TOOWOOMBA
QUEENSLAND
JULY 2020

GRAINS RESEARCH UPDATE

DRIVING PROFIT THROUGH RESEARCH

grdc.com.au

GRDC 2020 Grains Research Update Welcome

If you are reading this, then chances are you have taken time out from an extraordinarily tough season in our very sunburnt country to hear the latest grains research, development and extension (RD&E) information.

Welcome.

We at the GRDC understand how very challenging the current situation is for growers, advisers, agronomists, researchers and those associated with the grains industry across New South Wales and Queensland.

Drought takes an enormous toll financially, emotionally and physically on those working and living through it daily. We trust that these GRDC Grains Research Updates will offer you new research information to help guide your on-farm decisions this season and to be best placed to take advantage of future seasons. We also hope the Updates provide a chance to connect with your peers and temporarily escape work pressures.

We would like to take this opportunity to thank our many research partners, who, like growers and advisers, have gone over and above in recent years to keep trials alive in rain-deprived environments.

Challenging seasons reinforce the importance of rigorous, innovative research that delivers genuine gains on-farm. For more than a quarter of a century the GRDC has been driving grains research capability and capacity with the understanding that high quality, effective RD&E is vital to the continued viability of the industry.

Sharing the results from this research is a key role of the annual Updates, which are the premier event on the northern grains industry calendar and bring together some of Australia's leading grains research scientists and expert consultants.

To ensure this research answers the most pressing profitability and productivity questions from the paddock, it is critical the GRDC is engaged with and listening to growers, agronomists and advisers.

For the past four years we have been doing that from regional offices across the country. Through the northern region offices in Wagga Wagga and Toowoomba and a team of staff committed to connecting with industry, we are now more closely linked to industry than ever.

Today, GRDC staff and GRDC Northern Panel members are at this Update to listen and engage with you. This is a vital forum for learning, sharing ideas and networking, all of which are critical to effect successful change and progress on-farm.

Regards,
Gillian Meppem
Senior Regional Manager North

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Understanding consumer markets for sorghum for human consumption

Kirsty McKenzie and Anthony Saliba, Graham Centre for Agricultural Innovation, Charles Sturt University

Key words

Sorghum for human consumption, baijiu, consumer beliefs and attitudes about sorghum, sorghum and human health, sorghum and contemporary food trends

GRDC code

UCS00025 - 2015.01.18-Expanding options for sorghum- Food and Distilling

Take home message

Opportunities exist for higher value markets for Australian grain sorghum. While trading sorghum for the Chinese baijiu industry is currently challenging, growers would benefit from keeping up with developments in this potentially more lucrative market for grain sorghum. In the local market, sorghum has the potential to meet the needs of consumers for its health properties and for its gluten free status. Growers could benefit from following developments in this market and establish relationships with food manufacturers.

In Australia, sorghum is used mainly as animal fodder but there may be opportunities for expanding into higher value markets, both internationally and locally. Researchers at Charles Sturt University Graham Centre for Agricultural Innovation are investigating these markets, as part of the *Expanding options for sorghum: food and distilling* project funded by GRDC. The approach we take is focussed on consumer behaviours, attitudes and characteristics and we examine not just the size of these markets, but also why sorghum is valued, and whether sorghum from Australia would be acceptable to consumers. We focus on consumers because this information may help inform whether investing in entering existing markets, or activating markets is worthwhile. The research reported here focusses on one major international market, China, and also discusses potential within the local market.

In China, sorghum is the primary grain used in a popular traditional alcoholic spirit called baijiu. Baijiu is the most consumed spirit in the world and production of baijiu in China currently exceeds 12 million metric tonnes annually. China is not able to grow nearly enough sorghum to meet its requirements for this rapidly expanding industry and the Chinese baijiu market represents an enormous opportunity for Australian sorghum producers. In a preliminary phase of the research we interviewed baijiu producers about their knowledge about Australian sorghum. This research concluded that there may be opportunities for Australian sorghum in the short term, but that there was some ambiguity about consumer acceptance of Australian sorghum. To be sure that Australia would be positioned above any competitors that could produce below-premium grain cheaply, we conducted further testing with consumers to determine if Australian sorghum could be successfully marketed as a key ingredient of baijiu produced in China. A follow up survey with 2000 Chinese adults found that baijiu is frequently consumed; and that a majority of people thought it was healthy and that tradition dictated that they drink it. These beliefs were linked to consumption: people who thought that baijiu was healthy consumed more, as did people who drank it because of its traditional importance. We also found a high level of consumer acceptance of Australian sorghum in the production of baijiu, with the majority of consumers prepared to accept some proportion of Australian sorghum.

In Australia, the picture is very different. Sorghum is not a traditional part human diets, and we believe that there is very little consumer awareness about sorghum. For this reason, instead of conducting a survey on sorghum, we ran a series of focus groups to explore potential ways to encourage consumer interest in sorghum-based products. The gluten-free market in Australia is projected to grow significantly over the next five years. More generally, health is currently the biggest consumer food trend, and there is an emphasis on nutrient content and foods that can help manage and prevent illness. Sorghum is well-placed to meet the needs of consumers who are looking for gluten-free alternatives, and/or a range of health benefits. We used our data to construct three consumer archetypes, and then designed some potential products that might meet the needs of these consumers, including in relation to health.

In summary, our research suggests that there is (at least) one large international market for Australian grain sorghum. While there may be issues with trade relations and other barriers, *from a consumer perspective* this market has two very attractive characteristics. First, baijiu is linked to health and tradition. This means that people are unlikely to stop consuming it abruptly. Second, Australian sorghum would be acceptable to most consumers. In the Australian context, we could say that the consumer market is not yet activated. Sorghum is not linked to tradition, and most people have probably not even heard of it. However, it may be possible to market sorghum based on some of its health properties, and its gluten-free status.

Acknowledgements

The research undertaken as part of this project is made possible by the significant support of the GRDC, the author would like to thank them for their continued support.

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How has Millmerran's climate changed and what impact has it had on sorghum productivity

Jeremy Whish and Elizabeth Meier, CSIRO

Key words

climate, historic climate, changing yield potential, sorghum

GRDC code

CSP1806-01

Take home messages

- Increasing temperatures and reduced rainfall have lowered the yield potential of sorghum in many areas
- Avoiding high temperatures at flowering and using a conservative sowing trigger (>100mm PAW) can reduce the impact of a changing climate
- There is still room to reduce the yield gap with targeted sowing dates, nitrogen rates and soil water triggers despite a changing climate reducing sorghum yield potential.

Introduction

Australia's climate is warming, including an increase in average temperature, increase in number of days exceeding 35°C and a decrease in rainfall (CSIRO and BOM, 2015).

But what is happening at Millmerran? How will this affect the crops I grow? What can I do to manage this change?

These are some of the questions we have tried to address.

Over the last few years, several suggestions have been made to GRDC that have warranted our examination of sorghum production in response to changing climates. The key concern was that a changing climate had reduced the yield potential of central Queensland crops and would cause the key sorghum production areas to move south to cooler and less variable climates. In this paper we review local annual and growing season climates, sorghum production and compare these results to other sorghum production areas to see how or if things have changed.

Methods

Current climate was compared with historical climate using a climate normal approach to compare overlapping 30-year time periods. This is recognised as the most statistically sound method to determine if a change in climate has occurred (Arguez and Vose, 2011), and is recommended by the World Meteorological Organisation's standard for placing current climate conditions in a historical perspective. A simulation analysis of sorghum production in response to a range of initial soil water and sowing dates was then conducted using APSIM (Holzworth, 2014) to identify whether changing these management practices could mitigate the effect of any changes in climate.

How is the Millmerran environment changing?

Rainfall

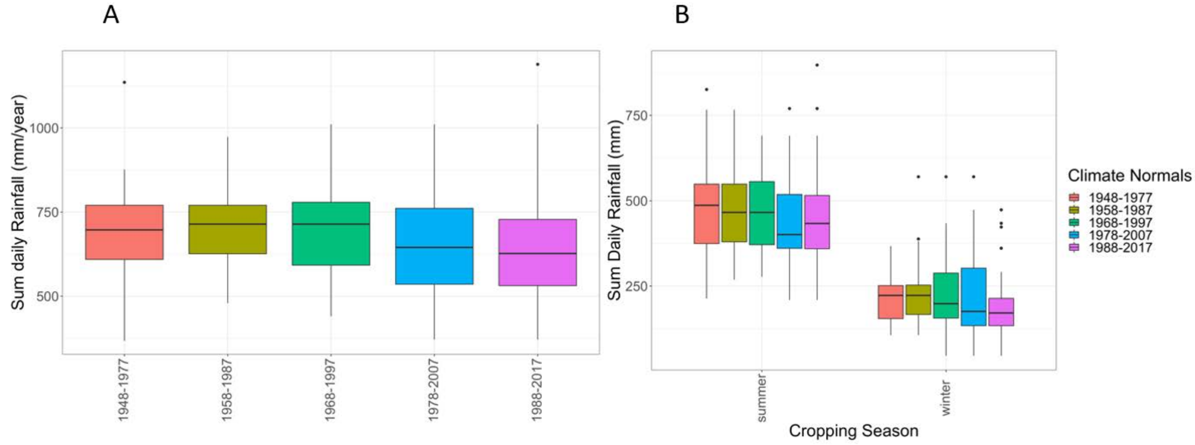

Figure 1. Sum of rainfall for each 30-year climate normal period on an annual (A) and cropping season (B) basis at Millmerran. The results show an increase in variability and a decline in the average rainfall over time. The decline has occurred in both summer and winter rainfall.

