds in the break crop year or the higher nitrogen following a legume break crop leading to growth in excess of what the season and in particular a dry spring could support. However, in a few experiments it may simply be the case that there was no factor limiting wheat on wheat production, and the inclusion of a break crop was not warranted.

In general terms, since 1990 when more effective herbicides were more widely available, rotations shifted to more continuos cropping and trials were more likely to be sown with no-till machinery both the yield of wheat on wheat and the likelihood of a response to lupin in the following year has increased at all levels of applied nitrogen. Interestingly since 1990 the water use efficiency of wheat following lupin has improved more than the water use efficiency of wheat following wheat, indicating improvements in management in the lupin year can improve the performance of following cereal crops.

Whilst the average response to lupin is 600 kg/ha we did find there are regional differences. Not surprisingly in low rainfall areas the response to lupin is lower than the rest of the state, in the order of 300 kg/ha. In this region there is also a trend that if the previous lupin crop grew well and yielded over 1.5 t/ha then the response of the following wheat crop will be larger than 300 kg/ha. Most other areas of the state provide average responses to lupin. The other exception is the high rainfall

south coast where the response to lupin is 900 kg/ha. This is attributed to the relatively high incidence and severity of take-all in this region. Consequently, what really matters in this zone is how well grass weeds are controlled in the lupin crop and not the performance of the lupin crop per se.

Both canola and oats do not provide consistent boosts to following wheat crops. If paddocks have a background level of relatively high cereal root disease then both oats and canola may provide fair to excellent breaks. If the paddock is relatively free from root disease then canola provides only a small boost to following wheat crop of around 200 kg/ha, whilst oats provide no boost to a following wheat crop. For canola this is particularly the case when it has been tested in non-traditional areas. For example, in the northern wheatbelt canola rarely provides a boost to following wheat. We suggest that apart from high rainfall southern zones both oats and canola should in the first instance be viewed as cash crops, in the second instance canola can be thought of as a problem solver for paddocks with high weed burdens, and the break crop effect of canola and oats for diseases should not be the primary consideration in making the decision to grow them or not.

What's missing?

- In recent years in WA the frequency of cereal cropping has been increasing. Coinciding with that increase has been an increase in the amount and frequency of nitrogen fertilisers, particularly liquid foliar fertilisers, and the use of fungicides – seed dressings, fertiliser coatings and foliar applications some of which do have an effect on root diseases such as Take-all. In addition, precision sowing has allowed farmers to sow their crops in rows offset from last year's rows. Will we still expect a break crop to provide sufficient yield improvement over and above these improvements to crop management, or has technology narrowed the gap to such an extent that a longer cereal phase is possible?
- There is limited data for canola and oats as a break crop for wheat compared to that available for lupin and field pea. Given both canola and oats are currently grown over a bigger area than field pea and lupin this may need to be addressed, particularly if canola expands into non-traditional areas.
- There have only been limited trials looking at the response of wheat to canola as a break crop at a wide range of applied nitrogen. It is true there a lot of nitrogen rate for wheat after canola and indeed nitrogen rate for canola after wheat trials have been conducted over the years but the majority of these trials did not include wheat in the canola year or a canola in the wheat year – so these trials cannot be used to discuss rotational effects.
- Canola area is expanding into northern regions and low rainfall southern regions. In the northern region there is limited data available and for the low rainfall south there is no data available. What is available for the northern region indicates canola provides a poor break crop for following wheat. For all of these regions there is probably a need to update this information using earlier flowering varieties like Tanami which may use water differently to previous varieties. It may be wise to include mustard and particularly canola quality mustards (juncea canola) in any further trials that occur in the northern regions as this species has only previously been tested twice.
- There is no data for break crop effects on oaten hay quality and limited data (1 trial) on dry matter production
- In the central and particularly northern agricultural regions of WA there is renewed interest in fallow. Once again although there have been numerous experiments looking at fallow in these regions, but we have very little information comparing fallow to break crops in a balanced way. Those that are available indicate fallow does not provide as big a yield boost as lupin or perform any better than field pea.
- With the exception of nitrogen fertiliser, few, if any trials have looked at the possibility of altering management in the break crop or response crop year. Possible treatments include: do different varieties of wheat respond to crop sequences differently? do varieties of canola provide a different break? can you reduce fertiliser inputs in the break crop year without having an effect on the following cereal crop? Can you increase the break crop effect by crop topping in the previous year? does sowing in-between last years rows reduce the level of root disease enough to improve the variability of closer cereal sequences?
- Apart from lupin and to a lesser degree field pea there is little information on the 2nd,3rd and 4th year of wheat following break crops in WA.
- There is scant information on effect of crop sequences on the yield and quality of next years barley crop

- There is no information comparing lupin-wheat-canola-barley rotation to other options.
- Only one trial has looked at lupin-wheat-wheat-barley.
- How break effects occur has not been completely elucidated. Many trials look at individual components – e.g. water use, take-all, residual nitrogen or sparing of nitrogen. But there has not been a systematic approach to trying to split the break crop effect into its components – e.g. 70% of the effect is due to a reduction in Take-all and 25% to increased water available for the following crop.
- Following on from components of the break crop effect is the idea of predicting in which situations farmers may get a break crop effect, the frequency/probability of the effect and the magnitude of the effect – and if the same effect can be gained from other means rather than using a break crop.

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Introduction to the database

Over 150 experiments have been conducted throughout WA since the 1960's to determine the rotation effects of leguminous or oilseed crops in a cereal based rotation. The vast majority of these have been conducted by the Department of Agriculture and the results of these experiments and the limited number of trials conducted by other organisations is available in various formats, but to date the results of all of these experiments have never been collated in the one place in a uniform way. This paper briefly describes the production of a Microsoft Access database which collates the available information and provides a summary of break crop effects in WA. It limits itself to trials where cereals following cereals are compared to cereals following a break crop. Therefore, although some trials are included which have pasture as a treatment, many pasture-cereal rotation experiments have been omitted if they did not include a break crop treatment. In addition, numerous trials look at the rate of applied nitrogen following break crops necessary for optimum cereal production, but many of these do not include a wheat treatment in the year prior to the nitrogen rates being applied – thus many trials looking at wheat following canola have not been included in the database.

Wherever possible I have attempted to source the information in the most basic form. For example, I have gained access to the results of Ian Rowland's long-term rotation experiments in individual plot format, as treatments grew or morphed over the years. The results of most other experiments have been collated from the DAFWA Plant Industries Experimental Summaries 1969-1990 and from the DAFWA electronic Research Information System which replaced this series since 1991. These usually form a more complete summary of individual trial events than published articles in refereed journals. For example the two years of wheat after field pea data does not appear in (Rowland *et al.* 1994) but did form part of the same series of wheat -wheat compared to field pea-wheat described in the paper and were reported in the DAFWA Plant Industry summaries.

It is a feature of the trials in the database that many included rates of applied nitrogen to the following cereal crops. The majority of experiments added the same rate of nitrogen to the cereal crop following a cereal crop as they did to a cereal crop following a break crop. In the database the actual rate of nitrogen applied is noted and in addition I grouped nitrogen rates into the following classes – 0, 1-25, 26-50,51-75, 76-100, >100 kg N/ha which from hereon in are referred to as 0N, 25N, 50N, 75N, 100N, and 150N. Users of the database can readily group nitrogen rates into their own groups.

Some researchers chose to put nitrogen only on cereal following cereal and not on the cereal following a break crop. Whilst the results of those trials appear in the database it is not possible to use them in any analysis where break crop x nitrogen rate response is looked at.

Data in the base

Fields which appear in the main database include trial information such as trial number, major personnel involved, site (Farmer name), Location (nearest town), agzone, soil type, Year (s) of experiment, what this years crop is and sometimes which variety was used*, nitrogen application rate (kg N/ha), what the previous 6 crops*, some coding for rotation types and phase (incomplete), general comments, and some brief information on any other treatment applied such as ripping, fertiliser, time of sowing.

Crop traits in the database include grain yield, grain yield of previous crop*, dry matter* – usually peak or harvest biomass (noted if otherwise), grain protein[#]. Plants included in the database: barley, canola, cereal rye, chickpea, faba bean, fallow, field pea, lentil, lathyrus, linseed, narrow-leafed lupin, albus lupin, yellow lupin, oats, serradella, sub clover, medic, volunteer pasture, summer crops, triticale, vetch and wheat. Distinctions are made between harvest, green or brown manured, ploughed in, not harvested or stubble removed treatments, mixes of species and other variations. (* indicates data included where available, [#] indicates data available for a very limited number of experiments.)

Notation for crop sequences and rotations used in this paper and on occasions in the database are as follows:

- Abbreviations for major crops are – wheat (W), barley (B), canola (N), lupin (L), field pea (Fp), linseed (Li), oats (O), fallow (Fa), vetch (V), chickpea (K), faba bean (H), and mustard (Mu).
- Crop sequences are listed in order e.g. LWW refers to lupin followed by wheat followed by wheat.
- Reference to the particular part or year of the crop sequence uses the notation /n. For example, for a LWW sequence LWW /1 refers to the first crop, lupin. LWW /2 refers to the first wheat after lupin and LWW /3 refers to the third crop, which in this case is the second wheat after lupin.

Additional information linked to the database include rainfall records for the nearest meteorological station to the experiment from which annual rainfall, growing season rainfall (May to October) and stored water has been calculated. Stored water is calculated for out of season rainfall where in the previous year 10% of November and December rainfall is assumed to be available for the new crop, in the year of the crop 20% of January and February rainfall, 55% of March rainfall, and 75% of April rainfall is added to the soil store. Water use (mm) was then calculated by summing growing season rainfall with stored water.

The database currently holds 10191 records (trial x year x this year's crop x previous crop(s) x nitrogen combinations) 6,000 of these are Ian Rowland's rotation experiments with individual plot data whilst the remainder of the trials/records are treatment means. The results of 167 trials appear in the database, around 165 are DAFWA experiments, one trial had CSIRO as the lead agency with DAFWA input and the remaining experiment is the rotation trial run by the Facey Group at Wickepin.

On the host computer links to original data sources are available.

Analytical approach

Data is stored in the database in raw form. For Ian Rowland's trials the data is presented for each plot of each trial for each year as the treatments changed over the long period of time each trial was conducted. For the remainder of the experiments the average treatment yield is presented for each trial x year x nitrogen rate combination.

In the database grain yield is presented as t/ha to allow users to analyse data in the raw form. In this paper when comparing crop sequences have chosen to present the yield of crop sequences t/ha or to use yield difference. Where yield difference (Ydiff) is the yield of one of the crops of interest in a crop sequence minus the yield of the yield of the same crop in a comparative crop sequence. For example, Ydiff = yield of wheat after lupin crop minus the yield of wheat on wheat. We have deliberately chosen not to use relative (%) yield. Relative yields can be misleading as a 10% yield decrease in a poor year (yield potential 0.6 t/ha, Ydiff = - 60 kg/ha) is worth less than a 10% increase in a good year (yield potential 3.0 t/ha, Ydiff = + 300kg/ha). In other words, Ydiff is of more use to growers than % yield as it more closely represents economic value. The statistical distribution of Ydiff is also more normal than relative yield. For example, in some experiments wheat following wheat fails to yield at all and consequently wheat after lupin has a spectacular relative yield increase. This tends to skew the distribution, whilst using Ydiff leaves the distribution closer to normal.

To avoid over emphasising the results of any one experiment I have where possible shown the raw data, a histogram of the frequency of achieving a range of yield improvements following a break crop, or where an 'average' response is a more useful way of expressing the data, as in response functions we have used the predicted means as calculated in REML. When necessary we endeavour to indicate the models used when calculating the predicted REML means.

Readers should note that Ydiff is calculated for each trial x year x break crop x n rate instance prior to statistical manipulation. It should also be noted that not all trials have all rotations in them; therefore, I urge caution in comparing break crop responses. For example, lupin-wheat responses cannot be directly compared to field pea-wheat responses, as they do not come from the same experiments. Indeed, the wheat on wheat yields change depending on which series of experiments is under consideration.

Unless otherwise indicated in the text the following method as suggested by David Tennant in PYcal is used to calculate water use efficiency (WUE, kg/ha/mm) in this paper.

WUE = GY/available water
= GY/(GSR+store – (GSR+store/3))

where GSR+store = growing season rainfall + storage, and water loss is calculated by dividing GSR+store by 3. In dry years, the standard water loss of 110 mm described in (French and Schultz 1984) could approach and even exceed the estimate of crop water use, yet measurable and sometimes economically viable yields are often obtained. A case can be argued for replacing the 110 mm with 33 % of estimated crop water use, to give lower water loss in dry years.

Brief comments on the trials

The predominant cereal crop tested has been wheat (over 140 trials) with much less information on the rotation benefits or otherwise for following barley (26 trials) or oat crops (7 trials). The value of other break crops for a following canola crop has been tested in 19 trials.

In the early years of the trials (1960's-70's) the main leguminous plant types tested were sub-clover and medic-based pastures. In the 1980's there was shift in emphasis to include crop legumes, particularly narrow-leafed lupin (over 100 trials) on sandy textured soils and field pea (45 trials) on the sandy loams to clay loam soils. The break value of other legume crops such as chickpea (10 trials), faba bean (3 trials), vetch (4 trials) and lentil (2 trials) etc. have not been as extensively tested as lupin and field pea. Of the oilseed crops canola has been used in 31 trials as a break crop, linseed/linola three times and mustard twice. The break crop value of the following grain crops has not been tested lathyrus (tested as manure crop but not as a grain crop), juncea canola, crambe and narbon bean

Rotation experiments have been conducted throughout the grain producing areas of WA. The locations have been Arrino, Badgingarra, Balla, Bencubbin, Beverley, Binnu, Bolgart, Chapman, Darkan, Doodlakine, Dowerin, East Chapman, East Hyden, East Newdegate, East Nokanning, Eneabba, Eradu, Esperance, Fitzgerald, Gairdner River, Geraldton, Gibson, Gnowangerup, Grass Patch, Konnongorring, Korbel, Marchagee, Mayanup, Merredin, Mingenew, Morawa, Mt Barker, Mt Madden, Mullewa, Nabawa, New Norcia, Newdegate, North Mullewa, Northam, Northampton, Nyabing, Pindar, Pingaring, Quairading, Salmon Gums, South Carrabin, Teninidewa, Three Springs, Varley, Wellstead, West Katanning, West Nokanning, Wickepin, Wongan Hills, and Yorkrakine

In many experiments the genotype, variety or indeed species used is not indicated (e.g. crop is called vetch which could be *Vicia sativa* or *Vicia benghalensis* etc.) and rarely if ever are more than one genotype of each species used. This makes it very difficult to determine if there are any genetic differences in rotational benefit provided by say one canola line versus a second line or indeed if there are differential responses between wheat varieties. There have been some attempts to determine if different genotypes of canola provide more of a break crop for following cereals, however the experiments were inconclusive and abandoned (e.g. specifically Karoo versus others, 00ES30 at Gibson with Dr R Loughman).

A feature of many trials in WA has been the lack of a sufficient control treatment (e.g. wheat does not appear in each year), lack of all phases of a rotation appearing in every year, and many trials have been started but ran out of steam after a few years as personnel left the various organisations, organisations changed priorities or funding ran out.

We will now move on to looking at a number of potential break crop species and the response of wheat following those species.

Lupin

Narrow-leafed lupin has been the most widely examined break crop species with over 150 trial x year combinations available in the database. If we look at the raw data from all of the trials (Figure 1) we can see the range of yields obtained in the trials. The majority of wheat on wheat (WW /2) yields are less than 2.5 t/ha indicating that in the trials conducted to date it has been difficult to achieve yields higher than 2.5 t/ha with wheat sown after wheat.

In general, it is also noticeable that the majority of wheat after lupin responses above the 1:2 ratio line occurs when wheat on wheat yields are below 1.5 t/ha, indicating an agronomic issue with wheat-wheat which the inclusion of lupin helps to remediate. Invariably these issues have been identified in individual trials to be the presence of Take-all or high levels of annual ryegrass or brome grass. The outlier on the y-axis of yields of lupin-wheat at or above 4 t/ha when wheat-wheat yields less than 1.0 t/ha are from the trial 91KA111 at West Katanning in which Take-all was a factor which severely limited the yield of wheat on wheat and a wide range of break crops such as lupin, field pea and canola provided a good break from the disease. Similarly, the outlier where WW /2 yields close to zero and LW /2 yields 2.5 t/ha is from a trial at South Carrabin in 1995 where brome grass became very difficult to control in wheat on wheat plots.

Similarly, there are occasions where the lupin sequence fails. For example, the outlier on the x-axis where WW /2 yields 1.8 t/ha and LW /2 yields close to zero are from a trial in 1983 at Nabawa (78C1) where wild radish was not able to be controlled in the lupin phase and the weeds swamped the following cereal crop. In later years the availability of diflufenican solved this issue, although in recent times wild radish has again become harder to control in the lupin year with selective herbicides.

Overall though wheat sown after lupin out yields wheat after wheat. A linear relationship can be fitted to the response of wheat after lupin compared to wheat after wheat over a wide range of wheat on wheat yields. This relationship is:

GY of LW /2 = 0.9(GY of WW /2) + 0.7, $r^2 = 0.47$, $P<0.001$.

If the outliers discussed earlier are removed the relationship is improved to:

GY of LW /2 = 0.9(GY of WW /2) + 0.6, $r^2 = 0.58$, $P<0.001$.

If we were to constrain the regression through the origin the regression would become:

GY of LW /2 = 1.34(GY of WW /2), $r^2 = 0.45$, $p<0.001$.

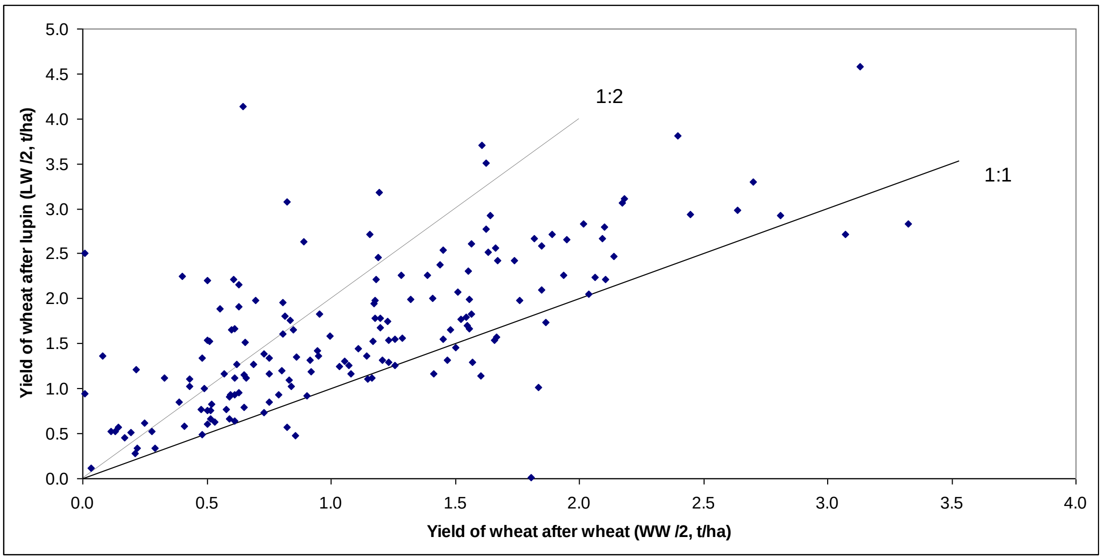

Figure 1 **Relationship between the yield of wheat on wheat (WW /2) and the yield of wheat sown after lupin (LW /2) in 88 trials (167 trial x year combinations) in experiments conducted throughout WA since 1974. Linear curves show 1:1 and 1:2 ratios.**

Another way to look at the data set is to consider how the magnitude of the difference in yield between WW /2 and LW /2 and the frequency in which various levels of yield difference occur. In the first instance we will look at yield difference averaged across all rates of nitrogen applied to the second year of wheat. Figure 2 shows that whilst there are relatively few instances where Ydiff is more than 1.5 t/ha, in 9% of instances Ydiff is less than or equal to 0 t/ha, and the distribution is centred around 0-500 kg/ha range with the mean* increase in yield of being 603 kg/ha (se = 58 kg/ha) (*predicted mean from REML analysis with Year included in the model, which 'smooths' out the effect of seasons). Of interest is the high proportion of instances where Ydiff is less than 250 kg/ha, therefore we can look more closely at this in a cumulative frequency chart Figure 8. This shows that in 20% of instances the difference between LW /2 and WW /2 is less than 100 kg/ha.

