**A wet summer followed by a wet early winter and dry spring, a recipe for severe take-all damage to cereal crops in cereal dominant rotations.**

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**Abstract:**

Cereal on cereal crop sequences are becoming more common in cereal growing regions of Australia. This sequence choice is often made because cereal crops are deemed most profitable. In addition, the dry seasons encountered from circa 2000 to 2009 in many wheat growing regions in Australia meant that disease problems, like those caused by take-all, declined. However, substantial rainfalls throughout Australian grain growing regions may re-ignite disease problems and the cereal on cereal crop sequence may become a costly crop choice. We revisit some long term historical crop sequence experiments conducted in Kapunda in South Australia from 1983 to 1990 to determine what impact disease incidence at sowing has on wheat yield. In addition, we explore seasonal rainfall patterns to determine what conditions lead to a decrease in inoculum levels. During the period of investigation, take all incidence increased from 1984 to 1986, decreased to very low levels (< 10%) in 1987 and 1988, then increased again in 1988 and 1989. The decreases in incidence occurred in seasons where high summer rainfalls (Dec – March) (> 80mm) preceded the growing season. The increases in inoculum occurred following a wet cool spring (Sept – November) ( > 140mm) and comparatively dry summer. High levels of disease incidence did not necessarily affect crop yield. Crop yields declined linearly with increasing disease incidence in 3 years (1986, 1987 and 1988) out of the 8 surveyed. These three seasons had the highest summer rainfalls of the 8 surveyed. Different mechanisms appear to be acting on the crop in these seasons, as 1986 was quite wet, where disease free crops yielded 4.2 t/ha, while 1987 was dry, with disease free crops yielding just 2 t/ha. Overall, if inoculum levels are moderate ( > 25%) then crop yields may be reduced by 0.5 t/ha. This increases to around 1 t/ha if inoculum levels increase to 40% or more.

**Introduction**

Soil borne disease such as take-all, rhizoctonia, crown rot and root rot are present to some extent in most Australian soils and all diseases can reduce cereal crop yields. However, the increase in disease inoculum levels and the impact that diseases such as take all have on cereal yield is variable and dependent on seasonal conditions (Roget and Rovira 1991, Kirkegaard et al 200). It is essential to understand and quantify the nature of the variation in disease impacts on cereal yield, as farmers may become complacent and unwittingly employ cereal dominant rotations without recognising the potential downside risk. If there have been sequences of seasons with below average long term rainfalls, or abnormally wet summers, then it is possible the inoculum levels of diseases like take-all have been suppressed (Roget and Rovira 1991). Often, statewide distributions of inoculum levels for take-all follow the rainfall isohytes (Yates 1985), where the inoculum levels are higher in the wetter regions. Similarly, the run of seasons can result in either a buildup or decline in inoculum levels. The buildup in inoculum levels can even occur in low rainfall districts and it is important that farmers are aware of how quickly disease can buildup or decline, as any buildup in inoculum levels can affect the threat associated with growing cereals in sequence.

Historical experimental crop sequencing data from Kapunda in South Australia were reanalysed to explore how quickly inoculum levels can change in a continuous wheat rotation. In addition we also considered how frequently, an under what seasonal conditions inoculum levels affected cereal crop yields.

**Methods**

Two experiments were conducted at Kapunda, South Australia in the 1980s. In the first, continuous wheat (cultivar ?) was subjected to three different tillage treatments; conventional cultivation (cc), reduced tillage (rt) and direct drilled (dd). Each treatment was replicated 9 times. Therefore, in each year 18 plots of wheat were harvested. In addition, inoculum levels were assessed where disease incidence was assessed 6 – 8 weeks after sowing (~ gs 30 - 40) where the roots from 20 to 25, wheat plants within each plot were scored for the incidence and severity of the take –all.

An additional experiment (rotation) was conducted in 1985, 1986 and 1987 where wheat was grown following a pasture, lupins or wheat. Each treatment was replicated 6 times and these data were also included in the analysis, and designated as part of the rotation trial. Wheat yields were measured at harvest and inoculum levels were again measured at 6 – 8 weeks after sowing.