Temperature

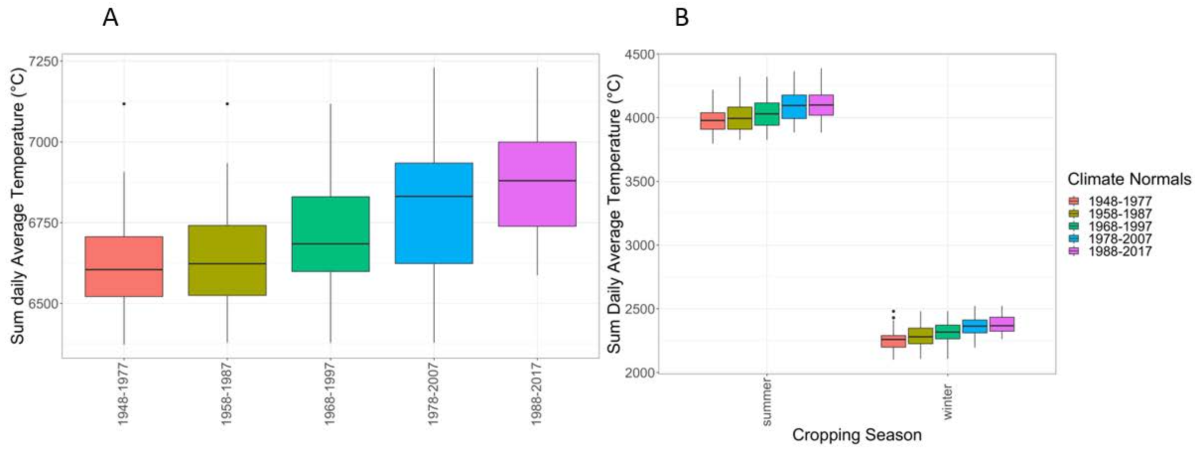

Figure 2. Sum of daily average temperature on an annual (A) and cropping season basis at Millmerran. Average temperature showed a continual increase in heat to the most recent climate normal (1988-2017). The change in accumulation of heat was similar in both summer and winter growing seasons.

Extreme temperatures

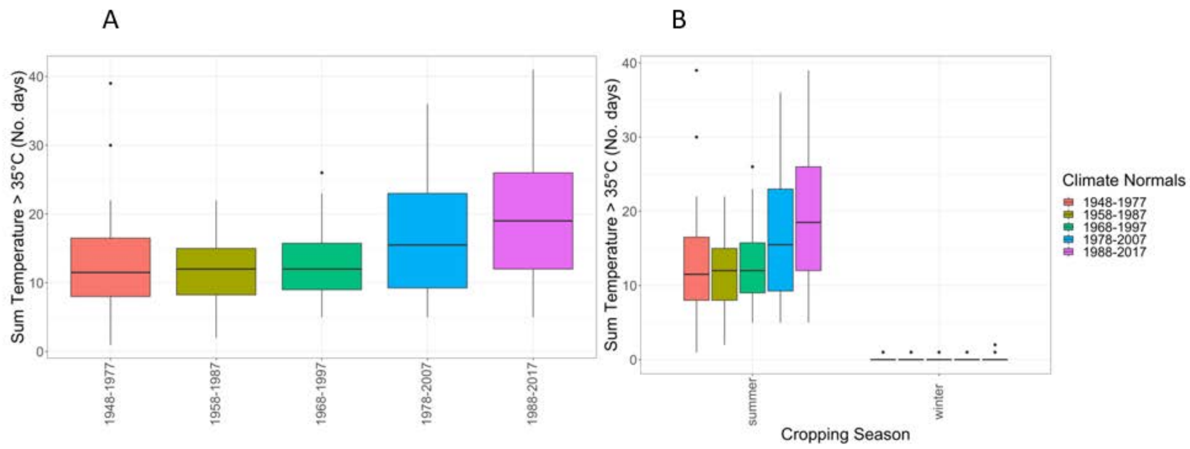

Figure 3. Number of days of extreme temperatures (above 35°C) summed on an annual (A) and growing season (B) basis. The days above 35°C follow a similar pattern to the heat sum on an annual basis increasing to the most recent normal (1988-2017). Extreme temperatures occurred in the summer only.

How will these changes in climate affect sorghum?

Higher temperatures increase the rate of crop development and the amount of water transpired by the crop. If rainfall remains stable or decreases then this will increase the chance of moisture stress occurring in the crop. However, if the growing period of the crop can be matched to the timing of rainfall then it may be possible to maintain or increase crop grain yield despite an annual reduction in rainfall.

To identify whether the yield potential of sorghum crops had changed over the last 60 years a series of simulations were undertaken. The 60-year period from 1958-2017 was used for this analysis and sub-divided into two climate normals – 1958-1987 and 1988-2017 - that could be compared.

Water stored within the soil helps to buffer crops from variability in the climate. In order to understand the effect on yield of changes in the climate, the median yield from a crop sown into a full profile of water was compared across the 60-year period. This approach was expected to demonstrate the least difference between the two climate normal periods, because each site by sowing date combination had optimal soil water at sowing. The study was completed for a selection of locations ('transects') in both the eastern and western parts of the GRDC northern growing region (Figure 4).

Sorghum crop yields sown on a full profile of soil water

For northern sites of the western transect (from Mungindi north) there was little change in yield except for a reduction in yield of around 0.5 t/ha at the extremes of early sowing and late sowing (Figure 4). For the northern sites of the eastern transect there was a clear reduction in yield for sites north of Goondiwindi, especially for sowing dates before November. For the eastern transect there were distinct groupings of change in yield: improved yield between Goondiwindi and Moree for crops sown between November and January, and decline in yield on the Liverpool Plains that worsened with later sowings and culminated around a mid-December plant.

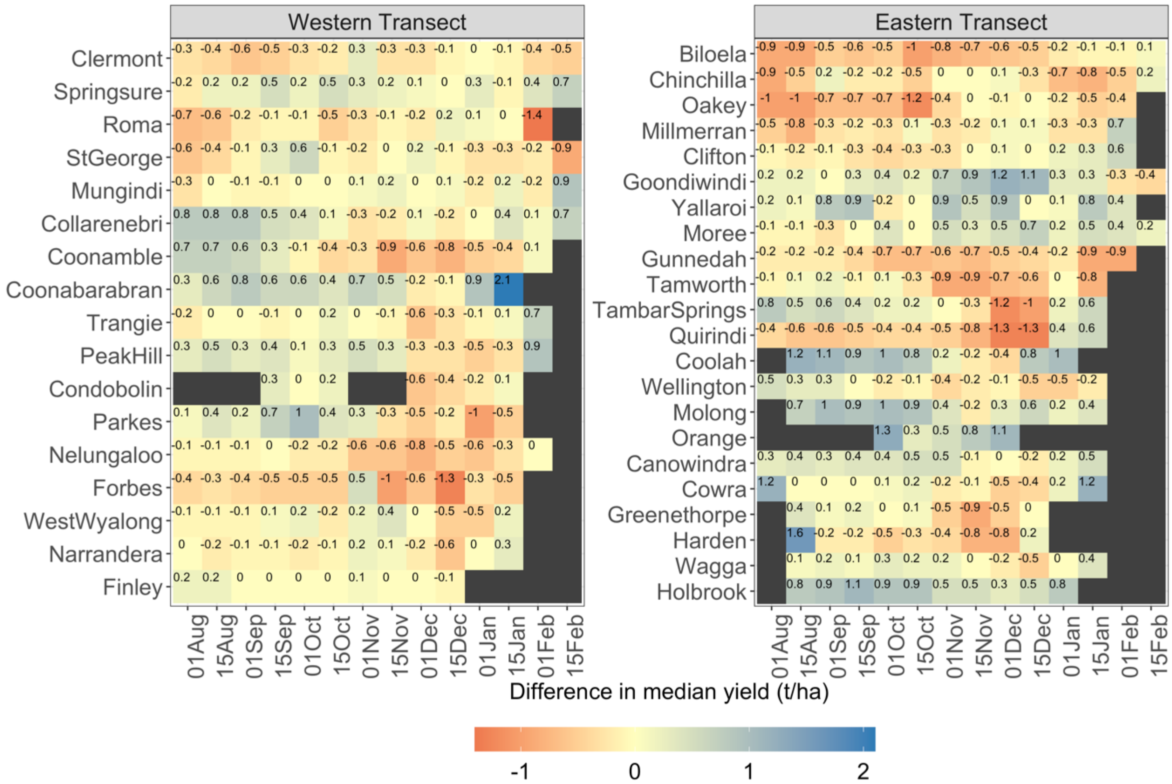

Figure 4. Difference in median yield of sorghum crops between climate normals 1958-1987 and 1988-2017 when sown into a full profile of water, for different sowing dates for locations divided into western and eastern transects. Red shading in cells indicates a decrease in yield, blue indicates an increase, and yellow indicates sowing dates where there was minimal to no difference in crop yield. Only median yields from sowing dates that had fewer than 50% failed crops are included (other location-sowing date combinations were considered unsuitable for crop production and are coloured black). Values within each cell are the difference in yield between the climate normals (t/ha).

What has been the effect of changing climate on yield when there isn't a full profile of soil water at sowing?

The objective of simulating sorghum crop yields in response to a full profile of water in the previous step, was to understand whether the most recent 30-year climate normal period was different to the previous 30-year normal in terms of its effect on crop yield. However, it can be inefficient to wait for a soil profile to fill because producing adequate crops regularly, can more be financially rewarding than waiting for ideal conditions (such as a full soil water profile) to occur. In this section we present results for crops sown into a profile with an initial amount of 100mm of available soil water. This amount is towards the lower end of soil water that would be present when a decision to sow occurs (the general sowing rule for western sites (west of the Newell highway) is commonly, 150mm of plant available water). In the eastern sites with higher rainfall 100 mm is more common. The use of 100mm for both transects is a compromise.