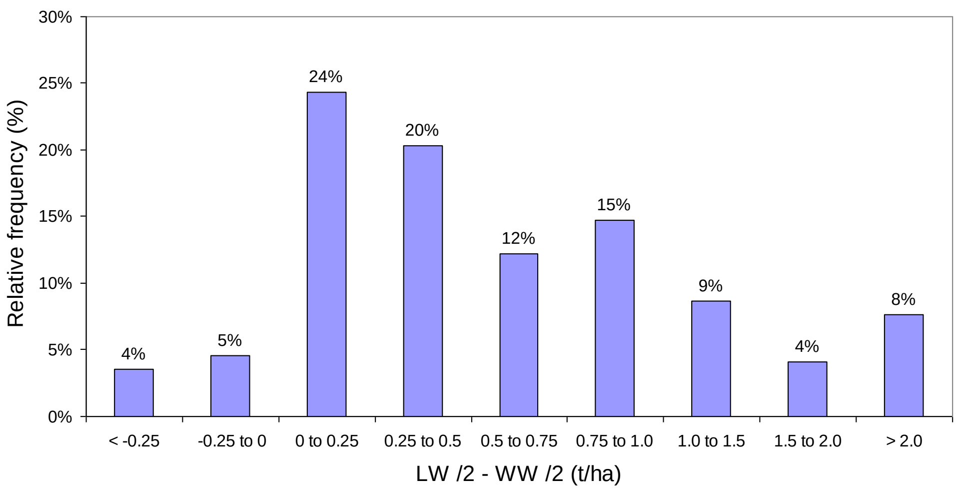

Figure 2 **Relative frequency (%) in which the difference in yield (Y diff, t/ha) between wheat following lupin (LW /2) and wheat after wheat (WW /2) falls into 9 yield categories. Data are from 167 trial x year combinations in 86 trials conducted in WA since 1974.**

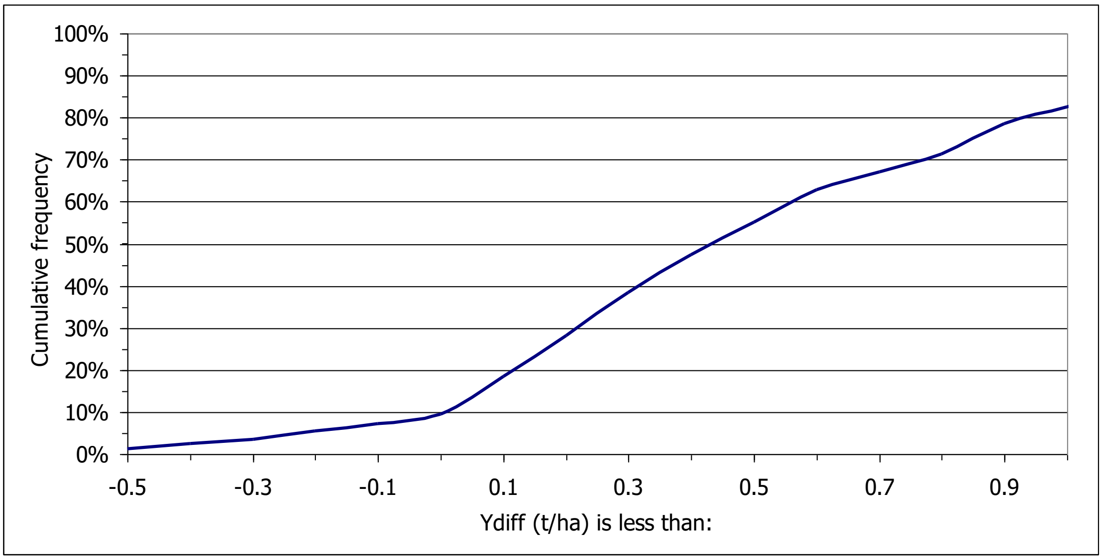

Figure 3 **Cumulative frequency (%) in which the difference in yield (Y diff, t/ha) between wheat following lupin (LW /2) and wheat after wheat (WW /2) is less than x t/ha.**

Although wheat sown after lupin usually out yields wheat after wheat it is useful to consider some of the occasions where wheat after lupin fails and to consider why. Some examples of individual situations where lupins failed to improve the wheat yield were:

- 82ME53 (1983) Wodgil soil type and poor season with growing season rainfall of only 182 mm.
- 79GE36 (1981) at Binnu on a deep sand where the authors indicate the natural infertility of the site was not overcome by either nitrogen or the inclusion of lupin.
- 75GE9 (1975) at Morawa where a bad infestation of annual ryegrass reduced yield of wheat and authors note the density of ryegrass was slightly greater in plots following lupin.
- 86M44 (1989) at South Carrabin on a yellow loamy sand (possibly Wodgil) where yield of all treatments was poor due to extremely low rainfall in spring of only 19 mm in August and 8mm in September which equates to 44% of the long-term average rainfall. In this situation dry matter of wheat did respond to lupin (either LW or LWW) but the increase was not reflected in yield.
- 75BA6E (1975) where low rainfall in August of 52 mm (57% of long term average) limited response in both 75BA6E (early sown crops in 1974) and 75BA6L (late sown crops in 1974) regardless of previous species.
- 84M52 (1985) the author (French) comments "responses in dry matter production up to mid September were greater than the response in grain yield. This is probably due to insufficient rainfall in late September and early October to allow conversion of this matter into grain yield".

A common theme in the explanations provided for situations where both wheat on wheat and wheat on lupin fail appears to be dry springs. Thus, lupins can only provide a boost if the season allows it. However, a consistent explanation in the authors comments is that the wheat after lupin had grown better than wheat after wheat, therefore at least it was set up to make use of spring rainfall if and when it appeared.

As seasons influence the magnitude of any break effect it can be useful to compare the upper limit water use efficiency of the different rotations. To do this we have produced modified French and Shultz (French and Schultz 1984) figures for the two rotations and fitted by eye a boundary line encompassing most of the data points (Figure 4 and Figure 5).

The potential water use efficiency of wheat after lupin as described by these boundary lines at 19 kg/ha/mm is greater than that achieved by wheat after wheat of 15 kg/ha/mm. As available water increases both rotations show a decreasing ability to achieve potential yields, however lupin-wheat rotations are able to maintain their superiority to wheat-rotations over a wide range of available water (Table 1).

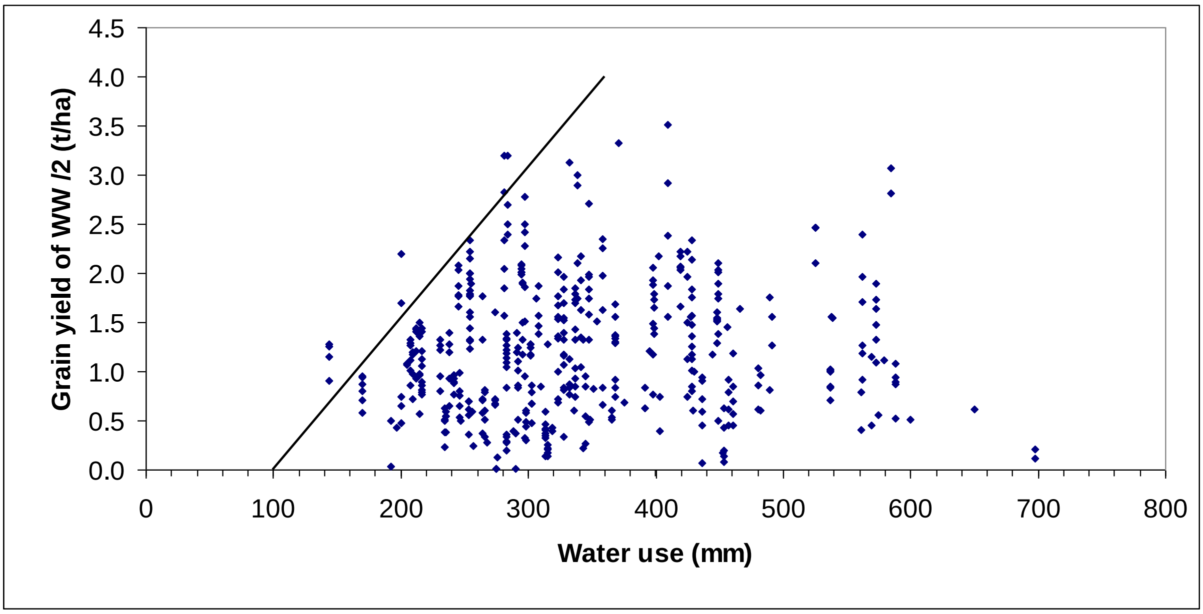

Figure 4 **The relation between grain yield of wheat following wheat (WW /2) and water use (mm) from Western Australia crop sequence experiments. Slope of boundary lines is equivalent to 15 kg/ha/mm.**

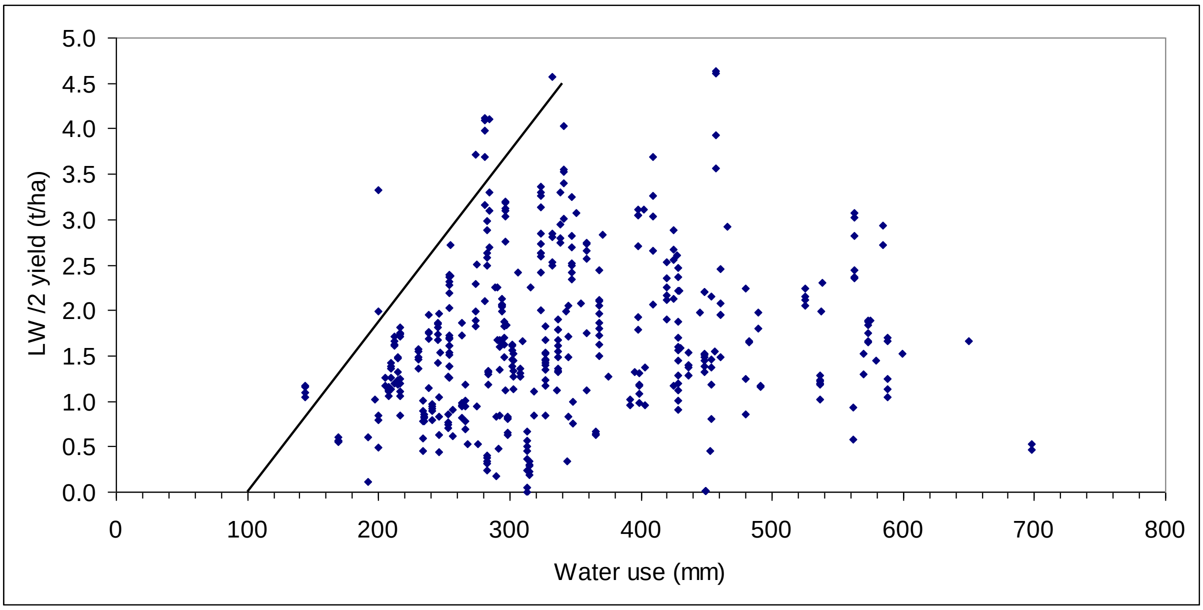

Figure 5 **The relation between grain yield of wheat following lupin (LW /2) and water use (mm) from Western Australia crop sequence experiments. Slope of boundary lines is equivalent to 19 kg/ha/mm.**

Table 1 **Water use efficiency (WUE) decreases as available water increases of both lupin-wheat and wheat-wheat rotations.**

Estimated available water (GSR+ store, mm)	WUE (as a % of potential*) of: WW /2	LW /2
Less than 300 mm	22%	31%
300 to 400 mm	18%	27%
400-500 mm	14%	22%
>500 mm	12%	16%
Overall	16%	25

P (last years crop) <0.001, l.s.d (p = 0.05) = 1%
P (GSR+store) <0.001, l.s.d (p = 0.05) = 4%
P (last years crop x GSR+store) <0.001, l.s.d (p = 0.05) = 5% for same level of crop, 2% for same level of GSR+Store

* Potential yield = 19 x (GSR +store-100)

Does the rate of nitrogen applied in the 2nd year change the response?

It is widely known one of the major effects of lupin will be the residual nitrogen they supply to the following crop. Up to date the response to lupin we have considered has been across all fertiliser nitrogen rates applied to the following wheat crop. In order to evaluate the effect of fertiliser nitrogen on Ydiff we first grouped rates of applied nitrogen into five groups labelled 0N, 25N, 50N, 100, 150N, where 0N = all treatments where no fertiliser nitrogen was applied, 25N = where up to 25 kg N/ha was applied, 50N = 25 to 50 kg N/ha, 100 N = 50 to 100 kg N/ha, and 150 = more than 100 kg N/ha. We then restricted the dataset to 30 trials which included at least four of these five groups so that n= 66 for all N groups except 150N which had 44 observations. Residual maximum likelihood (REML) models were then fitted using Genstat 10 with N group as the fixed effect and Trial.Year as the random effect.

Overall fertiliser nitrogen has a significant ($P<0.001$) but small effect on Ydiff. The largest Ydiff was when no fertiliser nitrogen was applied where Ydiff was 556 kg/ha. Ydiff decreased as fertiliser nitrogen rate increased so that at the highest group of fertiliser nitrogen applied 150N Ydiff was 396 kg/ha (Figure 6).

Figure 7 and Figure 8 allow us to consider the frequency of the response to lupin in following wheat over a wide range of applied nitrogen. Adding fertiliser nitrogen slightly increases the frequency of nil or negative responses. Thus, when no fertiliser nitrogen is applied the frequency of a Ydiff less than zero is 15%, whilst at all other rates of applied nitrogen the frequency is more than 19%. The increase in frequency of instances where wheat after lupin yields are lower than WW /2 as fertiliser nitrogen rates increase may be the result of improved broadleaf weed growth (primarily wild radish) following lupin, but it is most commonly reported to be the phenomena of haying off, wherein the growth of wheat after lupin with additional applied nitrogen is too large for the amount of water available in spring during seed filling and the wheat crop following lupin effectively dies off whilst the lower biomass produced in the wheat on wheat sequence is more in tune with the available water.

Similarly, the frequency of small positive yield differences increases as the rate of applied nitrogen increases. Indeed, the yield difference category which shows the widest spread of frequencies between fertiliser nitrogen groups is the 0-250 kg/ha category (Conversely the frequency of medium yield differences decreases as the rate of fertiliser nitrogen increases. Thus, as fertiliser nitrogen rate increases the frequency of Ydiff in the ranges 0.25 to 0.5 t/ha and 0.5 to 0.75 t/ha decrease. The change in response to fertiliser nitrogen either side of a Ydiff of 250 kg/ha indicates that when 'potential' yield increases following lupin are at moderate levels adding fertiliser nitrogen reduces the magnitude and frequency of the response.

The frequency of large positive yield differences is not affected by fertiliser nitrogen. Thus, there is an equal frequency of producing large yield differences at a wide range of applied nitrogen. We could hypothesise therefore that achieving large responses to lupin compared to wheat on wheat depend on factors other than fertiliser nitrogen. i.e. agronomic factors such as the weed and disease break offered by a clean lupin crop may be more important than the nitrogen effect if large yield boosts are to be achieved.

In summary the most consistently large yield increases following lupin will occur if no fertiliser nitrogen is applied to the second-year wheat. On average, adding fertiliser nitrogen will only have a small effect on potential yield difference. The most noticeable effect of fertiliser nitrogen appears to occur when potential yield differences are in the range of 0 to 250 kg/ha. In this range applying nitrogen increases the frequency of low yield difference events.