Statistical analysis

The ‘asreml’ library from R v2.12 was used to conduct a meta- analysis of these two trials. Initially the objective was to determine what impact take-all inoculum had on crop yield in each of the 8 seasons and formally explore whether the effect of take-all inoculum on crop yield varied from one season to the next. The data were analysed using a mixed model, where the year (categorical) and inoculum (continuous) were fitted as main effects and as an interaction in the fixed model. In the random model treatment within year within the trial and block within year within trial was included in the random model. The random model accounted for the treatmet and block effects within a year that were part of the original trial design. These were of no interest here and were therefore included in the random model to improve the statistical fit of the data.

An equivalent statistical model was fitted to the log transform of inoculum levels. In this instance, the year and log(inoculum) level from the previous year were fitted to the log(inoculum). To determine what effect previous inoculum levels had on inoculum levels in the current season, and whether such a relationship changed from one season to the next. Data from the rotation trial was excluded as inoculum levels in the break crops were not recorded. Again, year and log of previous inoculum were fixed. Treatment within year and rep within year were again included in the random model to improve model fit.

Inoculum levels from the rotation trial were also analysed to determine if break crop effects on inoculum levels from 1985, 1986 and 1987 were stable, or varied from season to season. In this instance, year and previous crop type (lupins, pasture or wheat) were fit to inoculum levels. Rep within year was fit in the random model.

**Results**

**Inoculum trends.**

Inoculum levels (log transformed) in the previous year did not influence inoculum levels in the following year, at least when grown in continuous wheat. The statistical model was altered, where year was fitted to inoculum levels to determine the temporal trend in the data. In this continuous wheat system, inoculum levels remained high in 1983 to 1986. Levels declined in 1987 and 1988, but then increased in 1989 before again declining in 1990 (Figure 1).



Figure 1. Trends in the log of inoculum levels for take-all from 1983 to 1990.

In the rotation experiment, inoculum levels in the wheat crop were influence by the proceeding crop, but this did vary with year. In 1985, inoculum levels in wheat were similar irrespective of the previous crop. In 1986, inoculum levels were lower in wheat, when grown after a lupin crop, than wheat grown after pasture or wheat. In 1987 inoculum levels were lower in wheat when grown after lupins and after pasture than in wheat grown after wheat (Figure 2). Overall, seasonal factors contributed to a steady decline in inoculum levels, but this decline was hastened when lupins were grown prior to wheat.



Figure 2. The influence of the previous crop on log innoculum levels in a wheat crop.

**Inoculum effect on wheat yield.**

As expected, wheat yields varied markedly from season to season. High yielding seasons occurred in 1984, 1986 and 1988, where crops yielded 3.6, 4.3 and 3.4 t/ha respectively. In contrast, 1985 (2.16 t/ha) and 1990 (2.08t/ha) were low yielding. The influence of inoculum level on wheat yield varied considerably from one year to the next. In 1986,1987 and 1988, significant yield loss occurred when inoculum was present where an inoculum level of 25% reduced crop yield by at least 0.5 t/ha. This increased to at least 0.9 t/ha when inoculum levels increased to 40%. In the remaining seasons, inoculum did not statistically reduce crop yield, and the relationship between inoculum level and wheat yield was not statistically different from zero (Figure 3).



Figure 3. Relationship between grain yield and take all disease incidence in 1986, 1987 and 1988. These were the only seasons with a significant trend. In each year, the line does not extend beyond the maximum level of take-all incidence recorded in wheat plots in that season. The equations of the lines are, 1986 : yield(t/ha) = 4.28 – 0.021(incidence), 1987: yield(t/ha) = 2.96 – 0.050(incidence), 1988: yield(t/ha) = 3.45 – 0.025(incidence).