There was an increase in crop failures (cells shaded black) between crops sown on a full profile of soil water (Figure 4) and those sown into a profile containing 100mm (Figure 5). This difference in initial soil water also explains the use of wide row configuration and 150mm soil water trigger that is used by many grain growers along the western transect. However, despite these differences in yield arising from differences in initial soil water. The general patterns of changes in yield and optimal sowing dates between climate normals were the same. There were minimal differences in yield

between climate normals for the north-western sites, but a decrease in yield potential for the eastern sites. The November to mid-January sowing dates between Goondiwindi and Moree continued to demonstrate an increase in yield for the more recent normal, while later sowing in the Liverpool Plains continued to demonstrate a yield reduction.

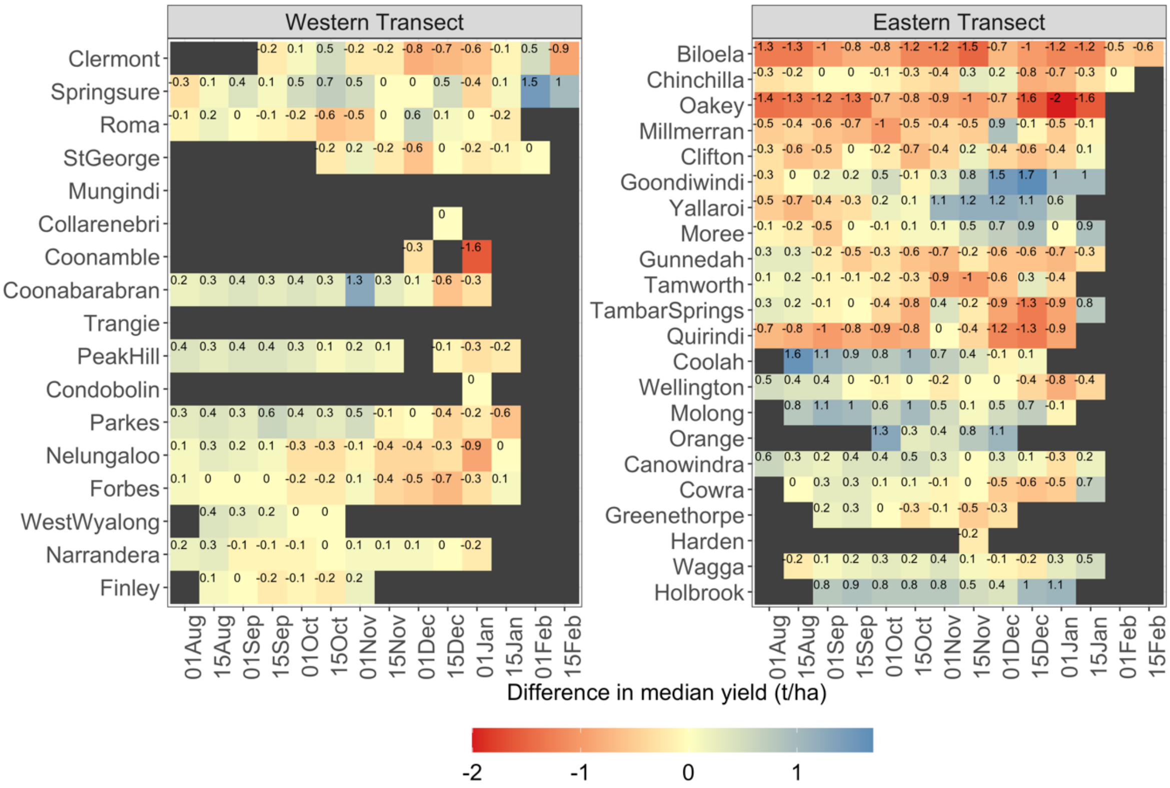

Figure 5. Difference in median yield of sorghum crops between climate normals 1958-1987 and 1988-2017 when sown into a profile of 100mm of water, for different sowing dates for locations divided into western and eastern transects. Red shading indicates a decrease in yield, blue shading indicates an increase in yield, and yellow shading indicates sowing dates for each location with minimal to no difference in yield. Only median yields from sowing dates that had fewer than 50% failed crops are included (other location-sowing date combinations were considered unsuitable for crop production and are coloured black). The values within each cell specifies the magnitude of the difference in yield between the climate normal periods (t/ha).

Why are yields changing?

Rainfall

The availability of water to the crop is the key determinant of yield in Australia. The value of stored soil water is its ability to buffer the demands of the plant in between rainfall events and ensure optimal plant growth. The timing and size of rainfall events are critical to maintaining this buffer as is the specific soil type. In general, the quantity of in-crop rainfall decreased or remained neutral across locations in both eastern and western transects, although there was an increase in in-crop rainfall at a few locations (e.g. Coonabarabran, Goondiwindi and Millmerran for some times of sowing). These locations are those that showed an increase in water limited yield potential (Figures 4 and 7) and highlight that this increase in rainfall pattern has directly resulted in increased yield.

Millmerran shows a similar trend to Goondiwindi though the magnitude is less has seen an increase in rainfall for crops sown in late October to mid- November over the last 30 years despite a slight decline in summer rainfall overall.

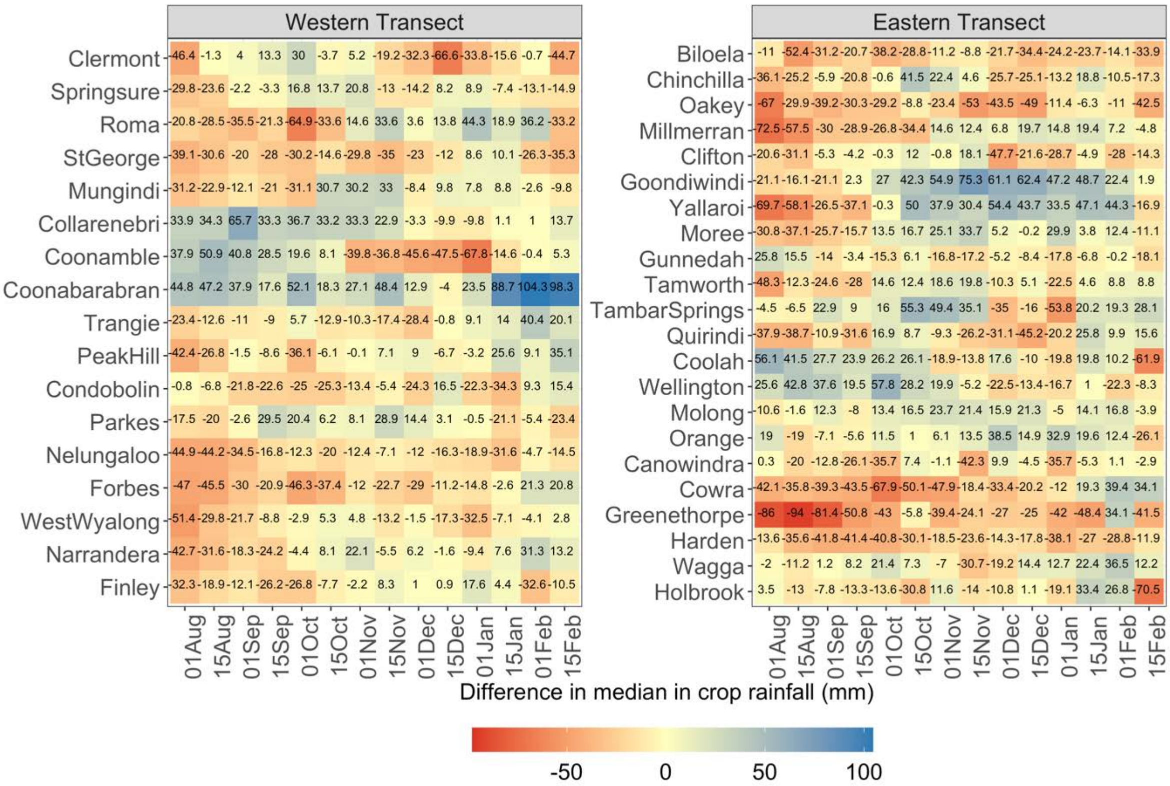

Figure 6. Difference in median in-crop rainfall for the 14 different sowing dates between the two climate periods 1958-1987 and 1988-2017, for locations in western and eastern transects. Red shading indicates a decrease in in-crop rainfall, blue shading indicates an increase in rainfall, and yellow indicates sowing dates with minimal to no difference in rainfall between normals. The values within each cell are the difference in median in-crop rainfall (mm).

Extreme temperatures

High temperatures around flowering can significantly reduce sorghum grain yield (Lobell et al., 2015; Singh et al., 2017; 2016). The difference in the number of days with temperatures in excess of 35°C increased between the past 30-year climate normal period (1958-1987) and the more recent 30-year normal (1988-2017). The increase in days with extreme temperatures was greater for the western transect, especially for crops sown between October and November. For the eastern transect there was a general increase in the number of days with extreme temperatures for all sowing dates before December. However, a few specific sites experienced a reduction in extreme temperatures; these sites and sowing dates correspond with those that experienced an increase in rainfall and consequently an increase in median yield potential (Figure 7).