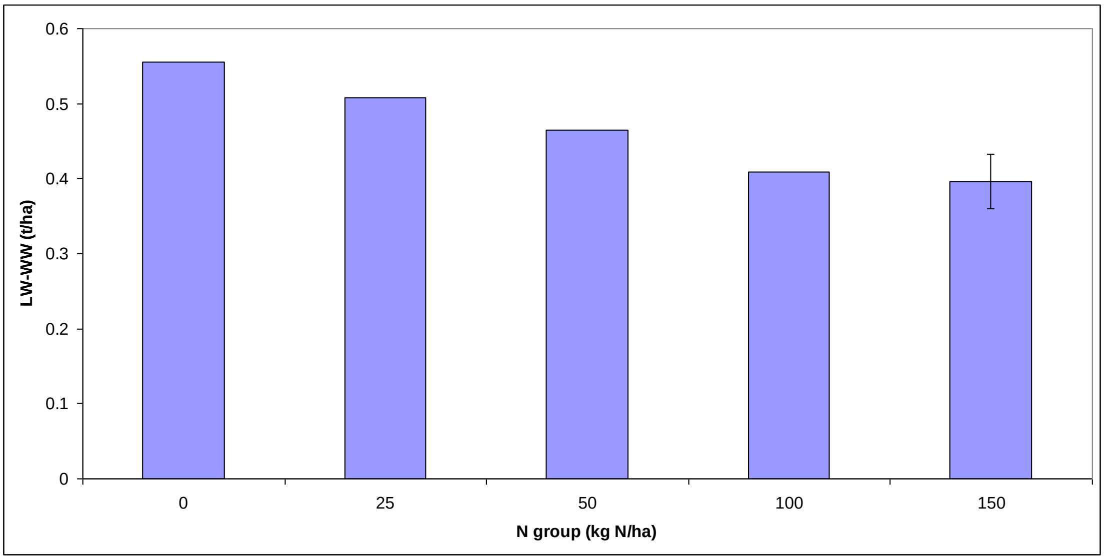

Figure 6 **Relationship between the rate of applied nitrogen (kg/ha) and the difference in yield between wheat after lupin (LW /2) and wheat after wheat (WW /2). Vertical bar indicates l.s.d.**

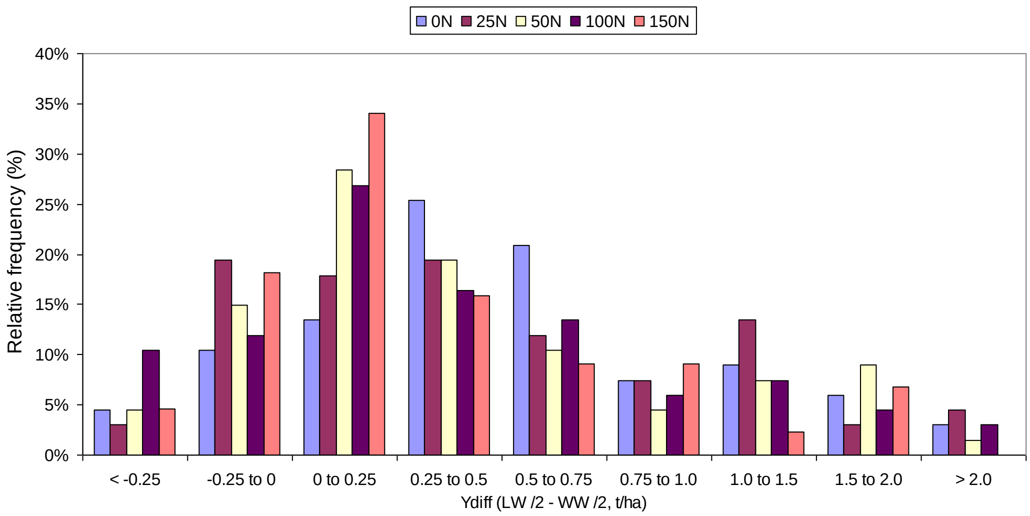

Figure 7 **Increasing fertiliser nitrogen rates reduces the frequency of a yield increase for wheat following lupin compared to wheat after wheat in 30 trials conducted in WA since 1976. (67 trial x year combinations).**

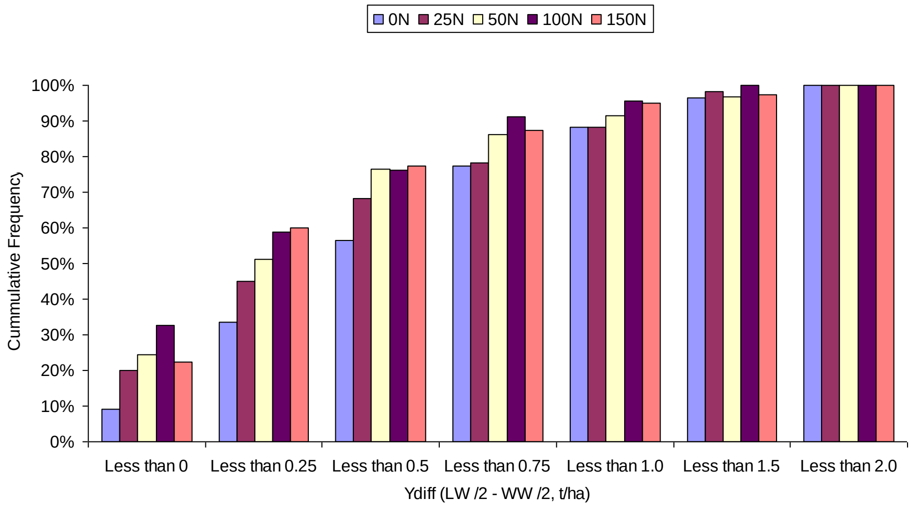

Figure 8 **Cumulative frequency of producing a given yield increase for wheat following lupin compared to wheat after wheat in 30 trials conducted in WA since 1976 (67 trial x year combinations).**

Does the response change with location or time?

As we have a large data set conducted over many years at our disposal it may be possible to determine if the response to lupin has changed over the years and then to propose why these changes may have occurred. Trials which include wheat after lupin sequences compared to wheat after wheat sequences have been conducted in WA since 1974. However, no trial has been conducted for all of the years since 1974 in the same location. Often though, a series of similar experiments are conducted in nearby locations. Therefore, we could group the experiments by Lupin Agzones (Figure 9). This provided a reasonable data set for lupin Agzones 5 (Medium rainfall – Central) and 6 (Medium rainfall – Great Southern) for the period 1983-1995, lupin Agzone 7 (Low rainfall – East) for the period 1983-1997, and for lupin Agzone 8 (South coast) for 1975-1995. To produce a similar length data set for the major lupin growing area of the Geraldton port zone we combined lupin Agzone 1 (High rainfall – North) and 2 (Medium rainfall – North) to provided a data set for the period 1974 to 1994. There was insufficient data from Agzones 3 (Low rainfall- North) and 4 (High rainfall – Central and Great Southern), therefore they were excluded from any statistical analysis. Agzone was then included in the statistical model to compare between years and to reduce the influence of trials which had many fertiliser nitrogen rates compared to trials which had one or a limited range of nitrogen applied, in the first instance we used averaged trial x year data.

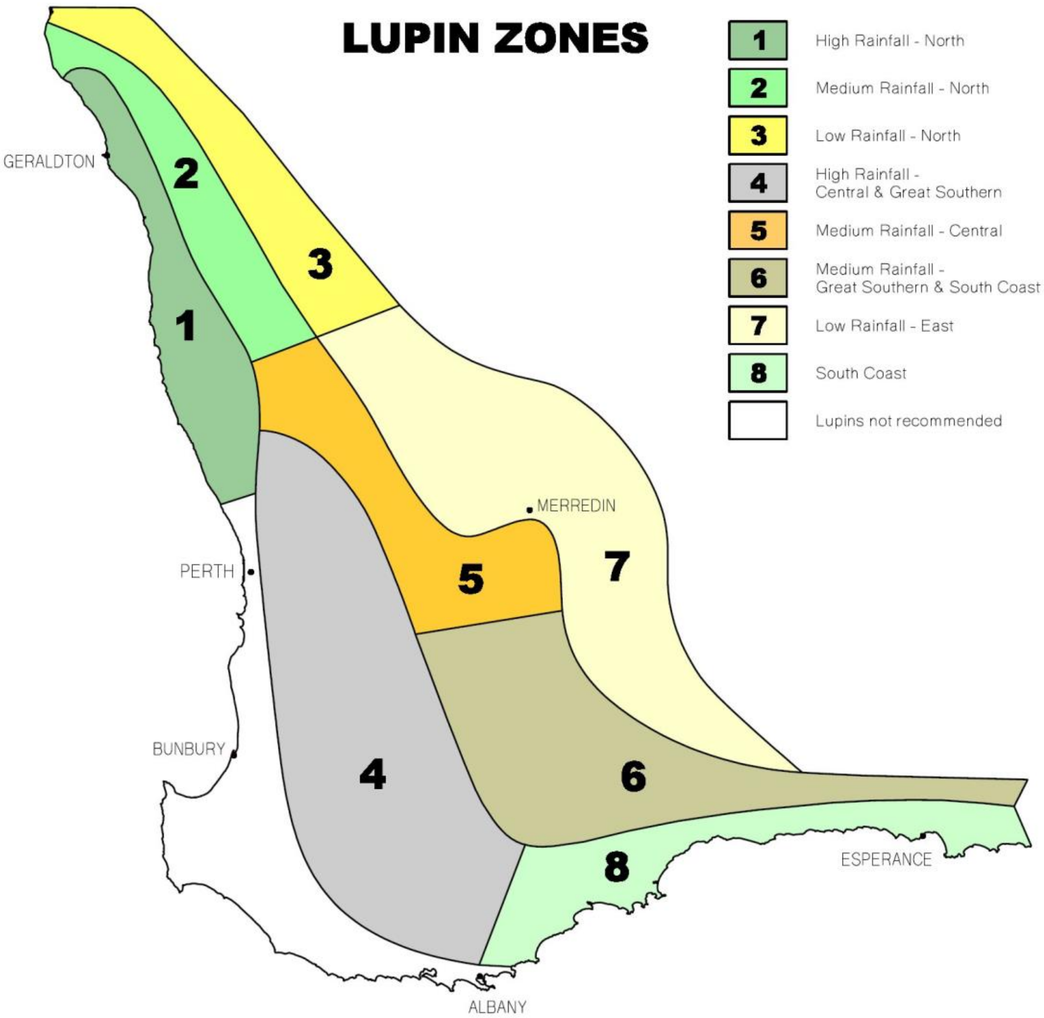

Figure 9 **Lupin Agzones in Western Australia as defined by the Department of Agriculture and Food Western Australia**

The difference in yield between wheat after wheat and wheat after lupin appears to change over time (Figure 10) with a gradual rising trend from 1974 up to 1990 when the difference in yield between LW /2 and WW /2 increases dramatically and then drops off again after 1993.

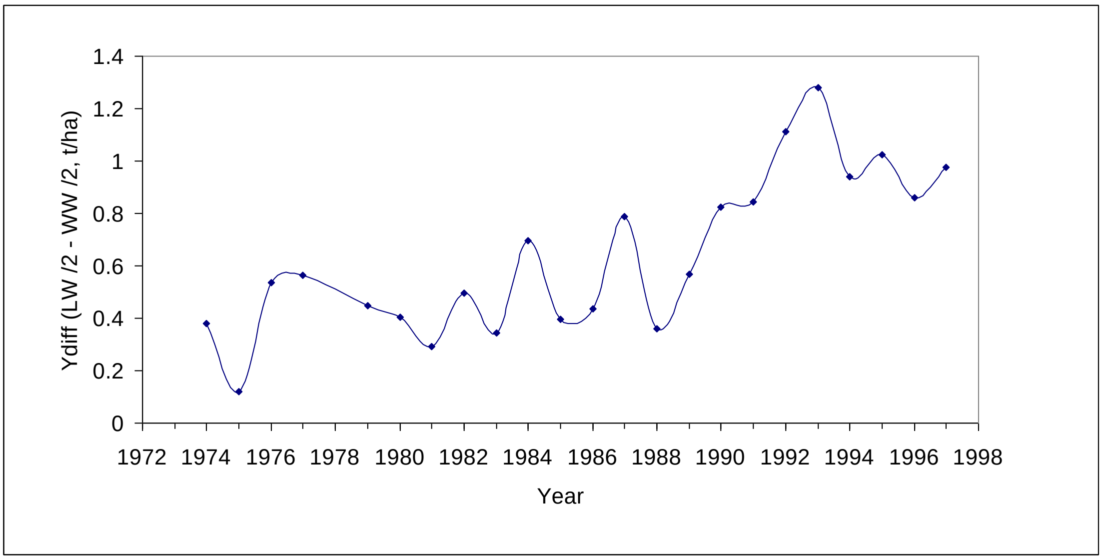

Figure 10 **The difference in yield between wheat after wheat (WW /2) and wheat after lupin (LW /2) appears to change over time.**

To investigate this observation further we restricted the data set to the years when the most number of lupin Agzones had trials, which was the period 1983 to 1995 (Figure 11). This showed a relatively flat period from 1983 to 1991 and then an increase in the period following. We can look at the relationship between wheat following wheat yields compared to wheat after lupin yields during these two periods in more detail (Figure 12). This showed that on average there had been little change in WW /2 yield ($P > 0.05$) with the average yield of WW /2 being 1.2 t/ha in the years 1983-1989 and 1.10 t/ha in the years 1990-95. During the same period LW /2 average yields had increased from 1.6 t/ha to 2.1 t/ha ($P < 0.05$) and there was a noticeable shift in the difference between yields of the two crop sequences over a wide range of WW /2 yields but in particular when WW /2 yields were less than 2 t/ha. What were the changes in the 1990's that led to an unprecedented increase in the difference in yield between LW /2 and WW /2? Was it environmental, such that we had a run of years that suited wheat after lupin more so than wheat after wheat? Or were there changes in agronomic practices which were of benefit to wheat after lupin or made lupin a better break crop?

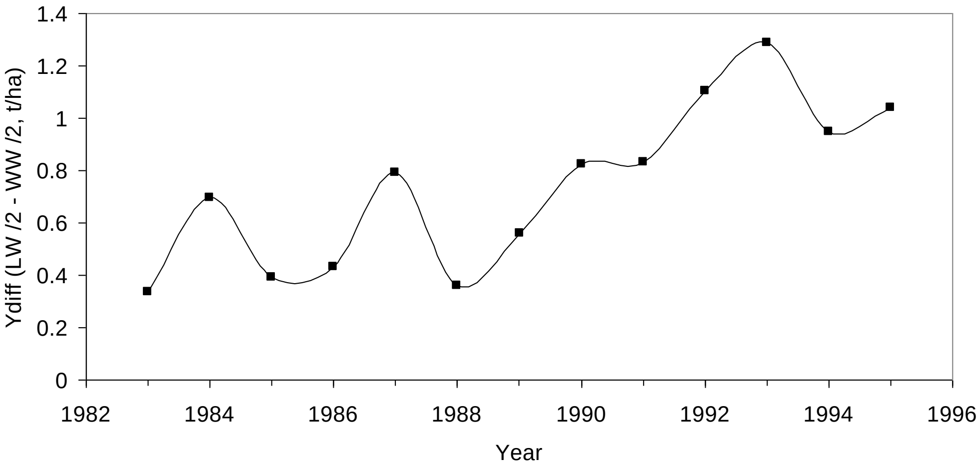

Figure 11 **The difference in yield between wheat after wheat (WW /2) and wheat after lupin (LW /2) from 1983 to 1995**

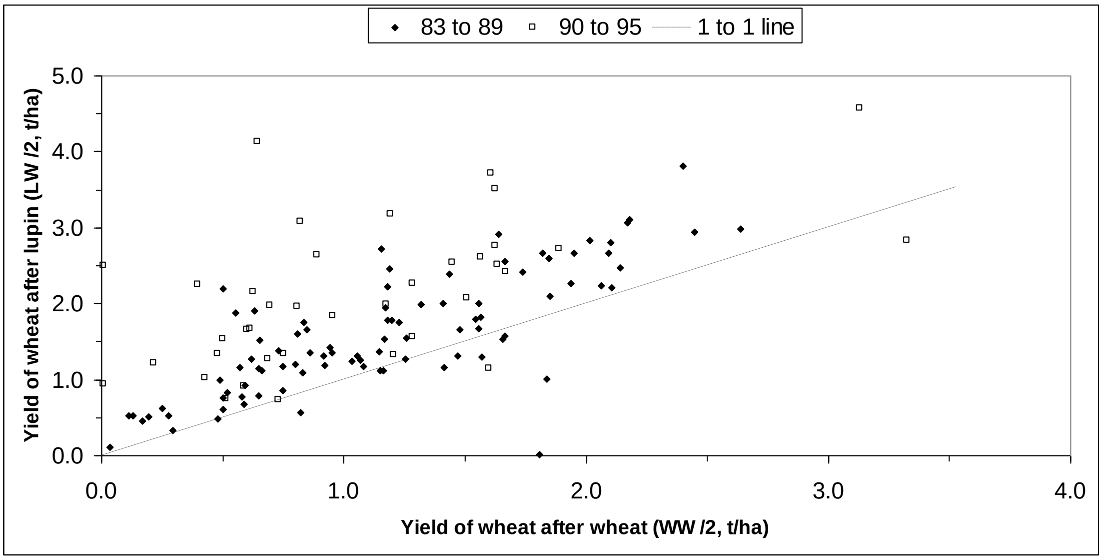

Figure 12 **Relationship between the yield of wheat on wheat (WW /2) and the yield of wheat sown after lupin (LW /2) for the period 1983-89 and 1990-95. Linear curve indicates the 1:1 ratio**

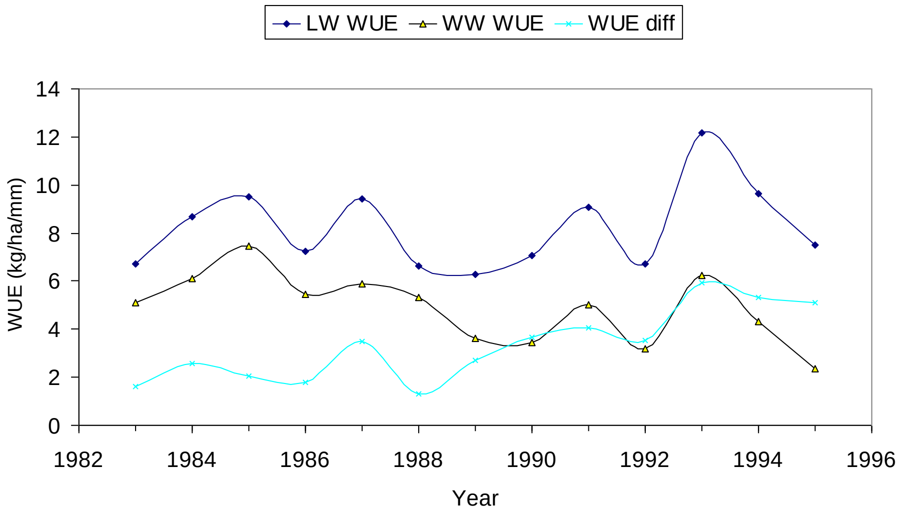

Figure 13 **Changes in the water use efficiency (WUE, kg/ha/mm) over the period 1983 to 1995 in WW /2 and LW /2.**

To separate the effect of rainfall from management we decided to compare the water use efficiency of the two sequences (Figure 13). This showed that the difference between the WUE of LW /2 and WW /2 was consistently above 3 kg/ha/mm from 1990. Around that period of time there was a shift to no-till machinery both on farms and for experimental purposes, there was a wider use of more effective herbicides for in-crop selective control of grass and broadleaf weeds in lupin crops, and rotations shifted to more continuos cropping as sheep numbers declined throughout WA. In general, comments from trials in the period 1990-95 indicated that the lupin plots were generally free from weeds and there were few reports of poor lupin growth in the trials. Thus, these changes seemed to be of benefit both for the lupin crop and the following cereal.

This is reflected if we further group the data into "1983-89" and "1990-95" wherein Ydiff was 1.0 t/ha from 1990 on compared to 0.5 t/ha in the seven years prior ($P<0.001$). The difference between "1983-89" and "1990-95" remained even when the peak year of 1993 was removed from the analysis. Of interest then was to see if the agronomic changes also changed the response to fertiliser nitrogen. i.e. with changes in agronomic practice can you maintain the yield difference or even increase the yield difference when nitrogen rate and overall yield increases? To do this we used the data set of trials which most rates of fertiliser nitrogen appear in and had to further reduce the data set as there were too few trials in the period 1990-95 which included rates of nitrogen above 100 kg/ha (n=6).