**Climatic conditions in the different seasons.**

Rainfalls in all seasons were remarkably good, where growing season rainfall (April – November) averaged 403mm and ranged from a low of 367mm in 1984 to 477 mm in 1986. Terminal drought would have been mild in all seasons, however the distribution of rainfall within the season did vary. Disease inoculum levels remained high from 1983-1986, but declined in 1987. In the 1986/1987 summer, 75mm of rainfall was recorded, almost double the trial average of 41mm and this may have contributed to the decline in inoculums levels for the 1987 growing season. 1987/188 summer was the second wettest, with 55mm of rainfall. The increase in inoculum levels in 1989 followed a wet spring in 1988 (153mm) and the second driest summer in the experiment (22mm).

Inoculum levels reduced wheat yield in 1986, 1987 and 1988. The 1986 growing season was characterised by a wet (216mm) start to the growing season and an equally wet spring (199mm). The crop would never have suffered moisture stress and conditions could only be described as perfect, unless the crop was exposed to waterlogging. Crop yields reached 4.3/tha. Under these climatic conditions, inncoulum levels in some plots were at 70% and these crops yielded just 2.8 t/ha. It is possible that in the favourable conditions root growth was compromised to such an extent that crop water use was compromised, and crops with high inoculum levels were unable to take advantage of the favourable conditions. Perhaps surprisingly, the effect inoculum levels had on wheat yield was negatively correlated with the amount of rain that fell in the previous summer (December, January and February) (r = -0.74, p > 0.05). Therefore when summer rainfall was high, inoculums levels reduced wheat yield. his could be because the summers of 1986, 1987 and 1988 were the three wettest encountered during the trial period. Further analysis found the coefficient of the impact that inoculum would have on wheat yield could be predicted by the equation, 0.0008\* summer rainfall + 0.0003 \* winter rainfall (june, july and august). The impact that take-all inoculum would have on wheat yield in these seasons is shown in Figure 3.

In 1987, winter rainfalls were good (193.2mm) but spring rainfall was the lowest (85.6mm). Crop yields were the lowest at 2. 95 t/ha, and it is likely that crops in this season finished in a situation of terminal drought. Even though inoculum levels were low in 1987 (< 20 %), the levels of inoculum present significantly compromised crop yield. In this situation, an inoculum level of 10% reduced crop yield by 0.5 t/ha. The good early winter rainfalls in 1987 would have ensured the crop was growing vigorously, and the yield penalty may have occurred as a result of increased exposure to terminal drought. 1987 was unique at this site, as there was only one other season with low spring rainfall (1990). There were low levels of inoculum in the soil in 1990, and the slightly wetter winter may be been sufficient to ensure the inoculum levels present in the soil did not affect yield.

There were similarities between 1988 and 1986 as good winter rainfalls (193 mm) were followed by good spring rainfalls (153mm), thus the conditions may have been favourable for inoculum buildup late in the season that then compromised the crops ability to extract the extra moisture that would have been available. However, without dedicated soil moisture equipment, it is difficult to determine exactly how yields were suppressed.

**Towards predicting yield loss through take-all, or predicting the economics .**

At least two requirements need to be satisfied to calculate the risk take-all possess to Australian farmers adopting cereal dominant rotations. The first is to consider the value of understanding the factors that give rise to a build up in inoculum levels, both prior to the crop being planted and once it has been sown. From a statistical perspective this should be simple, particularly if early models (eg Roget and Rovira 1991) can be validated. The following years inoculum level should be predicted using a combination of the previous years inoculum level and some climate variables. However, in the study conducted here, this was not possible with the data available. IE no relationship could be derived between the innoculum level in year 1 and the innoculum level in year 2 and various interpretations of rainfall. Inoculum levels crashed and recovered, but at both the plot level, and at the whole of trial level, clear relationships could not be established. This has important ramifications. Firstly, in a cereal crop it means the population in the following crop can increase from a low base. The implication is that a cereal on cereal crop is never safe, and the only way inoculum levels seem to be suppressed was through the use of a lupin crop. Even here a break crop resulted in high levels of inoculum in 1 year (Figure 2) and season was more important than crop type in influencing the inoculum level.