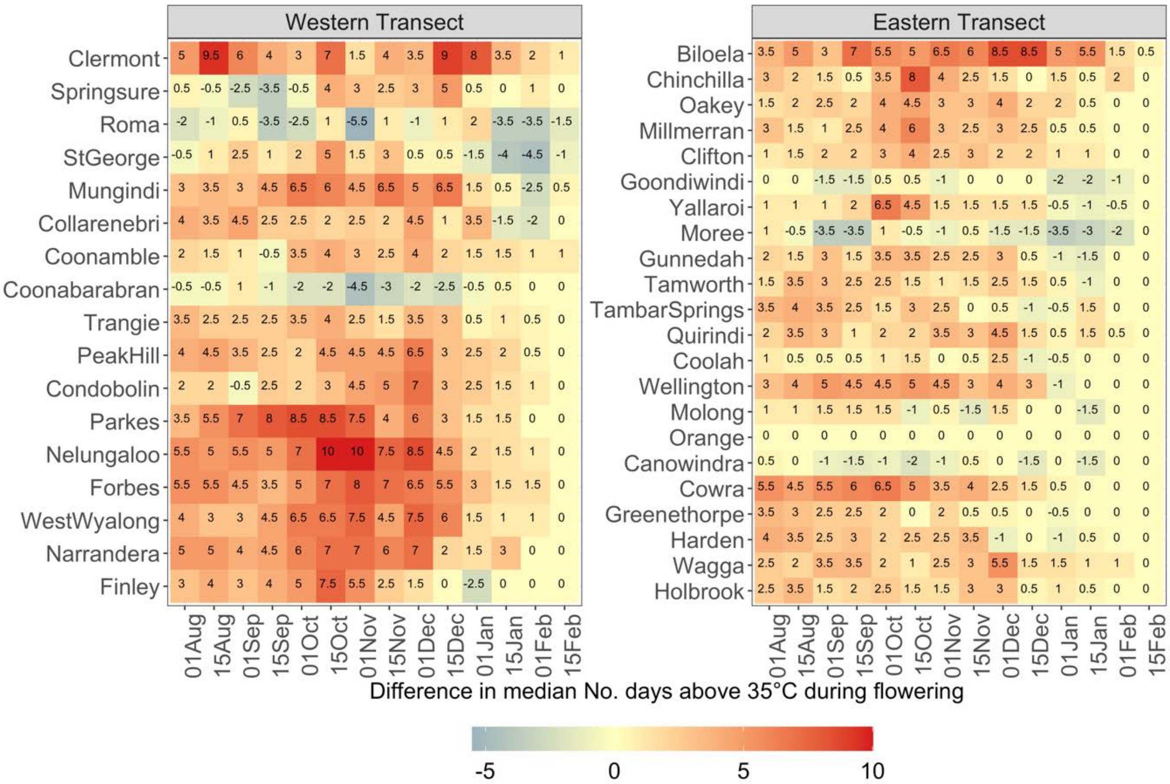

Figure 7. Difference in the median number of days above 35°C during flowering for the 14 different sowing dates between the two time periods of 1958-1987 and 1988-2017, for western and eastern transects within the northern grain zone of eastern Australia. Red indicates an increase in rainfall while blue indicates a decrease, yellow highlights those sowing dates with minimal to no difference. The values within each cell are the difference in median number of days above 35°C during flowering.

So, what does it mean and what can I do?

The climate of Australia's sorghum production area has changed, with increases in the average daily temperature, an increase in the number of days with extreme temperatures during flowering, and a decrease in in-crop rainfall for many locations. These changes have resulted in an overall reduction in crop yield potential. However, despite this decrease the yield potential has not been reduced to a point where it is no longer economical to grow sorghum. Good agronomy and the use of high soil water triggers at sowing will help maintain profitable returns under changing climates. For sites that had an increase in yield for some sowing dates, this could be traced to increased rainfall and a decrease in extreme temperatures during flowering. However, these increases were relative only to the areas historic production and not an increase above traditionally high yield regions. Thus, despite a decrease in the yield potential over the study period for many areas, this decrease has not caused a noticeable shift in sorghum production areas, and so NSW is not the new central Queensland for sorghum production.

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How has Yallaroi's climate changed and what impact has it had on sorghum productivity

Jeremy Whish and Elizabeth Meier, CSIRO

Key words

climate, historic climate, changing yield potential, sorghum

GRDC code

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Rainfall

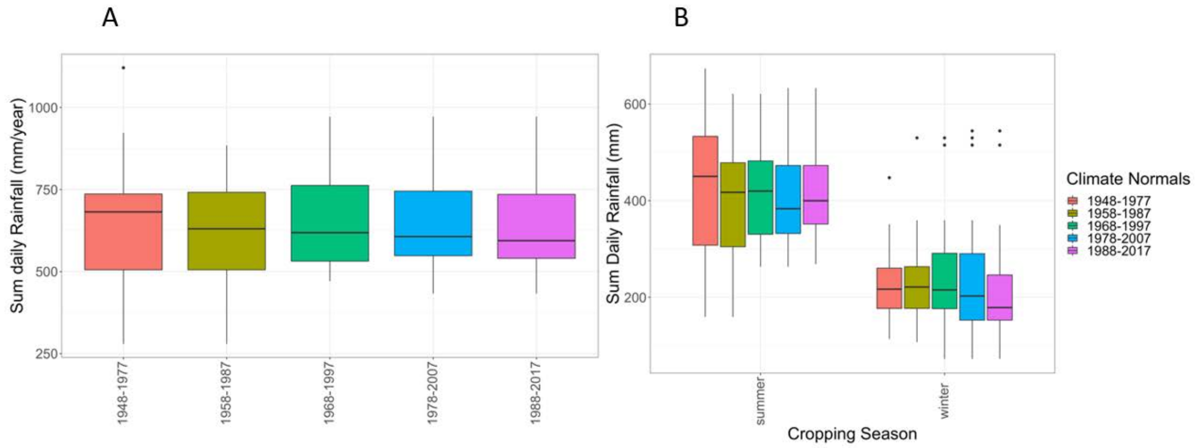

Figure 1. Sum of rainfall for each 30-year climate normal period on an annual (A) and cropping season (B) basis at Yallaroi. The results show a reduction in variability and slight lowering of the average rainfall over time. The decline has occurred in both summer and winter rainfall.

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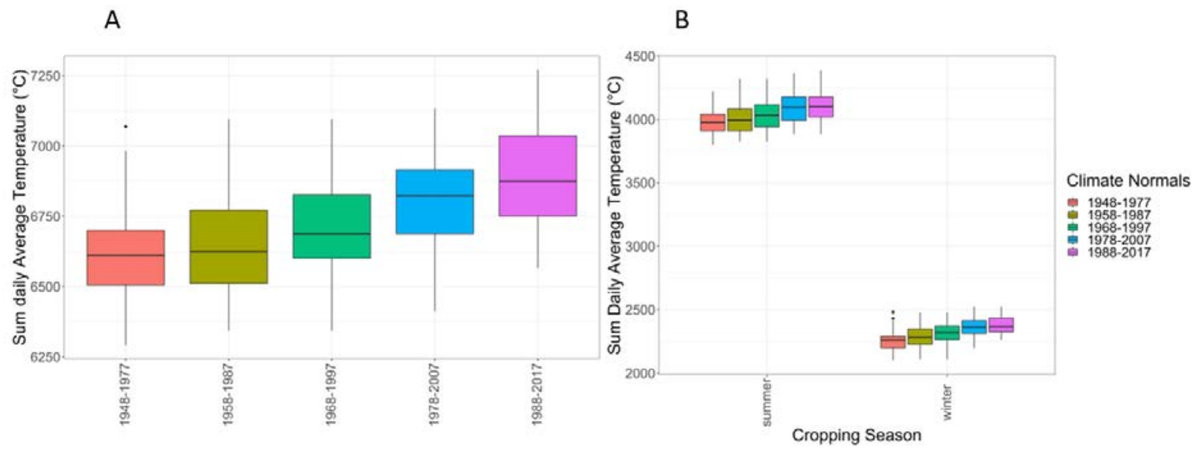

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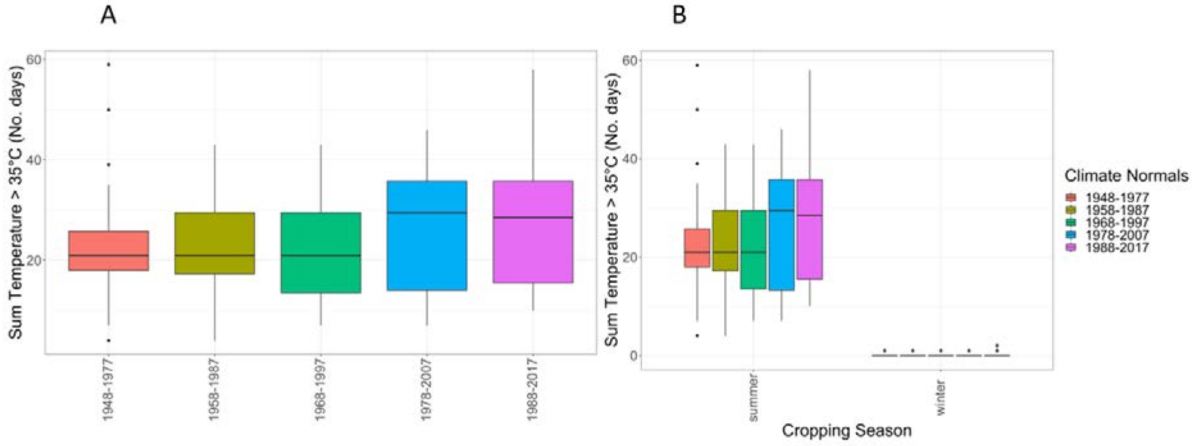

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Sorghum crop yields sown on a full profile of soil water

For northern sites of the western transect (from Mungindi north) there was little change in yield except for a reduction in yield of around 0.5 t/ha at the extremes of early sowing and late sowing (Figure 4). For the northern sites of the eastern transect there was a clear reduction in yield for sites north of Goondiwindi, especially for sowing dates before November. For the eastern transect there were distinct groupings of change in yield: improved yield between Goondiwindi and Moree for crops sown between November and January and decline in yield on the Liverpool Plains that worsened with later sowings and culminated around a mid-December plant.