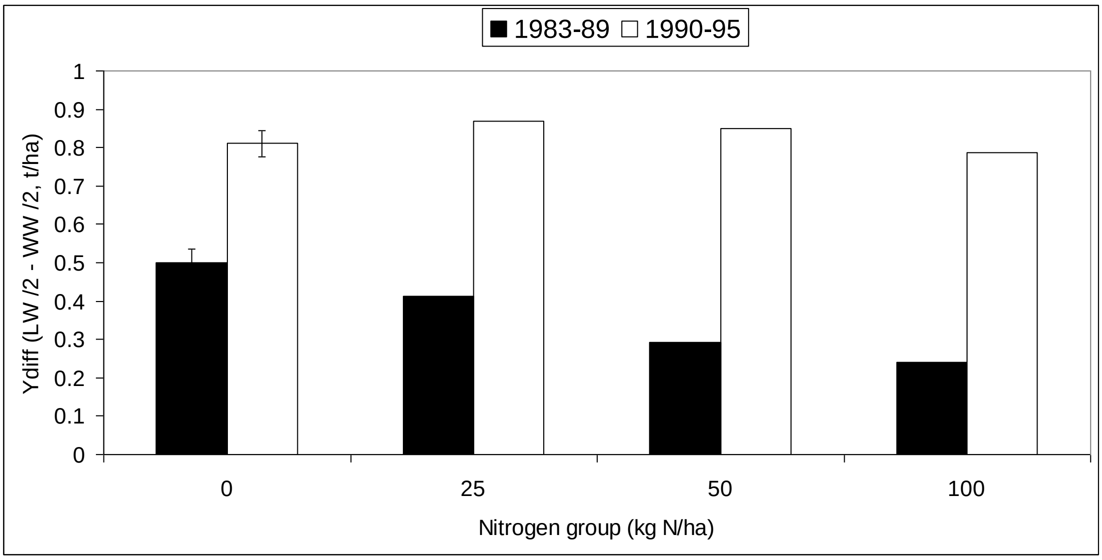

Figure 14 Response of Ydiff (LW /2-WW /2 in t/ha) to fertiliser nitrogen (kg N/ha) in the wheat year in the period prior to and after 1990.

Prior to 1990 as the rate of nitrogen increased the difference in yield between LW /2 and WW /2 decreased. However, since 1990 fertiliser nitrogen has no effect (P>0.05) on the difference in yield. It appears that since 1990 wheat after lupin continues to respond to increasing rates of fertiliser nitrogen whereas in the previous period wheat after lupin did not respond to increasing rates of fertiliser nitrogen whilst wheat on wheat did (Figure 15). We suggest here that due to the availability and widespread use of effective grass herbicides it was possible to grow with more certainty a grass-free lupin crop and thereby reduce the incidence and severity of cereal root diseases. Thus, wheat grown after lupin was healthier and therefore more able to respond to nitrogenous fertiliser.

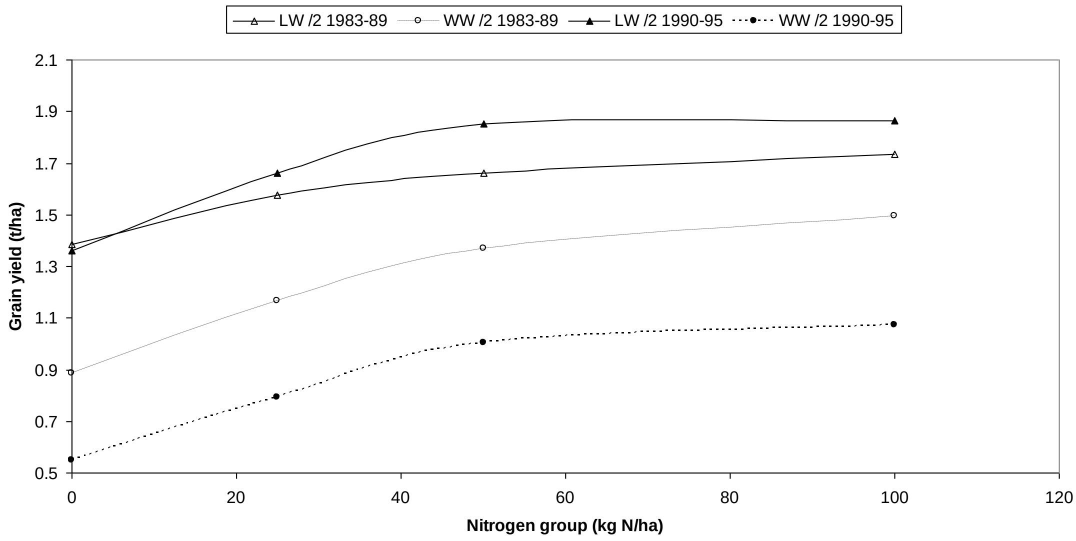

Figure 15 Yield of LW /2 and WW /2 (t/ha) to a range of applied nitrogen in the wheat year in the period prior to or after 1990.

Location

To determine if the location of the experiment influenced the size of any break crop effect following lupin we started by looking at the data set which averaged the nitrogen treatments within each Trial x year combination for all eight lupin Agzones. It was apparent that trials were not conducted in every year in every Agzone (Table 2). Therefore, to reduce the influence of results from any one year we included Year in the fixed model (Year.Agzone) for the REML analysis. We found that lupin Agzone had no influence on the difference in yield between LW /2 and WW /2 (P = 0.103). It was apparent that some of the outliers mentioned earlier where high take-all at 91KA111, brome grass blow-outs in 92SC21, and radish blow-out in 78C1 were having a large overriding effect. i.e. weed blow-outs override any location effect. Therefore, we decided to leave those instances out of the analysis. When this was done we were left with an incomplete dataset in Agzones 3 and 4 (Table 2), therefore we decided to exclude these Agzones from the analysis as well.

Yield boost following lupin in south coast areas (Agzone 8) are higher than the average of 0.6 t/ha. In Agzone 8 wheat following lupin out-yields wheat after wheat by 0.9 t/ha. Conversely in low rainfall eastern areas (Agzone 7) provides a yield boost to wheat after lupin of only 0.3 t/ha. In this instance the differential between these two Agzones does not appear to be the performance of the previous lupin crop. Lupins in the previous year yield 0.7 t/ha in Agzone 8 and in Agzone 7 lupin yields on average 0.9 t/ha. We suggest here that it is the consistent presence of damaging levels of Take-all in continuos cereal crops in Agzone 8 that leads to a large break crop effect in that region, rather than the growth of the lupin crop per se. Whilst in Agzone 7 the low availability of soil water in general, limits crop production and the potential size of any break crop effect.

Another broad grouping we considered was low, medium and high rainfall zones (Figure 16). We found wheat sown after lupin in low rainfall zones on average to be lower yielding than other rainfall zones and the difference in yield between wheat after lupin compared to wheat after wheat to also be lower in the low rainfall zone. Wheat after lupin in low rainfall zone average 1.3 t/ha (se = 0.1) compared to 1.8 t/ha in both medium and high rainfall zones. Whilst the difference in yield between wheat after lupin compared to wheat after wheat was 0.4 t/ha in the low rainfall zone compared to 0.5 and 0.6 t/ha in medium and high rainfall zones respectively. The yield of lupin in the previous year was also on average lower in the low rainfall zone at 0.8 t/ha compared to 1.4 t/ha in medium and 1.0 t/ha in high rainfall zones, whilst there was no difference in the yield of the previous wheat years wheat crop across rainfall zones ($P>0.05$). Therefore, growers in low rainfall areas should expect to grow lower yielding lupin and get less benefit from them than growers elsewhere.

Other groupings attempted were CVT zones (L1-5, M1-5, H1-5) where we limited the data set in a similar fashion as for Agzones where we did not include the outliers and did not include CVT zone L4, H4 and M5 due to insufficient number of trials in those zones. This analysis confirmed that south coast high rainfall (H5) is the part of WA where the largest average increase following lupin has been achieved. The next best region is the medium rainfall region encompassing Wongan Hills (M2) which also produces the highest average gross yields after lupin.

Therefore, if we remove the major overlying effect of weed blow-outs or extreme responses to take-all we can define the rainfall zones and locations where responses to lupin may vary.

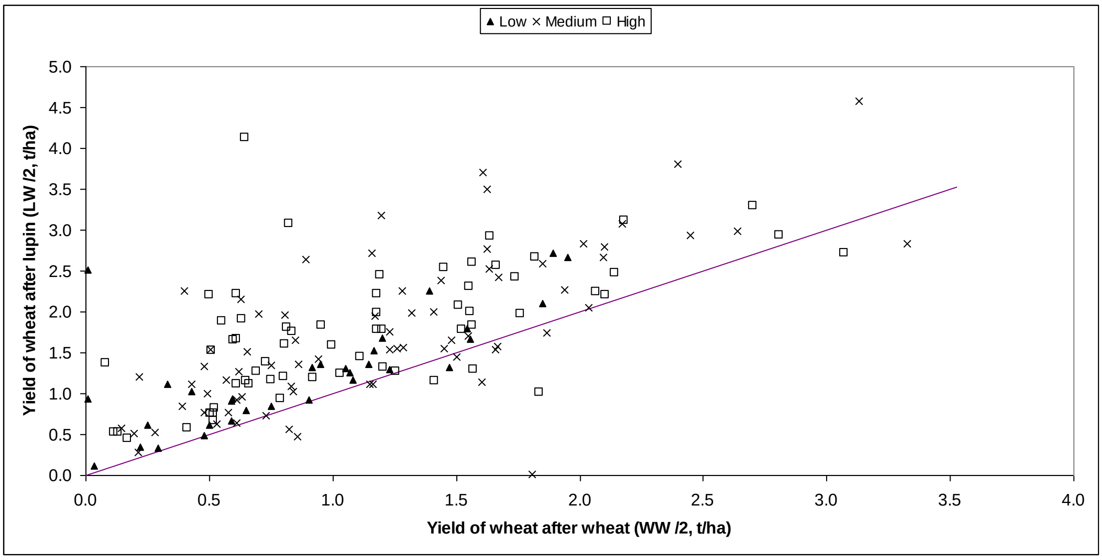

Figure 16 **Relationship between the yield of wheat on wheat (WW /2) and the yield of wheat sown after lupin (LW /2) in low, medium and high rainfall zones in WA. Linear curves indicate the 1:1 1:2 ratio.**

Table 2 **Location (lupin Agzone) has some effect on the magnitude of the yield difference (Ydiff) between wheat after lupin and wheat after wheat.**

	Outliers kept		Outliers removed	
Lupin Agzone	Ydiff (t/ha)	No. of Trial x Year observations	Ydiff (t/ha)	No. of Trial x Year observations
1 High rainfall – North	0.5	35	0.5	28
2 Medium rainfall – North	0.4	22	0.4	20
3 Low rainfall- North	0.5	5	*	5
4 High rainfall – Central and Great Southern	0.7	7	*	6
5 Medium rainfall –Central	0.7	32	0.7	31
6 Medium rainfall – Great Southern	0.6	17	0.6	17
7 Low rainfall – East	0.5	27	0.3	25
8 South coast	0.9	22	0.9	21
P l.s.d	0.103		<0.001 0.3	

Table 3 CVT zone has some effect on the magnitude of the yield difference (Ydiff) between wheat after lupin and wheat after wheat.

CVT Zone	n	Ydiff	LW	GYpL	GYpW
H1	26	0.5	1.6	1.2	1.4
H2	9	0.4	1.6	2.1	2.3
H4	1	*	*	*	*
H5	26	0.9	2.0	0.7	1.4
L1	5	0.4	1.3	0.4	1.4
L3	22	0.3	1.2	0.8	1.1
L4	3	*	*	*	*
M1	20	0.4	1.5	1.5	1.3
M2	18	0.8	2.3	2.2	2.2
M3	16	0.5	1.9	1.0	1.8
M4	16	0.6	1.6	1.0	1.3
M5	1	*	*	*	*
Mean		0.5	1.7	1.2	1.6
P		0.004	0.002	<0.001	0.015
l.s.d		0.3	0.4	0.4	0.5

Does the performance of the previous lupin crop affect the yield of the following crop?

To evaluate the influence of the previous lupin crop on the response in the following wheat crop we used the data set of 167 trial x year combinations. Of those 101 trial x year combinations reported the yield of the previous lupin crop. We then grouped the performance of the previous lupin crop into 4 groups. We found however that the group where lupin yield was below 0.5 t/ha produced widely variable results, probably due to the numerous ways lupin could have failed such as drought or weed blow-outs not being taken into account. Therefore, we decided to not consider this group in any further analysis.

As the yield of the previous lupin crop increased the yield of the following wheat crop increased (Table 4). Therefore, different estimates for the relationship between the yield of WW /2 and LW /2 could be defined for each of the groups categorising the performance of the previous lupin crop (Figure 17). If the previous lupin crop yields over 1.5 t/ha, the relationship between WW /2 and LW /2 is steeper than the linear relationships for the other categories. Hence, we can expect if the previous lupin crop yields above 1.5 t/ha the yield of the following wheat crop will likely be greater than if the lupin crop had yielded yield below 1.5 t/ha.

Table 4 Performance of the previous lupin crop affects the performance of the following wheat crop

Grain yield of the previous lupin crop (t/ha)	Grain yield of wheat after lupin (t/ha)	Ydiff (LW /2 – WW /2, t/ha)
Less than 0.5 t/ha	Variable	Variable
0.5 to 1.0 t/ha	1.4	0.5
1.0 to 1.5 t/ha	1.6	0.7
More than 1.5 t/ha	2.2	0.9
P l.s.d	0.005 0.4	0.025 0.2

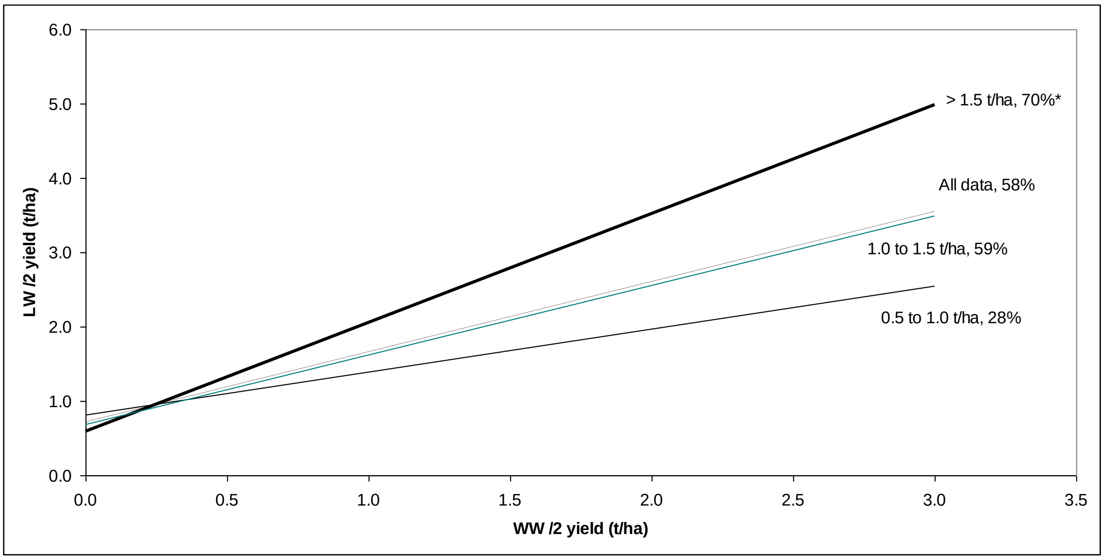

Figure 17 Relationship between the yield of WW /2 and LW /2 (t/ha) depends upon the yield of the previous lupin crop. * % variance accounted for by linear regression.

Does the agronomy imposed to the previous lupin crop change the response?

There is little doubt that lupin has an effect on following wheat crops. But can the magnitude of the response be changed by altering the management of the lupin crop? Certainly, the type and rate of residual herbicides used in the previous lupin crop can damage following cereal crops in certain situations. Similarly, other researchers have demonstrated the residual value of fertilisers applied in the lupin crop to following cereal crops. However, in these experiments wheat is not sown in the lupin year so it is not always possible to distinguish between direct or indirect effects of agronomic manipulation. In other words, did the agronomic manipulation directly affect next years wheat crop in which case you could have got the same effect by agronomic manipulation without growing lupin or did the agronomic manipulation affect the previous lupin crop and therein affect the following wheat crop?

One of the more common agronomic manipulations is to delay sowing. Ian Rowland conducted some experiments in 1975 comparing wheat sown after either early or late sown wheat or lupin. Overall sowing lupin early provided a small increase in the break crop effect for the following wheat crop (Table 5).

Table 5 Yield of wheat following either wheat (Gamenya) or lupin (Unicrop) sown either early (7th to 22nd May) or late (28th May to 13th June) in the previous year (Ian Rowland, unpublished data).

Trial	Sown early in previous year			Sown late in previous year		
	Previous year wheat yield	Previous year lupin yield	Ydiff in following year	Previous year wheat yield	Previous year lupin yield	Ydiff in following year
75A4	1.20	1.35	0.03	1.13	2.06	0.10
75BA6	0.93	0.69	0.17	0.38	0.53	0.15
75NO28	1.64	1.42	0.33	1.07	0.98	0.18
75WH9	2.19	1.13	0.68	2.50	1.14	0.47
Median	1.42	1.24	0.25	1.10	1.06	0.16
Mean	1.49	1.15	0.30	1.27	1.18	0.22

Included in Ian Rowland's 1975 trials were different lupin varieties. The two released *Lupinus angustifolius* varieties used were the early flowering cultivar Unicrop and the late flowering cultivar Uniharvest. In all but one trial there were no differences between the following wheat crops sown on one or the other variety. The one exception was 75WH9 where wheat grown after Uniharvest out yielded wheat sown after Unicrop by 278 kg/ha. There was no difference in the yield of Uniharvest or Unicrop in the year prior – both yielded about 1.1 t/ha, indicating both varieties grew quite well. We can speculate that the late variety Uniharvest may have produced more biomass to produce the same yield as the early flowering variety Unicrop, and therefore Uniharvest may have had a lower harvest index and consequently left behind more dry matter and organic nitrogen which may have been of potential value to the following wheat crop. However, given this phenomenon occurred only once, and farmers will inevitably choose lupin varieties for other reasons such as yield, disease and herbicide tolerance, and ease of harvest this is probably an unprofitable line of research.

More than one wheat after lupin – comparisons of WWW /3, WLW /3 and LWW /3 rotations

Of the 86 LW trials conducted in WA, 17 included LWW /3 treatments (Figure 18) and only 8 have WLW /3 treatments (Figure 19) which allow a balanced comparison to WWW /3. On average, LWW /3 out yields WWW /3 by 510 kg/ha (515 kg/ha in the 8 trials where WLW /3 appears), and WLW /3 out yields WWW /3 by 942 kg/ha. Thus, growing a lupin crop every two years is superior to growing a lupin crop every third year.

What rate of fertiliser nitrogen is applied had no significant effect (P = 0.35) on the average size of the difference in yield between LWW /3 and WWW /3. However, what rate of fertiliser nitrogen is applied to wheat in the third year did change the frequency of responses. When no fertiliser nitrogen is applied to the wheat in the third year on no occasion did WWW /3 out yield LWW /3 (Figure 18). Adding up to 50 kg N/ha resulted in WWW /3 on occasion out yielding LWW /3, however, in most instances LWW /3 still out yielded WWW /3.

The sequence which included lupin more frequently consistently out yielded both WWW /3 and LWW /3 regardless of what rate of fertiliser nitrogen was applied to the third year of wheat (Figure 19).