The key finding from this analysis is that it is not the amount of inoculum present in the soil at any given time that influences cereal crop yields. Rather it the prevailing environmental conditions that mean variations in inoculum levels then affect yield. This means the research effort should be expended on understanding the prevailing conditions that limit crop yield when disease is present, rather than focussing on the inoculum level perse. Research should also focus on characterising and understanding the buildup of inoculum in crop to determine how quickly these rate processes happen. If they are slow, a crop could develop a sufficiently robust root system and avoid post anthesis moisture stress. If the rate of develop is fast (as may be hypothesised in 1986,1987 and 1988), then the crop will be predisposed to moisture stress and be severely affected by inoculum levels, almost regardless of the starting population. Finally, break crops reduced inoculum levels, thus regardless of the prevailing weather conditions, this would definitely reduce the possible effects of inoculum levels in the following crop. However, this reduction was systematic and remarkably consistent, it did not interact greatly with year (Figure 2).

**Modelling the impact of climate and break crop choice on wheat yield.**

To build a rule set from this analysis to predict when innoculum levels will affect cereal yield, it could be done simply. Firstly, the temporal variations in inoculum levels should be ignored, simply because we do not have detailed experimental data that tracks the change in inoculums levels through time at relatively close (< 1 month) time intervals. Rather, a simple increase in inoculum should be defined for a cereal and a correspondingly lower level set for a legume or break crop. From figure 3, it would be acceptable to choose an inoculum level according to: exp(wheat.innoc – wheat.innoc/2), where wheat.innoc/2 is the inoculums level for the break crop. With this model, you could then predict what impact disease will have, given climate within the season.

Other random thoughts

Question Step 1 – When does disease incidence increase and when does it decrease, given season.

Tracking log of disease incidence through time, the declines and increases in disease are obvious. Given these were continuous wheat fields, it appears as though summer rainfall (high) combined with dryish winter (87) and another high summer rainfall (88) can keep disease levels low. This has been the pattern in much of the dryer areas.

NSW – the trial data show similar patterns, in some situations wheat yield responds to disease inoculums levels, in others it does not. A more detailed description of these analyses are coming.

**Summary for LUSO** ( bold means a model parameter that can be changed in LUSO parameter files)

General model for disease incidence is now:

Inc = **maxdisease** ^ **cropeffectondisease** \* IncPrev ^ **diseasecarryover**

(=exp(MMLI \* **cropeffectondisease**) \* IncPrev ^ **diseasecarryover** )

Where

Inc is incidence, as a percentage of maximum, capped at 100 and 0

**maxdisease** is the maximum mean incidence, this can be defined for an average season in the ‘parameters’ file, or by current season conditions (**diseaseIncidence**) in the stochastic parameters file (or MMLI is the maximum mean log incidence)

**cropeffectondisease** is the impact of previous crop on incidence factor – 1 means no effect, less than one reduced effect – depends on previous crop

IncPrev is the incidence of the previous year

**diseasecarryover** is the impact of previous incidence on incidence factor – 0 means no effect, ½ means that only low previous innoculum load reduces current load from maximum, 1 means a linear effect, 2 means that only high previous innoculum load lead to significant current load

General model for disease impact is now:

Imp = **diseaseimpact**\*(Inc-**mindisease**)\* **diseaseeffectoncrop**

Where

Imp is impact, as a percentage reduction in yield, capped at 100 and 0

**mindisease** is the minimum incidence required to cause an impact

**diseaseimpact** defines how strongly incidence above the threshold affects impact, this can be defined for an average season in the ‘parameters’ file, or by current season conditions (**diseaseImpact**) in the stochastic parameters file

**diseaseeffectoncrop** is how much the disease effects the particular current crop

\*\* in the model code impact and incidence are now percentages, not proportions

Based on Kapunda analysis:

Maximum Mean log incidence MMLI = -0.033\*DJF+3.8 (DJF is December, Jan, Feb rainfall)

**cropeffectondisease** is 1/2 after lupins and 2/3 after pasture

No effect of previous inoculum load detected - so **diseasecarryover** can be set to zero (?)

For impact **mindisease** set to zero – slope????

**diseaseImpact** = 0.0008\* DJF + 0.0003 \* JJA (JJA is June, July August rainfall)