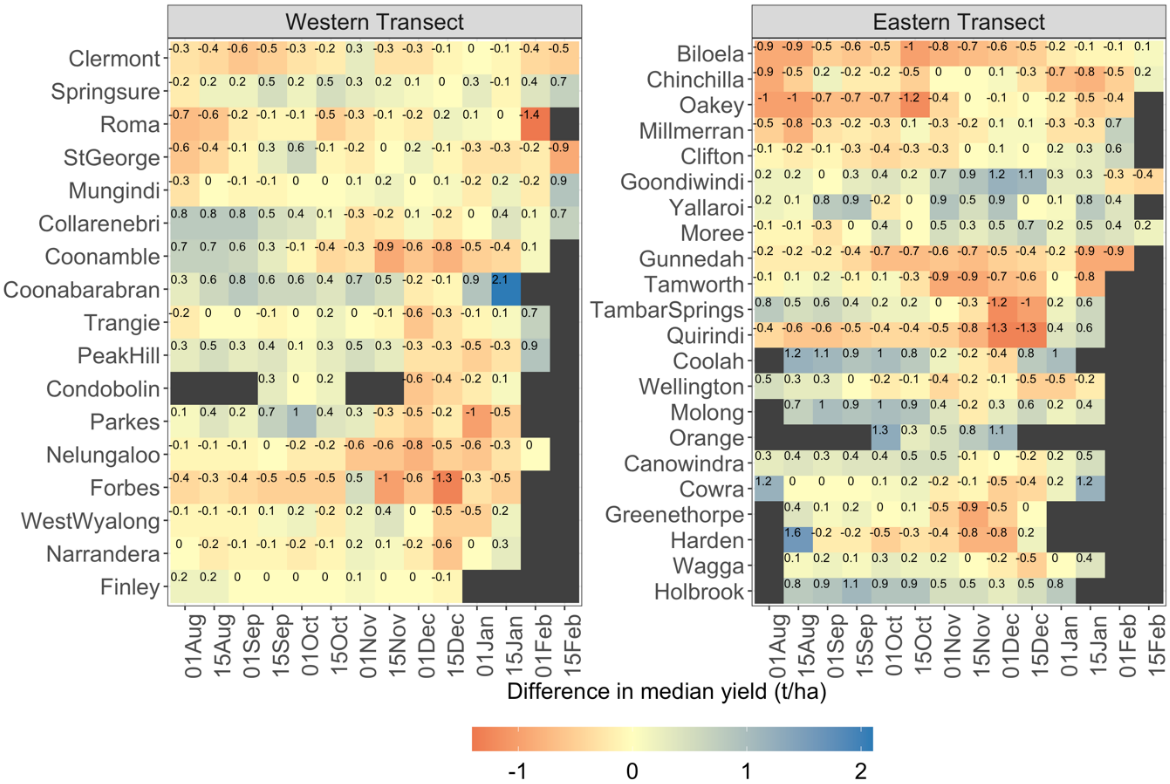

Figure 4. Difference in median yield of sorghum crops between climate normals 1958-1987 and 1988-2017 when sown into a full profile of water, for different sowing dates for locations divided into western and eastern transects. Red shading in cells indicates a decrease in yield, blue indicates an increase, and yellow indicates sowing dates where there was minimal to no difference in crop yield. Only median yields from sowing dates that had fewer than 50% failed crops are included (other location-sowing date combinations were considered unsuitable for crop production and are coloured black). Values within each cell are the difference in yield between the climate normals (t/ha).

What has been the effect of changing climate on yield when there isn't a full profile of soil water at sowing?

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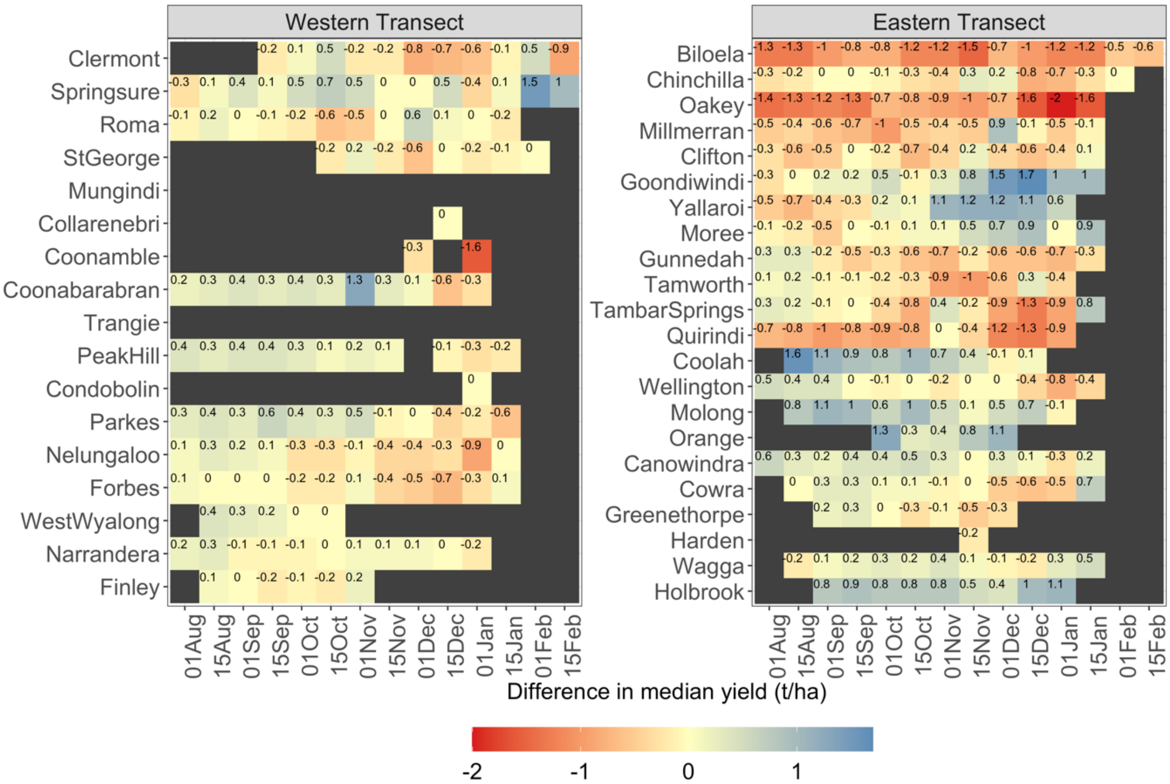

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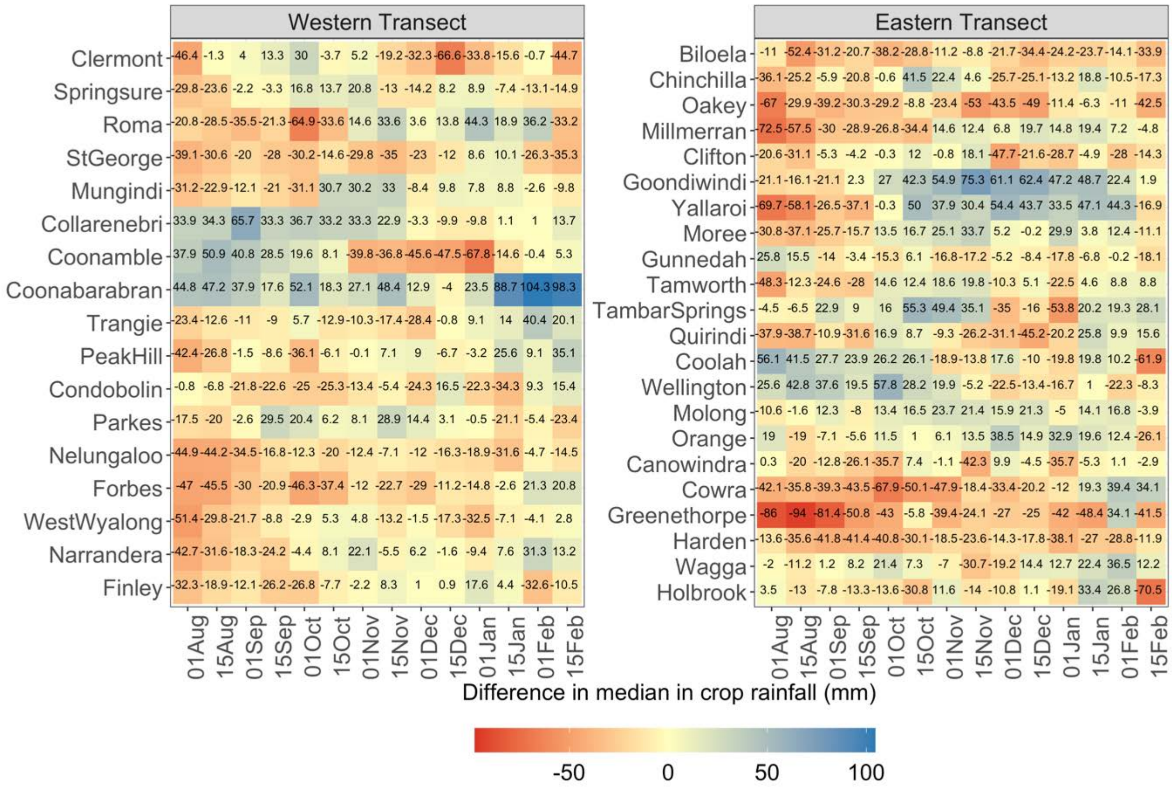
Why are yields changing?

Rainfall

The availability of water to the crop is the key determinant of yield in Australia. The value of stored soil water is its ability to buffer the demands of the plant in between rainfall events and ensure optimal plant growth. The timing and size of rainfall events are critical to maintaining this buffer as is the specific soil type. In general, the quantity of in-crop rainfall decreased or remained neutral across locations in both eastern and western transects, although there was an increase in in-crop rainfall at a few locations (e.g. Coonabarabran, Goondiwindi and Yallaroi for some times of sowing). These locations are those that showed an increase in water limited yield potential (Figures 4 and 7), and highlight that this increase in rainfall pattern has directly resulted in increased yield.

Yallaroi being one of these sites has seen an increase in rainfall for crops sown in late October to mid- November over the last 30 years despite a slight decline in summer rainfall overall.