Whilst we have demonstrated the differences between growing lupins every second or third year throughout WA at a range of fertiliser nitrogen rates there are not enough comparisons to consider regional or rainfall differences.

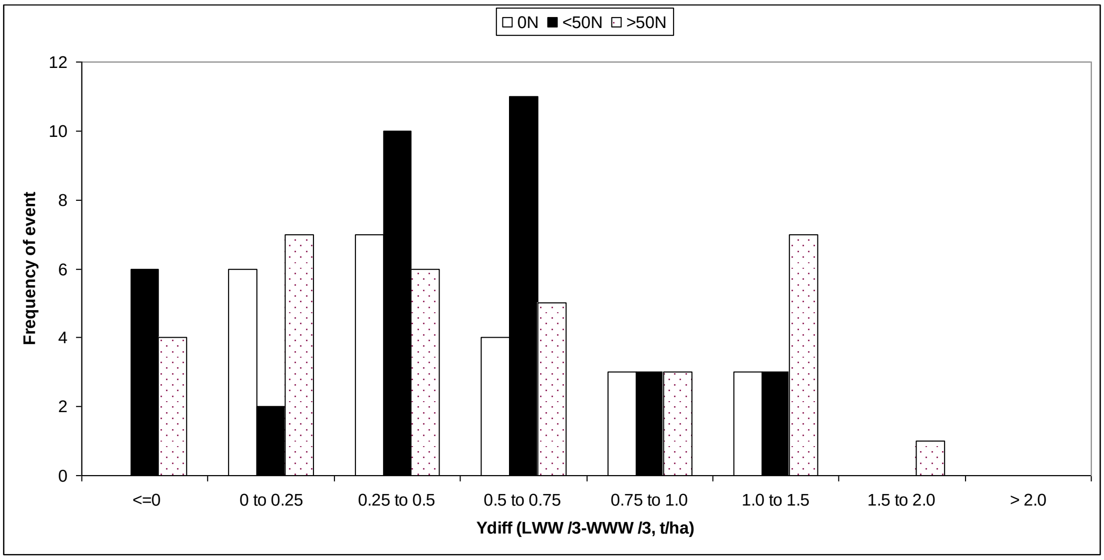

Figure 18 **Frequency of the response (Ydiff = LWW /3-WWW /3, t/ha) of two consecutive wheats following lupin (LWW /3) compared to wheat after wheat (WWW /3) in 29 trial x year combinations at a range of applied nitrogen (N groups in kg N/ha) in 17 experiments conducted throughout WA since 1982.**

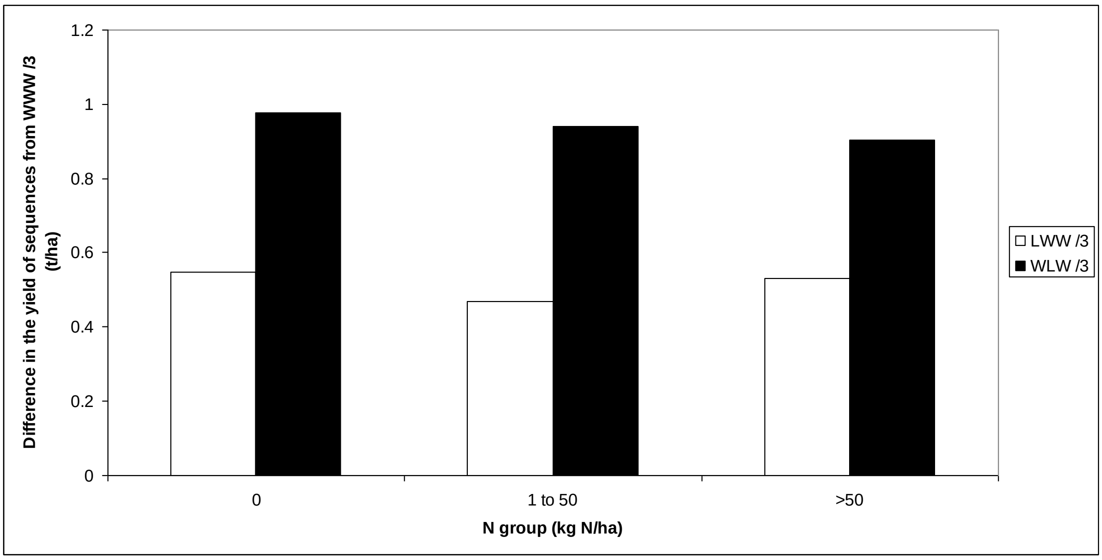

Figure 19 **Applied nitrogen has a minimal effect on the difference in the yield of a wheat crop sown in the third year of a crop sequence containing lupin (WLW /3 or LWW /3) compared to the yield of wheat after two wheats (WWW /3).**

LWWW sequence

There have only been two experiments which included LWWW /4 and WWWW /4 treatments which does not allow for generalizations to be made. The two trials were 83WH29 at Wongan Hills and 88E1 at Gibson. At Wongan Hills where no nitrogen was applied to the wheat LWWW /4 out-yielded WWWW /4 by 9% (120 kg/ha) whilst at Gibson with 102 kg N/ha applied LWWW /4 out-yielded WWWW /4 by 150% (1.8 t/ha). Therefore, no definitive conclusions can be made.

Table 6 Trial data from two experiments which included LWWW /4 and WWWW /4 treatments

Trial	Year	This years crop	Previous crop, 1 Year ago	Previous crop, 2 Years ago	Previous crop, 3 Years ago	kg N/ha	GY t/ha	% of WWWW /4
83WH29	1985	Wheat	Wheat	Pasture		0	2.2	164%
		Wheat	Wheat	Serradella		0	1.03	77%
		Wheat	Wheat	Fallow		0	1.33	99%
		Wheat	Wheat	Lupin		0	1.86	139%
		Wheat	Wheat	Erregulla Lupin		0	1.77	132%
		Wheat	Wheat	Wheat		0	1.53	114%
		Wheat	Wheat	Barley		0	1.76	131%
		Wheat	Wheat	Field pea		0	1.48	110%
		Wheat	Wheat	Wheat	Sub clover	0	1.59	119%
		Wheat	Wheat	Wheat	Serradella	0	1.32	99%
		Wheat	Wheat	Wheat	Fallow	0	1.03	77%
		Wheat	Wheat	Wheat	Field pea	0	1.12	84%
		Wheat	Wheat	Wheat	Wheat	0	1.34	100%
		Wheat	Wheat	Wheat	Barley	0	1.4	104%
		Wheat	Wheat	Wheat	Erregulla	0	1.49	111%
		Wheat	Wheat	Wheat	Lupin	0	1.46	109%
88E1	1991	Wheat	Canola	Lupin	Wheat	102	4	333%
		Wheat	Wheat	Lupin	Wheat	102	3.8	317%
		Wheat	Wheat	Wheat	Lupin	102	3	250%
		Wheat	Wheat	Wheat	Wheat	102	1.2	100%

LWWWW sequence

There have been two trials which included WWWWW /5 and LWWWW /5 comparisons, 85ME73 at Doodlakine and 87MT7 at Mt Barker. In both experiments there was no yield difference between the rotations.

Table 7 Trial data from two experiments which included LWWWW /5 and WWWWW /5 treatments

Trial	N group	Year	LWWWW /5	WWWWW /5	Grand Total
85ME73_74	0	1985	1.32	1.27	1.29
	25	1985	1.50	1.55	1.53
	50	1985	1.80	1.81	1.80
	75	1985	1.95	1.95	1.95
	100	1985	2.00	1.97	1.98
	150	1985	1.91	1.92	1.92
	Mean		1.75	1.75	1.75
87MT7	25	1989	1.62	1.59	1.60
Mean			1.74	1.73	1.73

Field pea

There have been 32 experiments conducted in WA comparing wheat after field pea (FpW /2) to wheat on wheat (WW /2). The majority of the experiments took place in low rainfall districts (16 in total, 8 at Merredin), whilst 13 trials have been conducted in medium rainfall districts (Newdegate 4 and Beverley 2) and only three in high rainfall areas (one each at Mt Barker, Northampton and West Katanning). There has been no response to field pea trial conducted in the major field pea growing region in WA – the medium rainfall mallee.

Wheat after field pea out yields wheat after wheat by an average of 453 kg/ha (S.E. = 88 kg/ha). In 89% of instances wheat after field pea performs equally as well to or out yields wheat on wheat (Figure 20 and Figure 21). Therefore, like wheat after lupin, wheat after field pea is occasionally no better than wheat after wheat.

However, unlike lupin-wheat rotations there were very few instances where wheat after field pea failed compared to wheat on wheat. In 1990 at Salmon Gums (68SG5) extremely poor spring rainfall (18mm in August and 13mm in September) resulted in low yields in general and all wheat crops grown with a high nitrogen status "haying off". Treatments with low nitrogen status such as the 27th continuos wheat crop or 3rd year wheat after medic yielded more than 400 kg/ha. Treatments with a higher nitrogen status such as wheat sown after medic or field peas or 52 kg N/ha applied to the 27th continuos wheat crop yielded 0.2 t/ha or less. At the opposite end of the spectrum, when wheat on wheat yields above 3.4 t/ha there were no instances where field peas provided a boost to following wheat crops. For example, in the trial 87NO84 at Konnongorring wheat responded positively to field pea in terms of both dry matter and grain yield at nitrogen rates below 30 kg N/ha in 1988, 1990 and 1992. However, at higher rates wheat on wheat on occasion produced more dry matter and grain than wheat after field pea. It is thought by one of the authors that carryover of high rates of imazethapyr (50 g a.i./ha) applied in the field pea year caused some minor root pruning to following wheat crops which may have limited late season dry matter production and yield (Ian Pritchard, pers comm.). Both cases highlight that changes in management (type or rate of herbicide, nitrogen rate or timing) can alter the probability of field pea maintaining a yield boost. Nevertheless, it would be interesting to have additional data from higher yield potential sites available so as to better define if yield boosts from field pea still occur as wheat on wheat yields approach 4 t/ha.

Although we have demonstrated a few instances where wheat after field pea is no better than wheat after wheat, there are instances where wheat on wheat yields poorly and sowing wheat after field pea can increase wheat yields dramatically. For example, the outlier evident in Figure 20 where wheat on wheat yields are less than 1.0 t/ha and wheat after field pea yields over 3 t/ha are from the same trial mentioned in the lupin section, 91KA111 where wheat on wheat performs poorly due to Take-all and field pea provides a similar break and yield response to lupin and canola.

The performance of crop sequences can also be looked at in terms of water use efficiency (WUE). Using the average site data, we fitted boundary lines to French and Schultz type charts for both WW /2 and FpW /2 sequences. Wheat after field pea had a similar intercept to WW /2 which is to be expected given the data came from the same sites, however the boundary or potential line for FpW /2 was 3 kg/ha/mm steeper than WW /2. It appears therefore that wheat after field pea has a greater water limited potential than wheat after wheat.

Most trials have been conducted in medium and low rainfall areas thus attempts were made to determine if responses to field pea differed between these two groups. REML analysis using the trial x year data set indicated there was no consistent difference between low and medium rainfall zones ($P>0.05$). As indicated earlier, only three trials have been conducted in high rainfall areas including the aforementioned trial at Katanning which showed very large increases in wheat after field pea, canola or lupin. Therefore, if we exclude trials from high rainfall areas the average response to field pea is decreased from 439 kg/ha to 397 kg/ha (SE = 72 kg/ha) which is not a significant decrease.

With one of the benefits of growing a legume crop such as field pea being symbiotically fixed nitrogen it is not surprising that if no fertiliser nitrogen was applied in the second year the response to field pea was greater than the average response. REML analysis was conducted on the data set where fertiliser nitrogen applied to the second-year wheat was grouped into 4 categories of 0N (no applied nitrogen), 25N (1-25 kg N/ha), 50N (26-50 kg N/ha) or 100N (more than 50 kg N/ha). Wheat after field pea with no applied nitrogen increased yield compared to WW /2 by 592 kg/ha (Figure 24). As the rate of applied nitrogen increased the magnitude of any yield increase due to field pea decreased (Figure 24) and the number of instances where FPW /2 out yielded WW /2 decreased (Figure 25). At rates of applied nitrogen greater than 50 kg N/ha the yield increase due to field pea was on average less than 212 kg/ha.

Unlike the lupin-wheat sequence there is not enough information from trials in similar locations over a reasonable length of time to consider if the response to field pea has changed over time.

We could determine no significant relationship ($P > 0.05$) between the yield of the previous year's field pea crop and the performance of the following wheat crop. We only had limited data for site x year combinations where field pea yields less than 0.75 t/ha (n=7) or more than 1.5 t/ha (n=7). Therefore, it is not surprising that the other categories tested of '0.75 to 1.0 t/ha' and '1.0 to 1.5 t/ha' which fall into the range of average field pea yields produce a similar range of possible wheat yields in the second year.

Overall field pea provides a consistent yield boost to following wheat crops. This is most likely a reflection of the relative ease with which an even weed free crop of field pea can be grown on most Western Australian soils, the subsequent reduction in soil pathogens such as fungal root diseases and nematodes that growing a weed free field pea crop provides, and the stability of its harvest index and subsequent contribution to soil nitrogen.

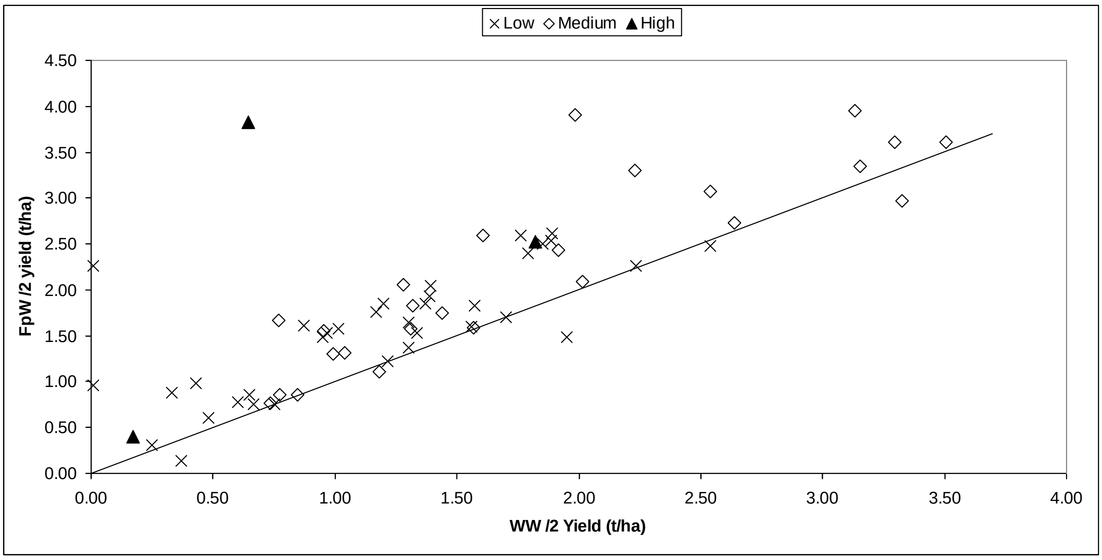

Figure 20 **Relationship between the yield of wheat on wheat (WW /2) and the yield of wheat sown before field pea (FpW /2) in 32 trials (63 trial x year combinations) in experiments conducted throughout WA since 1983. Linear curve shows the 1:1 line. Symbols show the rainfall zone in which individual trials were conducted.**

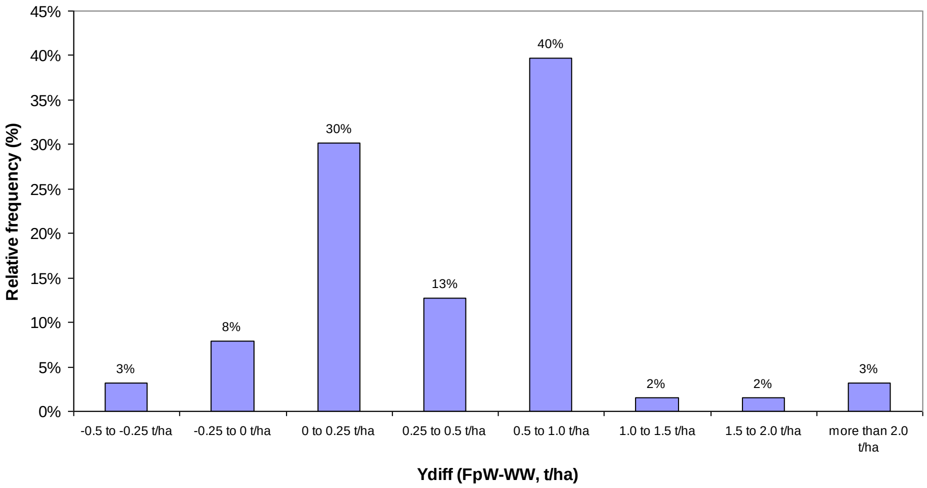

Figure 21 **Relative frequency (%) in which the difference in yield (Y diff, t/ha) between wheat following field pea (FpW /2) and wheat after wheat (WW /2) falls into 8 yield categories.**

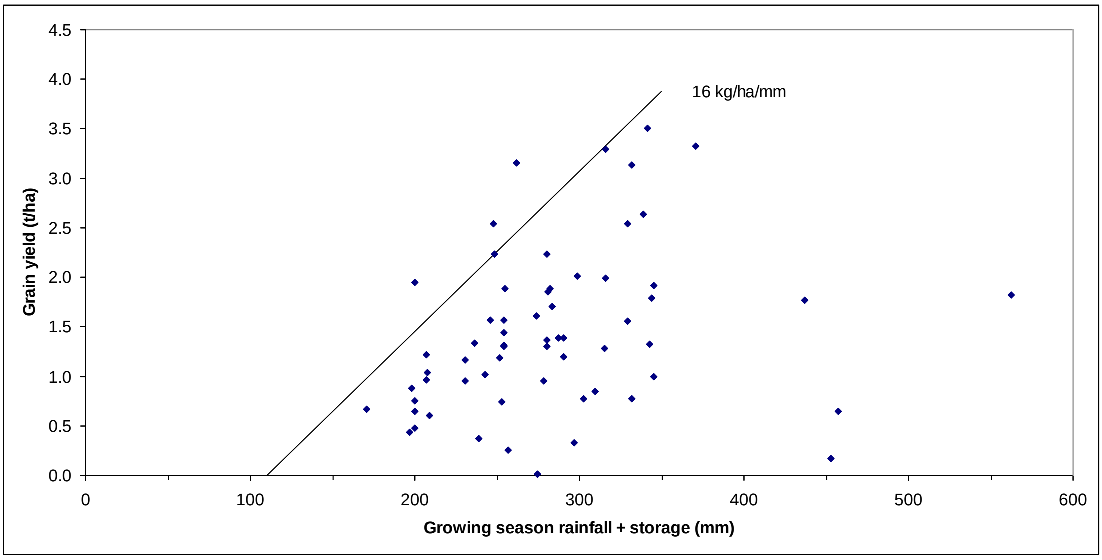

Figure 22 **Modified French and Schultz for wheat after wheat (WW /2) for Western Australia experiments comparing WW to field pea-wheat (FpW /2) sequences. GY (kg/ha) = 16 x (GSR+store – 110).**