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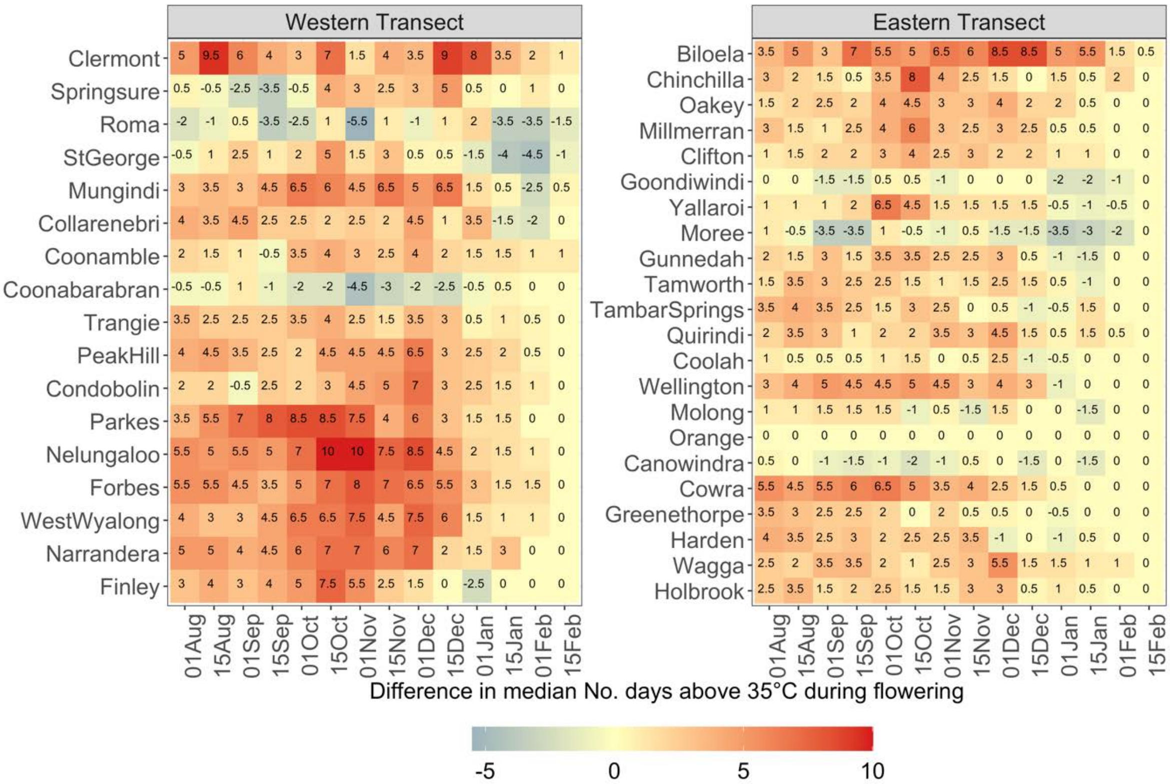
High temperatures around flowering can significantly reduce sorghum grain yield (Lobell et al., 2015; Singh et al., 2017; 2016). The difference in the number of days with temperatures in excess of 35°C increased between the past 30-year climate normal period (1958-1987) and the more recent 30-year normal (1988-2017). The increase in days with extreme temperatures was greater for the western transect, especially for crops sown between October and November. For the eastern transect there was a general increase in the number of days with extreme temperatures for all sowing dates before December. However, a few specific sites experienced a reduction in extreme temperatures; these sites and sowing dates correspond with those that experienced an increase in rainfall and consequently an increase in median yield potential (Figure 7).



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So, what does it mean and what can I do?

The climate of Australia's sorghum production area has changed, with increases in the average daily temperature, an increase in the number of days with extreme temperatures during flowering, and a decrease in in-crop rainfall for many locations. These changes have resulted in an overall reduction in crop yield potential. However, despite this decrease the yield potential has not been reduced to a point where it is no longer economical to grow sorghum. Good agronomy and the use of high soil water triggers at sowing will help maintain profitable returns under changing climates. For sites that had an increase in yield for some sowing dates, this could be traced to increased rainfall and a decrease in extreme temperatures during flowering. However, these increases were relative only to the areas historic production and not an increase above traditionally high yield regions. Thus, despite a decrease in the yield potential over the study period for many areas, this decrease has not caused a noticeable shift in sorghum production areas, and so NSW is not the new central Queensland for sorghum production.

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How has Mullaley's climate changed and what impact has it had on sorghum productivity

Jeremy Whish and Elizabeth Meier, CSIRO

Key words

climate, historic climate, changing yield potential, sorghum

GRDC code

CSP1806-01

Take home messages

- Increasing temperatures and reduced rainfall have lowered the yield potential of sorghum in many areas
- Avoiding high temperatures at flowering and using a conservative sowing trigger (>100mm PAW) can reduce the impact of a changing climate
- There is still room to reduce the yield gap with targeted sowing dates, nitrogen rates and soil water triggers despite a changing climate reducing sorghum yield potential.

Introduction

Australia's climate is warming, including an increase in average temperature, increase in number of days exceeding 35°C and a decrease in rainfall (CSIRO and BOM, 2015).

But what is happening at Mullaley? How will this affect the crops I grow? What can I do to manage this change?

These are some of the questions we have tried to address.

Over the last few years, several suggestions have been made to GRDC that have warranted our examination of sorghum production in response to changing climates. The key concern was that a changing climate had reduced the yield potential of central Queensland crops and would cause the key sorghum production areas to move south to cooler and less variable climates. In this paper we review local annual and growing season climates, sorghum production and compare these results to other sorghum production areas to see how or if things have changed.

Methods

Current climate was compared with historical climate using a climate normal approach to compare overlapping 30-year time periods. This is recognised as the most statistically sound method to determine if a change in climate has occurred (Arguez and Vose, 2011) and is recommended by the World Meteorological Organisation's standard for placing current climate conditions in a historical perspective. A simulation analysis of sorghum production in response to a range of initial soil water and sowing dates was then conducted using APSIM (Holzworth,2014) to identify whether changing these management practices could mitigate the effect of any changes in climate.

How is the Mullaley environment changing?

Rainfall

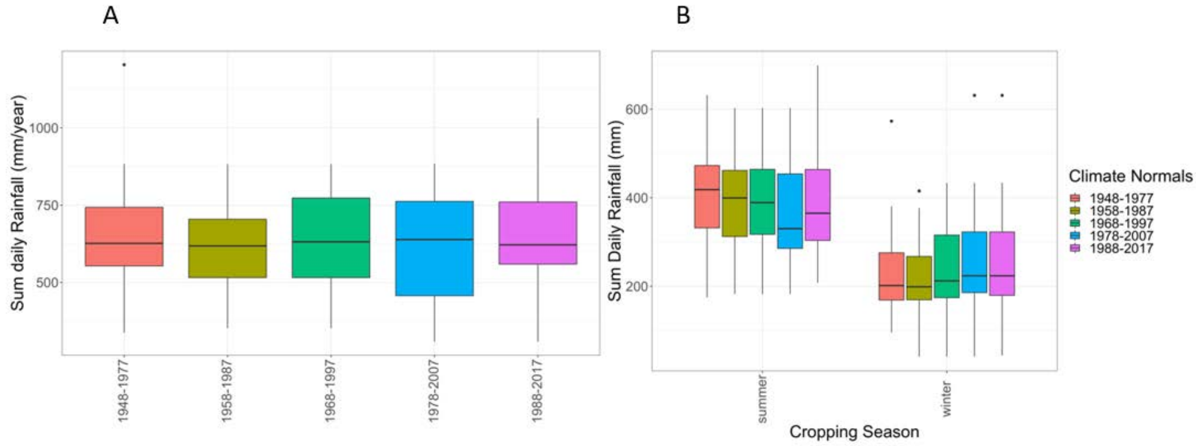


Figure 1. Sum of rainfall for each 30-year climate normal period on an annual (A) and cropping season (B) basis at Mullaley. The results show how rainfall has changed over time. In general, there has been little change in rainfall over the study period. A decline in summer rainfall has been compensated by a slight increase in winter rainfall.

Temperature

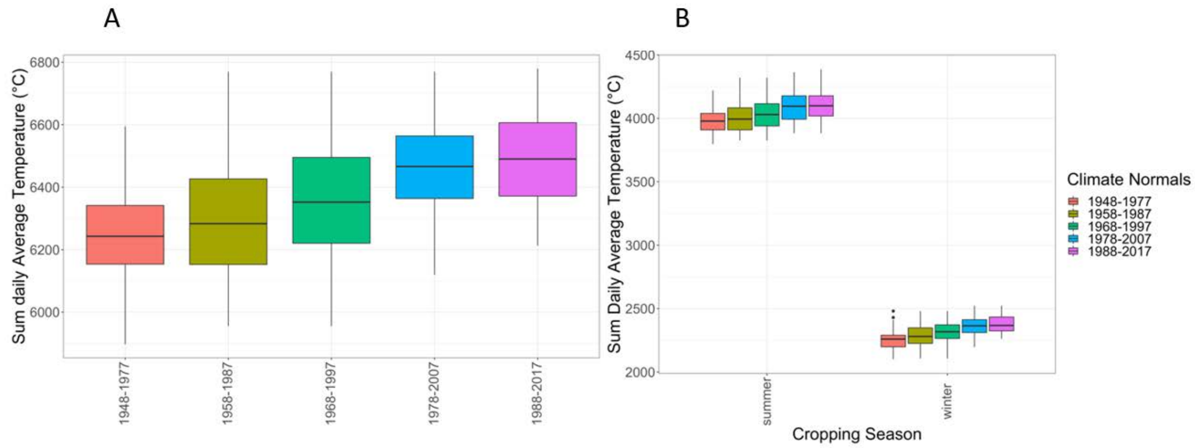


Figure 2. Sum of daily average temperature on an annual (A) and cropping season basis at Mullaley. Average temperature showed a continual increase in heat to the most recent climate normal (1988-2017). The change in accumulation of heat was similar in both summer and winter growing seasons.

Extreme temperatures

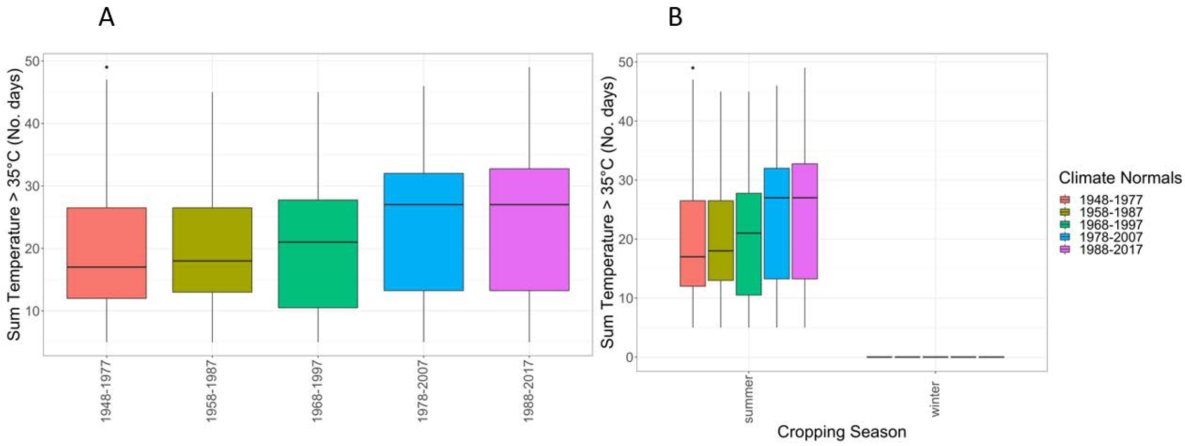


Figure 3. Number of days of extreme temperatures (above 35°C) summed on an annual (A) and growing season (B) basis. The days above 35°C follow a similar pattern to the heat sum on an annual basis increasing to the most recent normal (1988-2017). Extreme temperatures occurred in the summer only.

How will these changes in climate affect sorghum?

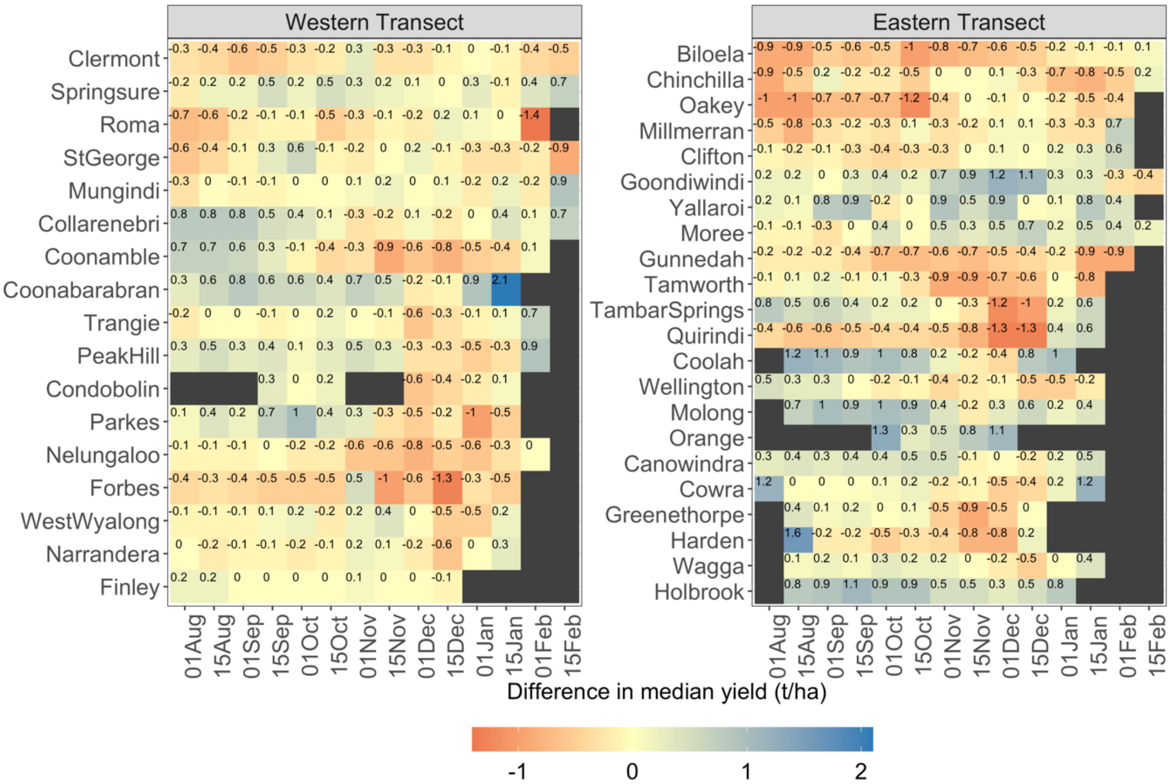
Higher temperatures increase the rate of crop development and the amount of water transpired by the crop. If rainfall remains stable or decreases then this will increase the chance of moisture stress occurring in the crop. However, if the growing period of the crop can be matched to the timing of rainfall then it may be possible to maintain or increase crop grain yield despite an annual reduction in rainfall.

To identify whether the yield potential of sorghum crops had changed over the last 60 years a series of simulations were undertaken. The 60-year period from 1958-2017 was used for this analysis and sub-divided into two climate normals – 1958-1987 and 1988-2017 - that could be compared.

Water stored within the soil helps to buffer crops from variability in the climate. In order to understand the effect on yield of changes in the climate, the median yield from a crop sown into a full profile of water was compared across the 60-year period. This approach was expected to demonstrate the least difference between the two climate normal periods, because each site by sowing date combination had optimal soil water at sowing. The study was completed for a selection of locations (‘transects’) in both the eastern and western parts of the GRDC northern growing region (Figure 4).

Sorghum crop yields sown on a full profile of soil water

For northern sites of the western transect (from Mungindi north) there was little change in yield except for a reduction in yield of around 0.5 t/ha at the extremes of early sowing and late sowing (Figure 4). For the northern sites of the eastern transect there was a clear reduction in yield for sites north of Goondiwindi, especially for sowing dates before November. For the eastern transect there were distinct groupings of change in yield: improved yield between Goondiwindi and Moree for crops sown between November and January, and decline in yield on the Liverpool Plains that worsened with later sowings and culminated around a mid-December plant.



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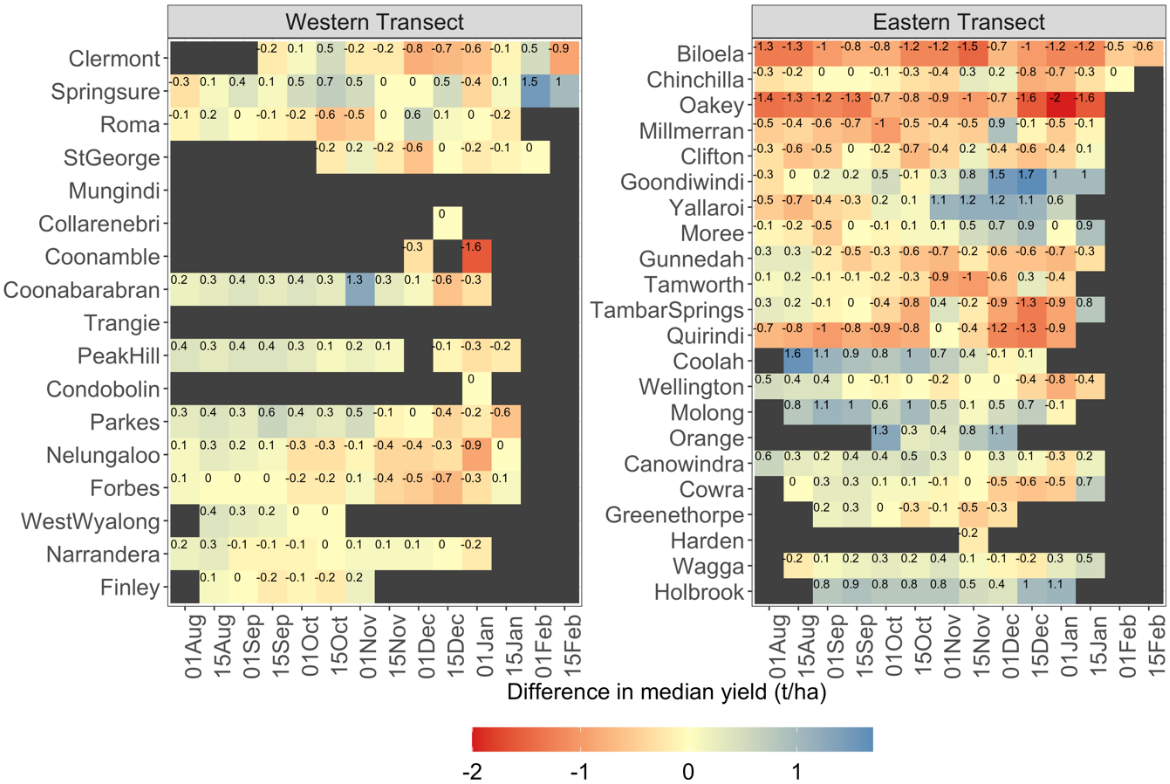