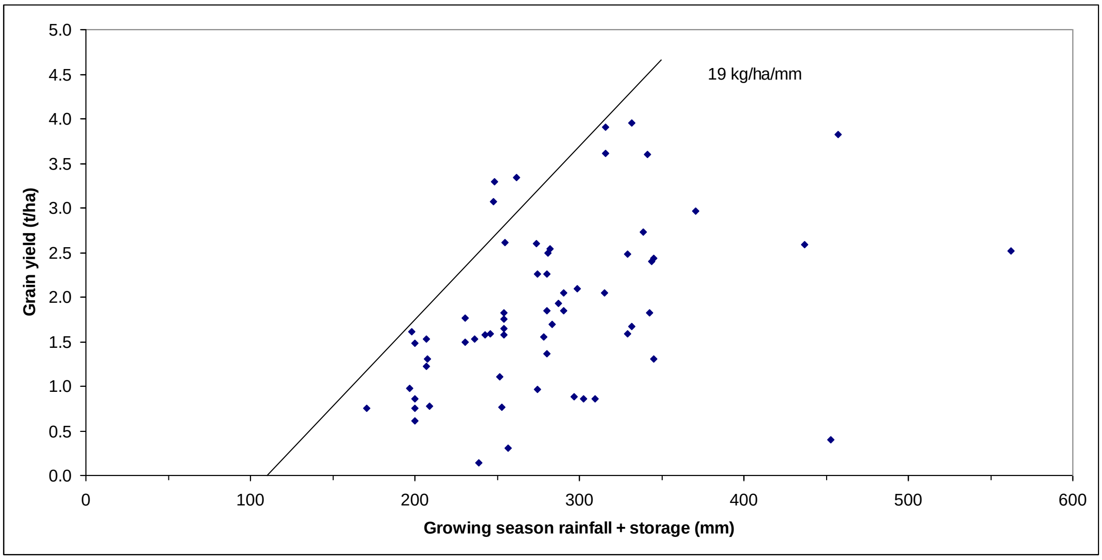

Figure 23 **Modified French and Schultz for wheat after field pea (FpW /2) for Western Australia experiments comparing WW to field pea-wheat (FpW /2) sequences. GY (kg/ha) = 19 x (GSR+store – 110).**

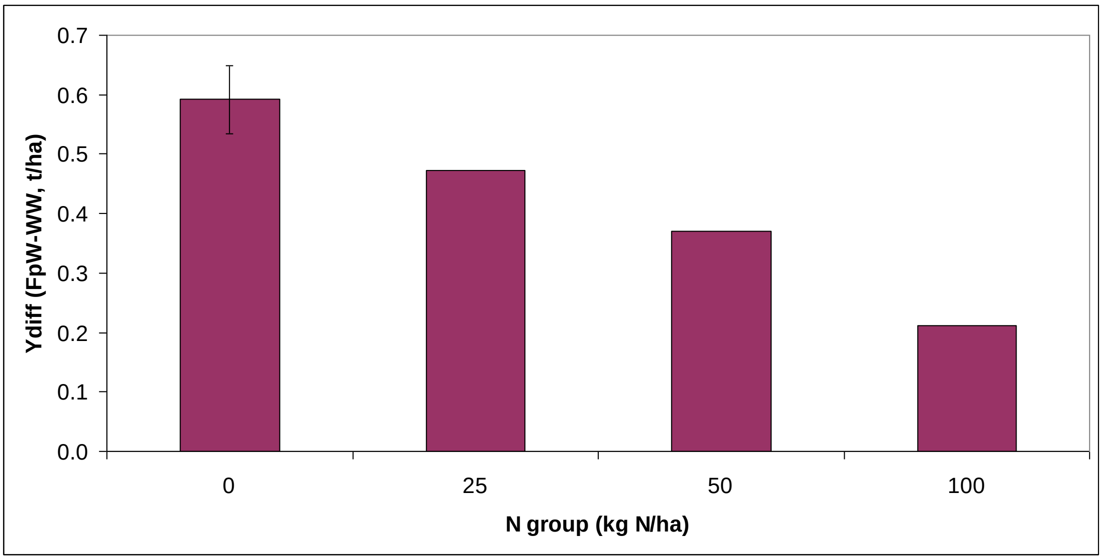

Figure 24 **Average response to nitrogen of wheat following field pea compared to wheat after wheat in 32 trials in experiments conducted throughout WA since 1983. P (reml) < 0.001. Bar indicates ls.d. (*P* = 0.05).**

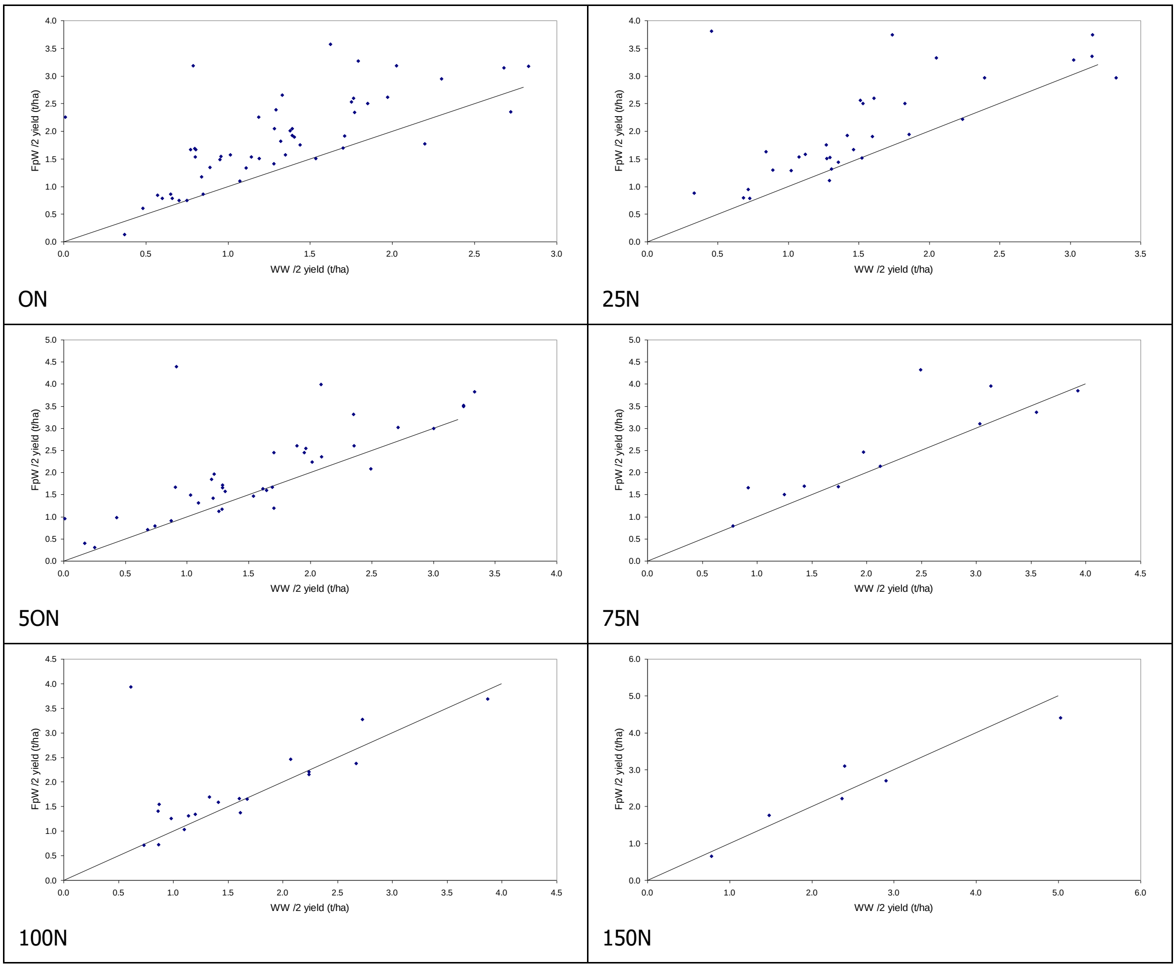

Figure 25 **Relationship between the yield of wheat on wheat (WW /2) and the yield of wheat sown before field pea (FpW /2) at six different rates/groups of applied nitrogen. Linear curves indicate the 1:1 line.**

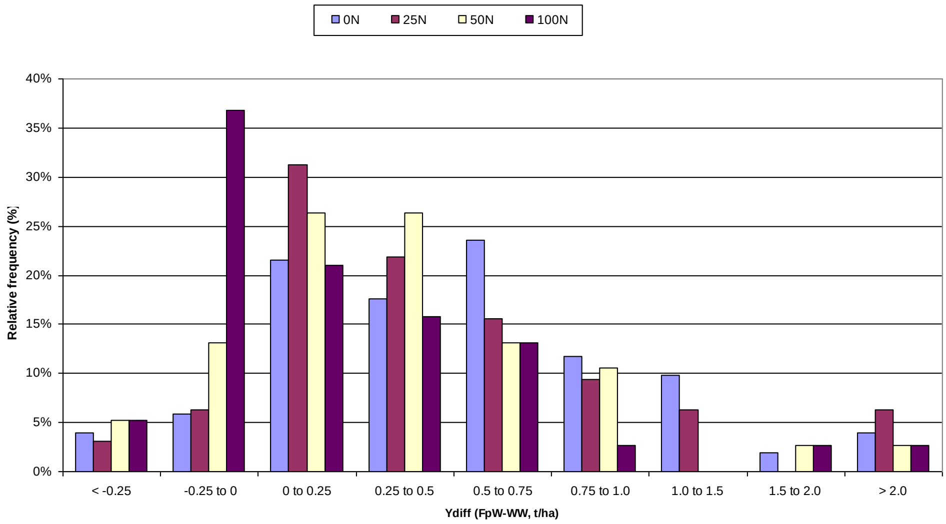

Figure 26 **Histogram of the response of wheat following field pea compared to wheat after wheat in 32 trials (162 trial x year x nitrogen combinations) in experiments conducted throughout WA since 1983.**

More than one wheat after field pea

The second wheat crop after field pea (FpWW /3) have only been compared to the yield of the third year of a wheat-wheat-wheat sequence (WWW /3) in 6 trials in WA. On average FpWW /3 out-yielded WWW /3 by 178 kg/ha (se = 113).

Out of the six experiments only three had fertiliser nitrogen applied to the wheat crop in the third year. For these experiments 87KA49, 87N25 and 87NO84 we grouped the rate of fertiliser nitrogen into 0, 1-25 (25N), 26-50 (50N) and more than 50 kg N/ha (100N). Responses of the third year of wheat to fertiliser nitrogen in both sequences varied from year to year for each trial, as did the differential effect. Therefore, for these experiments we found fertiliser nitrogen on average did not change the size of the difference in yield between FpWW /3 and WWW /3 ($P > 0.05$).

There has only been one experiment which included three years of wheat after both field pea and wheat. This was a trial at Wongan Hills, 83WH29 where FpWWW /4 yielded 1.12 t/ha and WWWW /4 1.34 t/ha.

Canola

Averaged across all 16 trials, years and nitrogen rates, wheat after canola (NW /2) out-yields wheat on wheat (WW /2) by 411 kg/ha (Figure 27, se = 201 kg/ha, n = 19). In 48% of instances yield increases were less than 250 kg/ha and in 16% of instances yield after canola is lower than wheat on wheat (Figure 28). Improvements in water use are small with NW /2 averaging 10.5 kg/ha/mm and WW /2 averaging 8.7 kg/ha/mm, a difference of only 1.9 kg/ha/mm.

Whilst there appear to be a relatively large number of instances where canola provides little or no benefit to following wheat it is apparent that in some situations canola can provide larger increases in the yield of following wheat (Figure 27). In particular at southern regions sites such as Esperance, Mt Barker and Katanning yield increases following canola can on occasion be more than 700 kg/ha. In these regions root diseases such as take-all are more prevalent and subsequently control of grasses which harbour the diseases can lead to dramatic yield improvements. This can be achieved in a wide range of break crops including lupin, field pea and canola. However, canola often finds favour with growers in such situations due the profitability of the canola in its own right in these regions and the wider adaptation of canola to a wide range of soil types.

It is also worthwhile to consider in more detail the trials in which NW /2 is lower than WW /2. There are 3 trials out of the 16 where Ydiff is equal to or less than zero. The trial x year combinations where this occur are:

- 93WH6 at Wongan Hills in 1995 in which WW /2 yielded 2.8 t/ha and NW /2 averaged 2.0 t/ha (LNW /3 was 1.9 and WNW /3 was 2.2 t/ha) when all treatments received 60 kg N/ha. In the same experiment LW /2 with no fertiliser nitrogen applied also averaged 2.0 t/ha (NLW /3 2.2 and WLW /3 1.8 t/ha). Thus, it appeared there was no limiting factor for WW /2 and indeed WWW /3 at this site.
- 96MW40 at Mullewa in 1997 where WW /2 yielded 2.6 t/ha, NW /2 2.4 t/ha, wheat after chickpea 2.6 t/ha and wheat after vetch 2.7 t/ha. Thus, it appeared there was no limiting factor for WW /2.
- 85C27 at Chapman Valley in 1985 where WW /2 yielded 1.6 t/ha, NW /2 1.5 t/ha, LW /2 1.4 t/ha, wheat after barley 1.6 t/ha, wheat after oats 1.4 t/ha, and wheat after medic 1.4 t/ha. At this site the authors comment that wheat after lupin and canola was more rapid in the early growth stages which led to them running out of water late in the season whilst wheat growing on slower growing plots were able to continue longer and consequently there was very little difference between the treatments at harvest.

Of interest is that the three trials where canola after wheat does not out-yield wheat following wheat are all from the northern agricultural region and that alternative break crops such as lupin are no better in these experiments. There is only one other trial x year combination from the northern region and that is 96MW40 at Mullewa in 1998 where NW /2 on average out yields WW /2 by 0.33 t/ha which is similar to the yield increase provided by chickpea or vetch at the site in 1998.

It is possible the poor break crop effect of canola demonstrated in the northern region could be the result of trying to grow varieties of canola that were not adapted to the region. Varieties are now available that are earlier flowering and in yield terms at least show better adaptation to low rainfall environments (e.g. Tanami). If these varieties also use water earlier in the season to produce their yield and then mature slightly earlier it is possible they may leave stored water for following crops. If the over use of water in spring by ill-adapted varieties used in the previous studies is the primary reason for the observed poor break crop effect (as suggested for 85C27) perhaps growing adapted varieties will improve the break crop effect. It is also the availability of early flowering lines that is driving the expansion of canola into northern regions and low rainfall regions of southern WA.

It may also be the case that in northern regions there are situations where there is no build up of damaging diseases as found in southern regions and therefore provided weeds can be controlled in the wheat following wheat sequences a break crop which provides no net nitrogen is not required. Additionally, in some instances it may simply be the fact that in northern regions there is insufficient available water at critical times to allow wheat following break crops to express any break crop effect. Whatever is the reason, there appears to be some scope for increasing the data set for comparisons between wheat after wheat vs. wheat after break crop sequences in northern regions to determine if the frequency of small or negative effects currently demonstrated is real or artefacts of a limited data set?

In previous chapters we have demonstrated the improvement in the response of wheat following the break crops lupin or field pea since 1990 and the adoption of no-till and increased use of grass herbicides. However, there is insufficient data available prior to 1990 (3 trials) to do such an analysis for canola.

Similarly, for such a widely grown crop as canola and such a common rotation of wheat after canola there is a remarkable lack of data available for the response of wheat after canola compared to wheat after wheat at a wide range of fertiliser nitrogen rates. From the data available it is evident that a wide range of responses are possible at a wide range of nitrogen rates from yield reductions up to yield increases of more than 2 t/ha (Figure 29). However, the majority of responses of wheat after canola compared to wheat after wheat are less than 250 kg/ha regardless of what rate of nitrogen is applied. Overall though, fertiliser nitrogen does not have a significant effect on Ydiff ($P > 0.05$).

Whilst a wide range of possible responses to nitrogen are possible it is evident that wheat after canola uses nitrogen more efficiently than wheat after wheat (Figure 30). Overall the nitrogen efficiency ratio of NW /2 is 83 kg/ha/kgN compared to 45 kg/ha/kgN for WW /2, with the nitrogen efficiency of both crop sequences and the difference between them becoming smaller as the rate of fertiliser nitrogen is increased.

We have previously demonstrated a wide range of possible responses for the first wheat crop following canola compared to wheat on wheat. Similarly, the limited number of experiments comparing the second wheat after canola to third year wheat shows variable responses. Canola followed by two wheats (NWW /3) compared to 3 wheats (WWW /3) has only been looked at in two trials - 79E12 at Gibson and 96MW40 at Mullewa. At Gibson NWW /3 out yielded WWW /3 by 1.04 t/ha (36%) whilst at Mullewa NWW /3 was 7% lower yielding, losing 150 kg/ha. Therefore, the main finding would be we need more information prior to concluding what the response of the second wheat after canola will be in WA

We have shown previously that the largest responses to canola occur in high rainfall southern sites. However, in recent years canola is being grown more widely in Western Australia including the central and northern wheatbelt and in low rainfall areas in the south. The results available in the database include only one trial for the low rainfall southern region (Grass Patch) and one trial each of the low, medium and high rainfall northern regions. As indicated earlier the northern regions trial results are not particularly encouraging with wheat after canola most commonly being no better or indeed lower yielding than wheat after wheat (Table 8). These results have wide ranging implications for the role of canola in the northern region wherein growers must consider canola only as a cash crop and decisions about growing canola should possibly ignore any break crop effect or indeed add in a negative break crop effect when deciding to grow canola at the expense of another wheat paddock.

Therefore, there seems to be enormous scope to conduct sequence experiments which include canola-wheat treatments in the regions of WA where canola varieties such as Tanami are being promoted and it would be worthwhile to include the canola-quality juncea lines in these experiments if they go ahead.

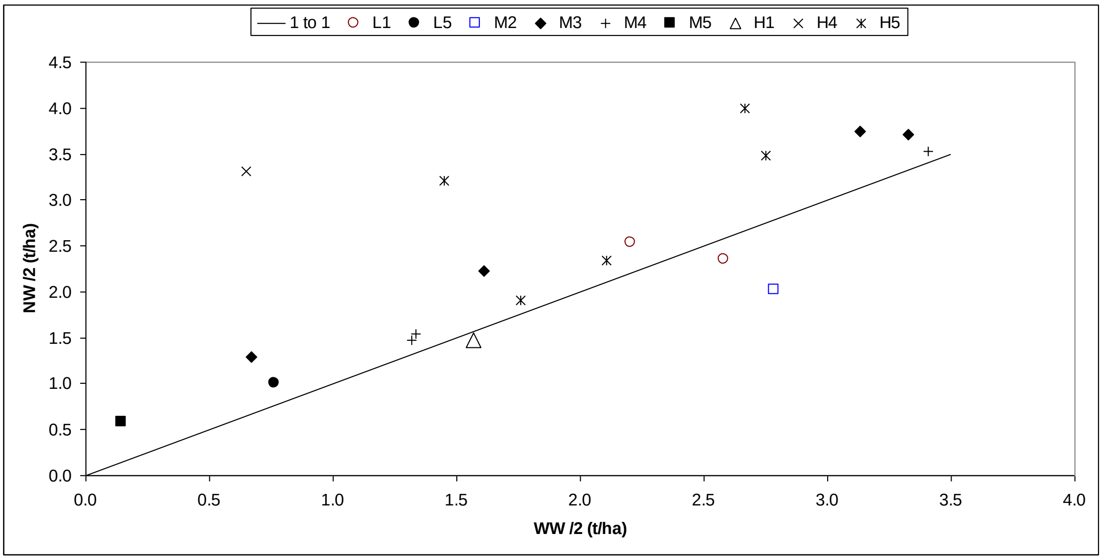

Figure 27 **Relationship between the yield of wheat on wheat (WW /2) and wheat on canola (NW /2) across 16 trials in WA. Symbols indicate the CVT zones throughout WA in which individual trials were conducted.**

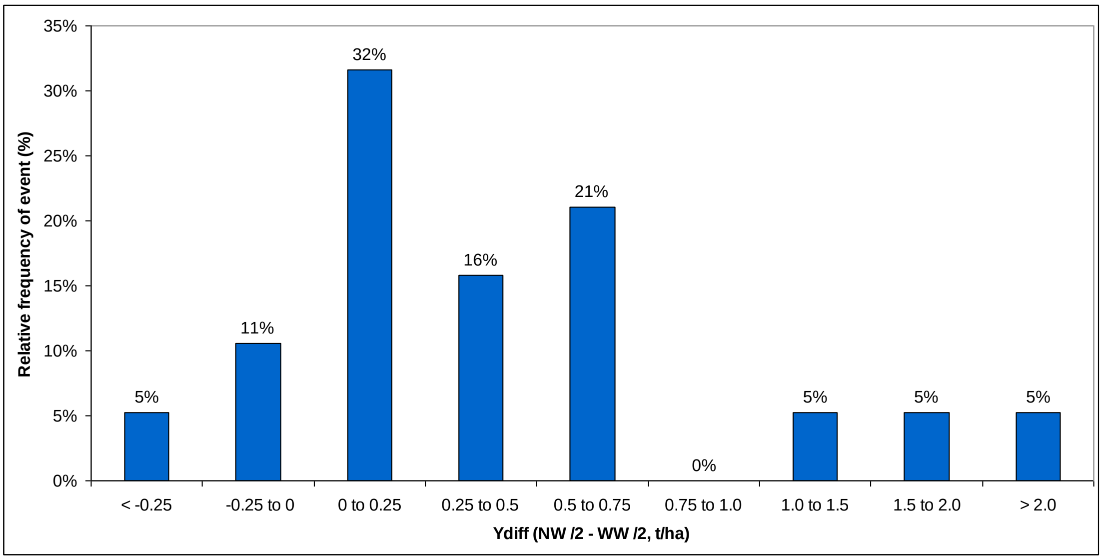

Figure 28 **Relative frequency in which the difference in yield between wheat following canola and wheat after wheat (Y diff) falls into 9 yield categories.**

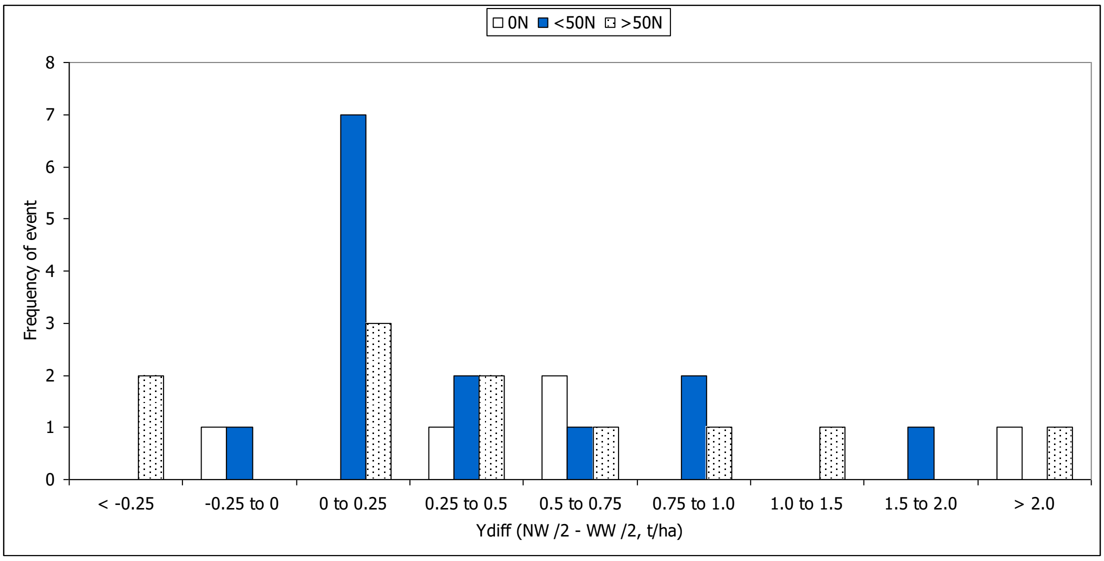

Figure 29 **Frequency in which the difference in yield between wheat following canola and wheat after wheat (Y diff) falls into 9 yield categories when events are grouped by rate of applied nitrogen to second year wheat.**

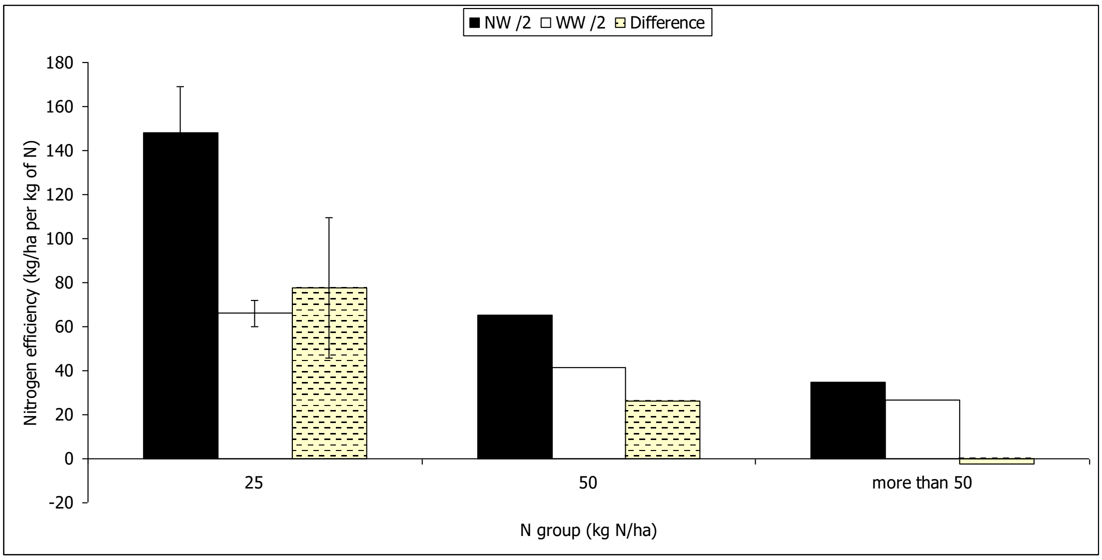

Figure 30 **Nitrogen efficiency of wheat after canola compared to wheat following wheat.**

Table 8 **Yield difference (t/ha) between canola-wheat and wheat-wheat sequences in northern regions of WA**

Rainfall zone	Trial	N group	Year 1985	1995	1997	1998
L	96MW40	50			-0.22	
		75				0.33
M	93WH6	75		-0.76		
H	85C27	0	0.00			
		25	0.01			
		50	0.01			
		100	-0.52			

Oats

Oats have appeared as a break crop in 21 trials, of which only 10 trials have included wheat-wheat comparisons – which does limit generalised comments. Averaged across those 11 trials, years and nitrogen rates, wheat after oats (OW /2) out-yields wheat on wheat (WW /2) by 353 kg/ha (se = 139 kg/ha). Biggest responses occur when WW /2 yields are low. In the majority of instances this is once again due to Take-all. For example, in 76E6 at Gibson, Take-all was at a level such that wheat on wheat was very poor (0.6 t/ha) and all break treatments were much higher yielding with OW /2 yielding 1.8 t/ha and wheat after lupin yielding 2.2 t/ha. Similarly, at Darkan (80NA6) wheat on wheat yielded quite poorly in the first few years of the experiment (0.4-0.6 t/ha) and the authors report take-all was high in this paddock. If these two trials are excluded wheat on oats averages 58 kg/ha (se = 78 kg/ha) more than wheat on wheat. i.e. in the absence of take-all oats is the same as growing wheat in the previous year.

In addition to the average yield response to oats being small if take-all is absent at the site is the noticeable number of events when growing oats in the previous year led to lower yields in the following wheat (Figure 32). Whilst this is a small data set, wheat after oats produces no increase compared to wheat after wheat in 38% of occasions. Therefore, unless growers know their paddock levels of Take-all are likely to damage wheat, growing oats may well be of little benefit.

Only two trials have rates of fertiliser nitrogen applied to the second-year wheat with quite contrasting results. These were 80NA6 in 1981, 1982 and 1983 and 85C27 in 1985. Averaged over the three years at Darkan (80NA6) applying nitrogen fertiliser to the second-year wheat after oats increased the yield difference. i.e. wheat after oats continued to respond to nitrogen fertiliser more than wheat after wheat. Once again take-all may have limited wheat after wheat's ability to respond to nitrogen fertiliser at this site. Whilst at Chapman Valley (85C27) WW /2 remained higher yielding than OW /2 at most rates of nitrogen, and applying nitrogen fertiliser had a variable effect (Figure 33).

There is only one trial which reports on oat-wheat-wheat (OWW /3) compared to WWW /3 – 79E12 at Gibson which indicated a 0.43 t/ha (29 %) yield increase for OWW /3 compared to WWW /3.

With the expansion of oats for grain and oaten hay production a case could be made for looking more widely at the response to oat crops and indeed the response of oats to different break crops as the picture is not clear from the data available in this database.

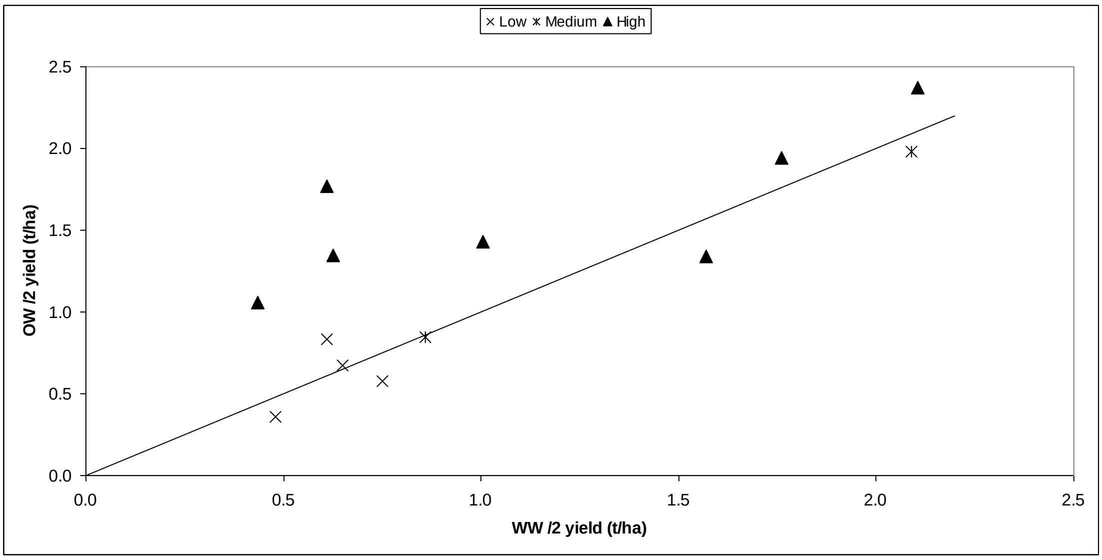

Figure 31 **Relationship between the yield of wheat after wheat (WW /2) and wheat after oats (OW /2) in WA. Symbols refer to low, medium or high rainfall zones where trials were conducted.**

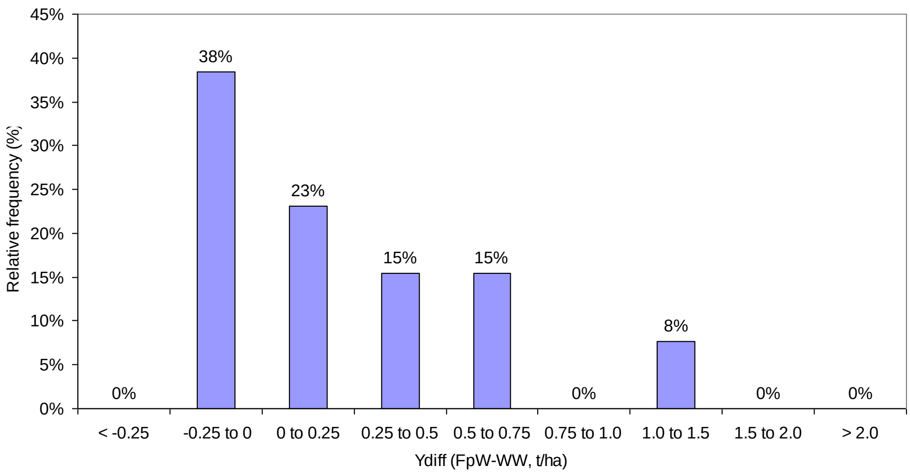

Figure 32 **Frequency in which the difference in yield between wheat following oats and wheat after wheat (Y diff) falls into 9 yield categories**

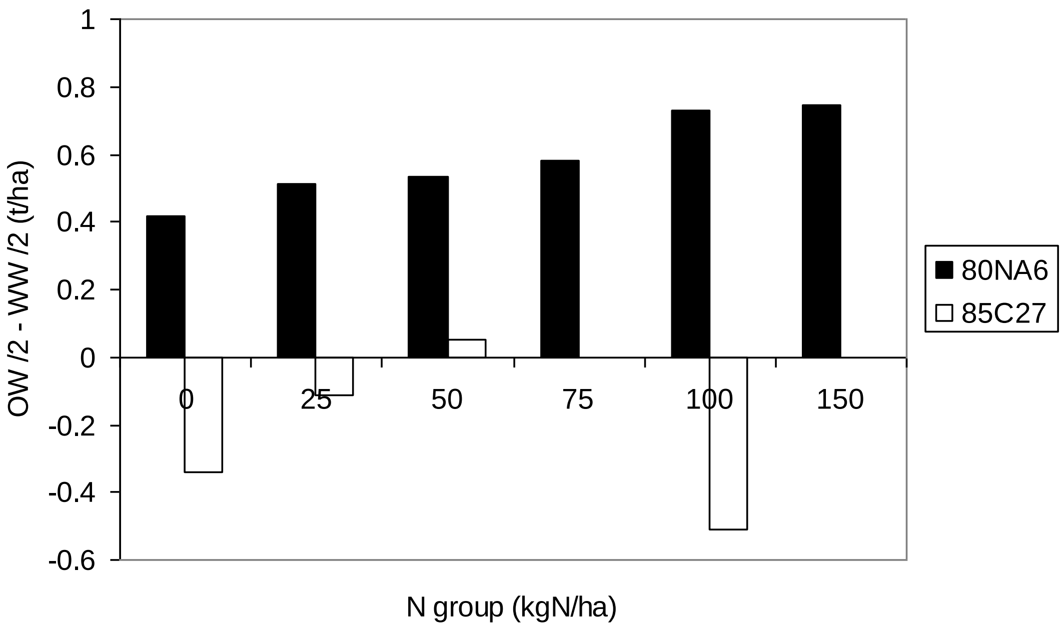

Figure 33 Response to nitrogen of wheat following wheat following oats compared to wheat after wheat (Y diff) in two experiments.

Comparing lupin, field pea and canola as break crops

Three experiments have compared LW /2, FpW /2, NW /2 and WW /2 in the same year (
Table 9). These are 93EB_gregory at East Beverley annex in 1993 and 1994, 92NO89 at Northam in 1992 and 91KA111 at West Katanning in 1992. Whilst this is a surprisingly low number of comparisons over 30 years of trials it is probably a reflection of researchers picking sites with soil types suited to either lupin or field pea and the low total number of canola trials.

As previously mentioned 91KA111 had high levels of Take-all and all break crops provided a very good break from the disease and subsequent large yield boost compared to WW /2. Of the three trials which had all three break crops 92NO89 provided the lowest break crop effect, with only canola providing a yield boost. The authors attribute the "unexpected significant yield advantage of wheat following canola may be explained by a surplus of nitrogen available to the crop following lupins and peas creating a large biomass which could not be supported due to the sudden seasonal finish and two weeks of hot temperatures in October. The canola is expected to have used nitrogen in the previous year creating a potential yield lower than after a grain legume but more achievable in 1992".

At the third site, 93EB_gregory at East Beverley annex, all three break crops provided a yield boost, with canola providing consistently less of a boost to wheat yield than either field pea or lupin.

Thus, the three trials provide three different responses – all boost yields a great deal; in a dry spring only, canola provides a boost; and both legume break crops outperform canola. Therefore, we have scant information to directly answer the question "I have had a run of cereal years and think I need a break crop. I can grow canola, lupin or field pea, which one will give me the biggest yield boost to my wheat crop?" Whilst it is true there is a lack of data which directly answers such a question there is sufficient experience and knowledge to talk individual growers through such a question with respect to their soil types, experience with each of the break crops, previous history, expected yields, likely disease status, known weed status etc. to help them make an informed decision.

Whilst direct comparisons between break crop options in the same paddock and the same year are limited we can make some comments on the magnitude and likelihood of achieving a break crop response with a given break crop. Lupin appears to be the species which provides both the largest average boost to following wheat and the most likely crop to provide some yield boost in most instances (Figure 34). Canola and oats are the species most likely to give no or a negative response. For canola there are over 20% of instances where the effect on the following wheat compared to wheat after wheat are less than or equal to zero. For Oats it is even higher, with over 40% of instances wheat after oats being no better than wheat on wheat. For both canola and oats, it appears a reliable break crop effect is most likely to occur if and when root diseases are affecting wheat on wheat. Even in these instances leguminous break crops can usually provide a similar disease break. Currently weed control is more readily achieved in canola crops therefore it is in high weed burden situations and in areas where canola is a reliable cash crop in its own right that canola will be chosen in preference to a legume crop such as lupin. It is hard to determine any possible situation where oats as a grain crop would be the first-choice break crop as the disease break is superior from canola and the legume break crops, and control of grass weeds in oats is problematic at best.

Consideration was given to as to why on average lupin provides a greater benefit than field pea? Lupin on average provides a yield boost compared to WW /2 of 0.60 t/ha and field pea 0.45 t/ha. One thought was that the lupin trials were located in more favourable locations than the field pea trials. Similarly, lupin trials appeared in a greater number of years, some of which may have been more favourable for a yield boost following a break crop. To see if either of these were true we limited the lupin data set to only include the years x zones where field pea trials appeared. We found that this actually increased the average response to lupin to 0.67 t/ha. Given this we suggest that soil type differences may play a role in the difference between field pea and lupin within the same zones. The sandy soil types on which lupins are invariably grown are more naturally infertile than the soils suited to field pea production. In addition, the sandy soils are known to harbour root diseases at higher levels, or the effects of diseases are more damaging than heavier soil types. These factors along with the possibility of other unknown factors add up to a slightly better response to lupin rather than field pea, within the same zones and years. We also note here that one of the main benefits in growing field pea is the early maturity of the crop which provides for timely crop topping to reduce weed seed set, which is seen by growers as a very useful management tool. As far as we can ascertain in no trial where field pea has been grown in the year prior to wheat has crop topping occurred. This one of the more useful benefits of growing field pea has not been used in trials to date.

Table 9 **Results of experiments comparing canola-wheat (NW /2), field pea-wheat (FpW /2), and lupin-wheat (LW /2) to wheat-wheat (WW /2) rotations in WA.**

				GY t/ha				Ydiff			% of WW /2		
trial	Location	Year	N	NW /2	FpW /2	LW /2	WW /2	NW /2	FpW /2	LW /2	NW /2	FpW /2	LW /2
91KA111	West Katanning	1992	0	2.94	3.19	3.56	0.79	2.15	2.40	2.77	373%	405%	452%
91KA111	West Katanning	1992	10	2.74	3.56	3.76	0.53	2.22	3.03	3.24	522%	677%	716%
91KA111	West Katanning	1992	80	4.22	3.93	4.61	0.61	3.60	3.32	4.00	688%	641%	753%
91KA111	West Katanning	1992	20	3.06	4.06	4.11	0.39	2.67	3.67	3.72	794%	1054%	1067%
91KA111	West Katanning	1992	40	3.59	4.39	4.63	0.92	2.67	3.48	3.71	392%	480%	506%
92NO89	Northam	1992	24	3.71	2.97	2.83	3.33	0.39	-0.36	-0.50	112%	89%	85%
93EB_gregory	Beverley	1993	60	3.74	3.96	4.58	3.13	0.61	0.83	1.45	120%	126%	146%
93EB_gregory	Beverley	1994	20	2.23	2.60	3.71	1.61	0.62	0.99	2.10	138%	162%	231%

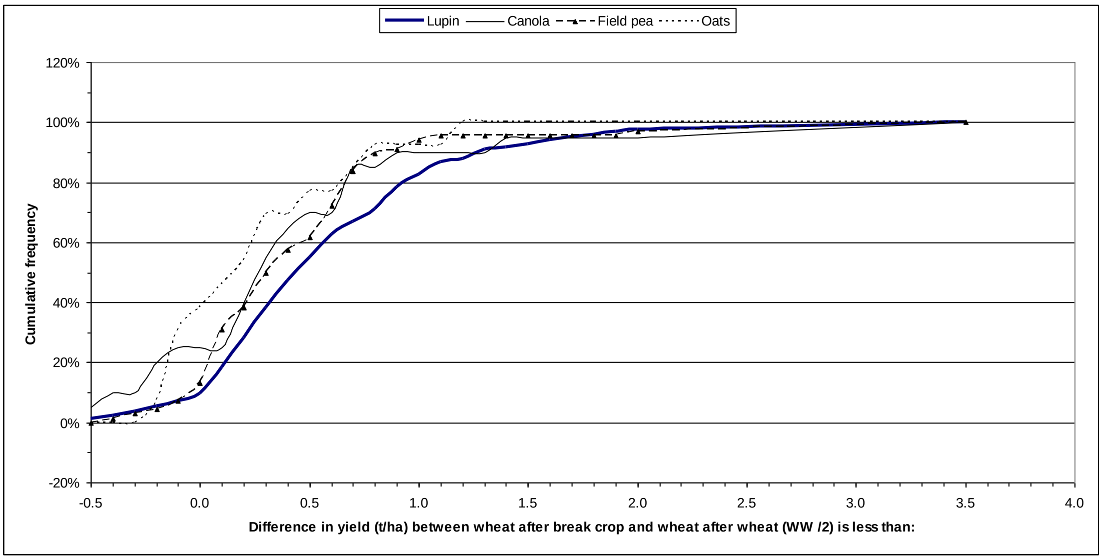

Figure 34 **Cumulative frequency (%) of the yield difference (t/ha) between wheat after four break crops (lupin, field pea, canola and oats) and wheat after wheat (WW /2) being less than:**

Other breaks – chickpea, faba bean, vetch, mustard and fallow

Minor crops such as chickpea, faba bean, vetch and mustard have only been included in a few rotation experiments in WA (Table 10). The average response to chickpea has been a yield increase compared to WW /2 of 200 kg/ha, making it on average one of the poorest break crops studied. This might be expected as chickpeas are renowned for hosting root lesion nematodes and compared to other legume species have been known to fix low amounts of nitrogen.

Faba bean as a break crop has only been tested in three trials. On average faba bean provides an average yield increase similar to chickpea of 200 kg/ha. This is in contrast to grower comments whereby wheat after faba bean is considered to be as good as it gets in areas where faba beans are well suited such as the Dongara area in the north of the state, Scaddan in the south east and Borden in the south west.

Similar comments could be made for vetch, where the bulk of the crop is grown in the Esperance region but no rotation trials have been conducted there which include vetch. On average, vetch increases wheat yield compared to WW /2 by 400 kg/ha. Trials in the north of the state at Balla and Northampton are included in this average, but the yields are very low with WW /2 yielding less than 300 kg/ha. If these trials are excluded, leaving us with only three trials to assess, the average increase due to vetch becomes 500 kg/ha. This probably serves only to illustrate the lack of information we have on response to vetch, chickpea and faba bean.

Indian mustard has only been tested in one trial at Beverley in 1993 and 1994 (Gregory 1998) where it maintained a 800 kg/ha yield improvement over WW /2 at both nitrogen rates (20 and 60 kg N/ha). With the interest in WA of both canola quality mustards and biodiesel quality mustards this promising result is obviously worth pursuing.

Finally, fallow has on occasions been included in trials which included other break crops and WW /2. On average fallow provides a yield increase over WW /2 of 300 kg/ha (Table 11). However, it is evident that the yield improvement does depend on which rainfall zone the trials are located in. Response to fallow is highest in high rainfall areas, increasing to a 600 kg/ha yield boost over WW /2. Interestingly in low rainfall areas where fallow is discussed most often as having a role to play the average yield boost is only 100 kg/ha, and as can be seen from the data widely varying results have occurred from a 0.72 t/ha boost at Merredin in 1977 to a 0.58 t/ha loss in 1985.

If we compare fallow to other break crops it rarely gives a yield boost equal to that available from lupin (Table 11). Wheat following lupin (LW /2) out yields wheat after fallow (FaW /2) in 100% of comparisons and by an average of 440 kg/ha. Whilst field pea followed by wheat (FpW /2) out yields FaW /2 by an average of only 80 kg/ha, it outperforms fallow/wheat (FaW) in 5 out of 7 instances. In this series of experiments pasture and barley provide little or no yield boost to following wheat in most of the experiments and fallow was found to perform similarly. Therefore, it appears if farmers can grow profitable and weed free lupins in particular, and to a lesser extent field pea, they have little to gain by considering fallow as an option. Indeed, given the only certainty with fallow is that there will be no income in the year a paddock is fallowed and the uncertainty in which it provides a yield boost compared to other options, fallow may only be a viable choice if the seasonal outlook strongly indicates growers will lose money if they sow a wheat crop. In other words, fallow may be best thought of as a tactical tool rather than systematic plan.

Table 10. Summary of the trials which included wheat after minor break crops (chickpea, faba bean, vetch and mustard) compared to wheat on wheat in WA.

	Chickpea	Faba bean	Mustard	Vetch
Ydiff (t/ha)				
Mean	0.2	0.2	0.8	0.4
S.E.	0.1	0.2	0.0	0.2
Min	-0.4	-0.1	0.8	0.04
Max	1.1	0.5	0.8	1.0
GY of wheat after break crop (t/ha)				
Mean	1.9	2.1	3.2	1.8
S.E.	0.3	0.2	0.8	2.6
Min	0.6	1.7	2.4	0.3
Max	4.2	2.4	3.9	3.3
n	13	3	2	5

Table 11. Summary of the trials which included wheat following fallow and a range of other crops compared to wheat on wheat in WA.

Trial	Location	Year	Ydiff (t/ha) of the following break crops Barley	Fallow	Field pea	Lupin	Oats	Pasture	Vetch	Wheat t/ha	Rank of Fallow
76A7	Avondale	1977		-0.16		-0.38	-0.01	-0.42		0.86	3
76E6	Gibson	1977		1.50		1.61	1.16	0.71		0.61	3
76M47	Merredin	1977		0.72			0.22	0.38		0.61	1
76N5	Newdegate	1977		0.33			-0.11	0.29		2.09	1
82C24a	Balla	1983		-0.08	0.06	0.37		0	0.04	0.25	6
82C24b	Northampton	1983		-0.01	0.23	0.28		0.08	0.22	0.17	6
83WH29	Wongan Hills	1984	0.16	-0.29	0.10	0.35		0.46		2.64	6
84M6	Merredin	1985	-0.99	-0.58	-0.42	1.13				2.20	4
84MT6	Mt Barker	1986		0.58	0.70	0.85				1.82	3
86Mull?	North Mullewa	1986		0.15	0			-0.15		1.70	1
88SC27	South Carrabin	1989		0.20						0.56	1
93EB_gregory	Beverley	1993	-0.31	1.17	0.83	1.45			0.12	3.13	2
Mean of species			-0.38	0.29	0.21	0.71	0.32	0.17	0.13	1.39	3
Fallow mean, for similar trials			-0.43		0.13	0.27	0.60	0.27	0.36		
Difference between fallow and species			-0.05		-0.08	-0.44	0.28	0.10	0.23		
Average Ydiff of species by rainfall zone											
L			-1.0	0.1	-0.1	0.8	0.2	0.1	0.0	1.1	
M			-0.1	0.4	0.5	0.9	-0.1	0.4	0.1	2.6	
H			*	0.6	0.7	0.7	0.6	0.1	*	1.1	

Some comments on break crop trial data

It is evident from the summary of trials conducted in WA comparing a range of potential break crops and continuos cereal that there is a lack of data for many crop sequences. For example, for many potential break crops there is no data for the performance of the second crop of wheat compared to three years continuos wheat (WWW /3). Interestingly computer models such as MIDAS do have such crop sequences as possible options. The performance of such sequences in models is then based on input from experienced agronomists or regional advisors. In the absence of data this is a fair and reasonable way to provide 'data' for the model. But if rotations such as canola-wheat-wheat are chosen by models on a regular basis as the optimum rotation it may be prudent to test the models assumptions in experiments or validate it with balanced grower data.

The fact that in previous work sequences longer then two wheat crops after a break crop have not been studied may well indicate that this information is not required or requires a great deal of commitment which research organisations and funding bodies are not prepared to meet. A case could be made that on-farm decisions are made either annually or at best with thought given for the next two or three seasons. If this is the case then one of the more efficient experimental methods is the cross plot design, otherwise known as the dynamic crop sequence trial (Tanaka *et al.* 2002). DAFWA have set up at least two of these experiments in recent years and they should provide in a short time frame some of the missing information from Table 12.

If, however, longer sequence information is required by industry then an alternative to setting up long term rotation experiments may be to collate from a very large number of farmers their individual paddock records. With suitable interrogation, trends in the performance of long crop sequences throughout WA could be attained. This is not a trivial task and will require some commitment from agencies and funding bodies to set up, conduct and interpret.

Throughout this paper we have described the break crop effect in yield difference. As we have demonstrated in numerous figures throughout the document the magnitude of the yield difference does not track the yield of wheat on wheat. i.e. the response to a break crop is not proportional. Indeed, for lupin the biggest yield effect occurs not when wheat on wheat yield is high but when wheat on wheat yields less than 1.7 t/ha. Therefore, we suggest that the percentage boost from a break crop (e.g. % of WW /2) may tend to decrease as the yield of wheat on wheat increases. Therefore, it may not be advisable to use a constant % boost in models that have a wide range of potential yields and it may indeed be more prudent to use a constant yield difference.

Table 12 **Number of trial x year instances that break crops and fallow have been compared to various sequences of wheat on wheat.**

Crop	Trial x year (n) 1st wheat	2nd Wheat	3rd wheat	4th Wheat	5th wheat
Wheat (t/ha)	358 (1.3)	250 (1.1)	199 (1.0)	168 (0.9)	145 (0.8)
Lupin	167	29	2	2	No data
Canola	19	2	No data	No data	No data
Field pea	63	11	1	No data	No data
Oats	13	1	No data	No data	No data
Chickpea	8	1	No data	No data	No data
Faba bean	3	No data	No data	No data	No data
Vetch	5	1	No data	No data	No data
Mustard	2	No data	No data	No data	No data
Fallow	12	1	1	No data	No data

Concluding comments

As expected the major and minor break crops do provide a boost to following cereal crops compared to wheat on wheat. These are not new findings, but we have learned by putting together the database and reviewing many years of data together some aspects that perhaps are new and interesting.

We have been able to demonstrate that changes to general farming practices do change the likelihood and indeed the magnitude of the break crop effect. Comparisons between trials conducted before and after 1990 indicate that since 1990 growers can expect a more frequent yield boost from a lupin crop and indeed a larger yield boost. This all makes sense when you consider the changes in the way we crop in WA since 1990. Since 1990 no-till has become the primary way farmers and researchers sow their crop, which allows crops to be sown earlier and for crop water use to be increased. In addition, since 1990 effective herbicides for control of grass weeds in broadleaf crops in particular allow for an increased root disease cleaning effect from break crops. These two major factors, amongst others, provide then for a higher yield potential in cereals and a greater yield boost from break crops.

Such a finding highlights how it is somewhat necessary then to update the 'break crop effect' when farming systems change. In recent years in WA the frequency of cereal cropping has been increasing. Coinciding with that increase has been an increase in the amount and frequency of nitrogen fertilisers, particularly liquid foliar fertilisers, and the use of fungicides – seed dressings, fertiliser coatings and foliar applications some of which do have an effect on root diseases such as Take-all. In addition, precision sowing has allowed farmers to sow their crops in rows offset from last year's rows. When the agronomy of growing cereal crops changes to such an extent can we still expect a break crop to provide sufficient yield improvement over and above these improvements to crop management, or has technology narrowed the gap to such an extent that a longer cereal phase is possible?

So, do you still need break crops for anything other than a herbicide resistance "tool"? In which case a break crop which is not as economically viable as a cereal crop will only be considered by growers in the event of a herbicide resistance risk or some other management issue, rather than as a yield boost to cereal production.

If indeed the break crop effect changes as farming systems change, or break crops are only a useful tool, this can lead to changes in the type of research DAFWA and others do. Some suggestions are: Set up rotation experiments in suitable locations using current cropping practices – as per 08GS01 at Katanning; Look at management of the following cereal crop to determine if different nitrogen regimes (flexi N over time) or fungicide programs do indeed alter the break crop effect; "Using break crops as a tool" i.e. how to maximise annual ryegrass or wild radish control in lupins that are only selected once every 4 or 5 years. i.e. a zero weed seed set target.

The database also highlights that there are many holes in the basic knowledge of any break crop effect for certain crop species. These may or may not be major issues depending on the adoption of the crop species in the future. For example, biodiesel and food grade mustard (*Brassica juncea*) is now available to growers but we have virtually no WA information on its break crop effect. Similarly, low rainfall canola (*Brassica napus*) varieties such as Tanami are now available, and we do not have much information on the magnitude of the break crop effect of canola in low rainfall or northern areas.

Similarly, oaten hay is an important industry throughout WA, but we have no data on the break crop effect of oaten hay compared to oats for hay or indeed what is the yield boost to dry matter or quality of the oats from other break crops.

Some crop sequences that farmers are currently using have never appeared in controlled experiments or if they have they have appeared very infrequently. Of course, it is never possible to consider every permutation possible, but it seems amazing that the lupin-wheat-canola-barley rotation has never been compared to any other rotation. Indeed, long cereal rotations with infrequent break crops are more the norm in WA nowadays, but we have limited data for such situations. Setting up experiments to consider these issues may not be the best way to consider this knowledge gap. Perhaps the interrogation of farmer paddock records as being conducted by DAFWA/CSIRO/Farmanco as part of our project or a concerted effort to put together farm case studies outlining what works and does not work throughout WA are two of the preferred ways to gather this information.

Why do break crops provide a benefit to following cereals? Most studies in WA have focussed on and in some cases attributed yield improvements to one of two aspects – residual nitrogen (Mason and Rowland 1990; Rowland *et al.* 1994; Rowland *et al.* 1988; Unkovich *et al.* 1994a; Unkovich *et al.* 1994b) or decreased cereal root diseases – particularly Take-all via control of host grasses (Cotterill and Sivasithamparam 1988a; Cotterill and Sivasithamparam 1988b; Macnish 1980) or combinations thereof. In rotation experiments there has been less emphasis on other aspects such as weed populations, nematodes, leaf diseases, cycling of nutrients (other than N), water use, various aspects of soil health or biological changes. Whilst these aspects have been researched in separate experiments there has been little attempt to bring all that information together in order to quantify or attribute their relative contribution to observed rotation effects.

It is feasible that many of the factors that contribute to a break effect can be individually assessed either through direct measurement (nematode species and number; SARDI DNA probe), guestimation (texture of soil and likely changes in soil structure and therefore water use implications), weed population dynamics (RIM, Weedwizard models) or indeed colloquial or research experience. However, there is not to our knowledge an accepted quantitative method to predict the expected break effect (size, duration) prior to planting a break crop. In a wide range of scenarios such a tool would be useful – e.g. if the break effect is small and the break crop in its own right is a high-risk enterprise either biologically or economically, are there other ways to achieve the same outcome? Alternatively, if the break crop effect is large for one year – will it last for 2-3 years? Once again these are factors being considered by the modelling component of our current GRDC project, and I imagine in putting together a mathematical model of break crop effects our inability to answer the above questions will be highlighted and DAFWA amongst others will need to have in place good quality rotation experiments to provide the necessary information.

Greenhouse gases, carbon sequestration and climate change are in the news. Do we have sufficient information for our current crop rotations and any other rotations that may develop in the future to plug into any carbon tax credit scheme? Once again good rotation experiments with appropriate controls can be used at any time to assess 'what ifs', when it becomes important to know the effect of our rotations on a certain soil parameter.

In conclusion then, after sifting through over 10,000 records from WA rotation trials I suggest we need more! We need information on the use of break crops in our modern farming system, we need to fill in the gaps of plant types and locations that have missed out previously, and we need to use these experiments to capture information on the changes our cropping systems are having on our planet.

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