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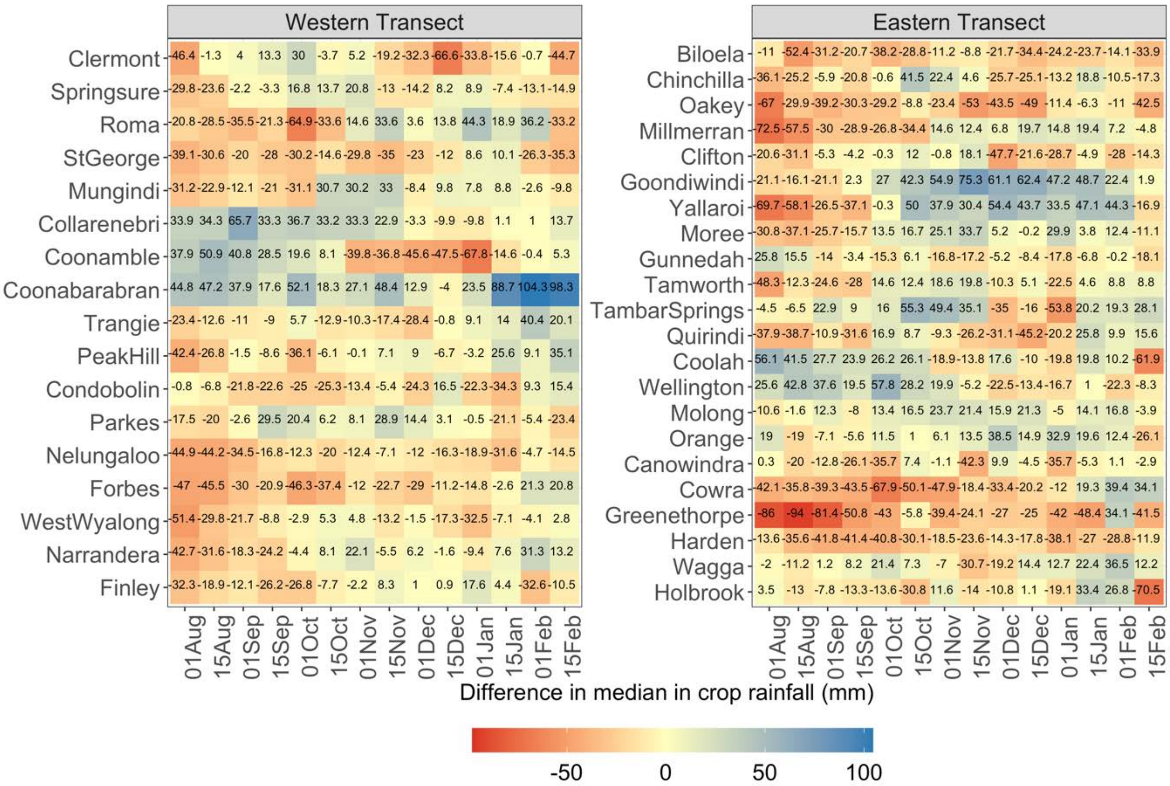
Mullaley being at a similar latitude to Gunnedah is assumed to behave in a similar way, though being slightly west the magnitude of the differences could be less but not as great as in Coonabarabran.



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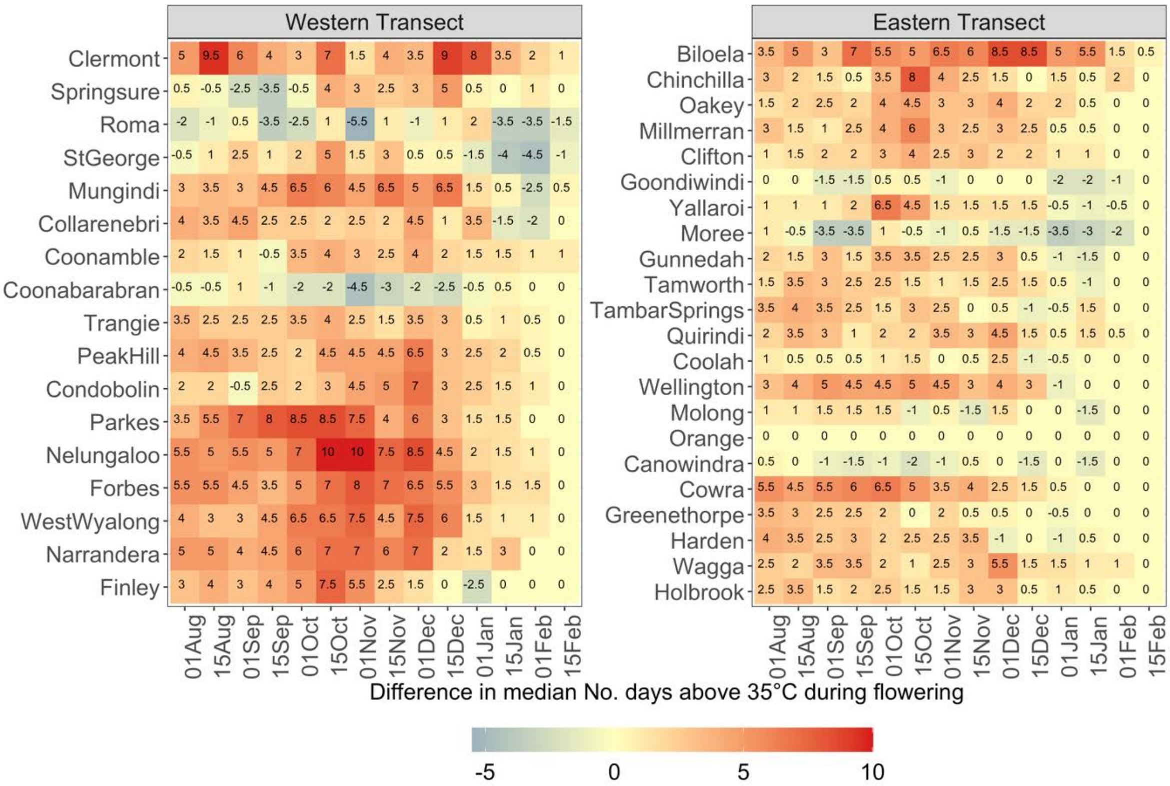

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Designing sorghum crops for Australia's climate in 2050

Graeme Hammer and colleagues, University of Queensland

Key words

sorghum, global warming, climate risk, crop adaptation, traits, management

Project code

CE140100015 - Australian Research Council

Take home messages

- Anthropogenic global warming demands that we think about how to adapt sorghum traits and management for likely future climates
- There is an urgent need to develop varieties with high-temperature tolerance to minimise the effects on seed set of increasing high temperature risk
- Existing approaches to adapting traits (genotype) and management (G×M) for effective use of water through the crop cycle remain relevant but will not be adequate to maintain productivity once global warming of ~2°C is reached and the positive effects of elevated levels of CO_2 on crop growth are counterbalanced
- Novel approaches seeking improvement in fundamental crop water use efficiency will be required.

Introduction

Climate risks pervade agriculture and generate major consequences on crop production. We do not know what the next season will be like, let alone the season 30 years hence. Yet farmers need to decide on genotype and management (G×M) combinations in advance of the season and in the face of this environment (E) risk. Beyond that, breeders must target traits for future genotypes up to 10 years ahead of their release. The considerable knowledge of climate, both past and future, gives us insight into climate variability and trends. Climate risks incorporate natural climatic variability, anthropogenic global warming, and their interactions. Climate trends introduce more uncertainty and reduce the relevance of experience depending on the rate of change. We know that CO_2 and temperature are increasing (Figure 1), and this influences rainfall patterns, high temperature risks, and water use efficiency for crops. The extent of global warming has already generated significant impacts on crops and is projected to have enhanced effects into the future. High temperature has both direct effects (e.g. on pollen viability and seed set) and indirect effects via increased vapour pressure deficit (vpd) that increases crop water use and exacerbates crop water limitations on crop performance. However, enhanced levels of CO_2 are known to improve water use efficiency in sorghum and act to partially counter the negative effects on the water balance from high temperature and vpd.

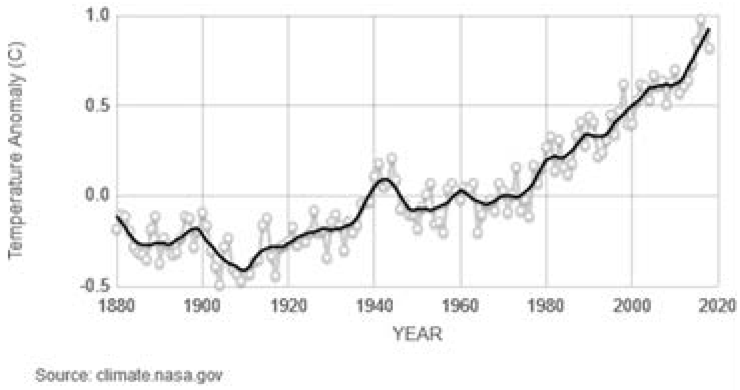

Figure 1. Observed global temperature anomaly (◦C) since 1880 relative to 1951 to 1980 average
(Source: NASA/GISS: https://climate.nasa.gov/vital-signs/global-temperature/)

The considerable knowledge of crop growth and development responses to CO_2, drought, and high temperature have been integrated into advanced crop simulation models in APSIM. Here we explore by simulation the design of crops best suited to current and future environments. A yield–risk framework is used to identify adapted G×M combinations. The yield–risk trade-off is a major factor confronting farmers managing cropping systems faced with significant climate risk.

Climate scenarios and crop simulation

Fifteen sites throughout the sorghum production region, each with long-term historical climate data (~100 years), were selected for the simulation study. Daily weather data for future climate conditions was derived from shifts in temperature and rainfall projected by 2050 from a total of 33 general circulation models (GCMs) (Figure 2). The shifts, relative to a 1990 base, in mean October through March temperature and precipitation for the north-eastern Australia region by 2050 show ranges of +0.7 to +3.3°C for temperature and −15 to +20% for rainfall for the 33 GCMs. Three GCMs were selected to represent optimistic, central, and pessimistic scenarios. The projected CO_2 concentration for 2050 was set at 541 ppm, and 400 ppm was used for the current climate baseline.

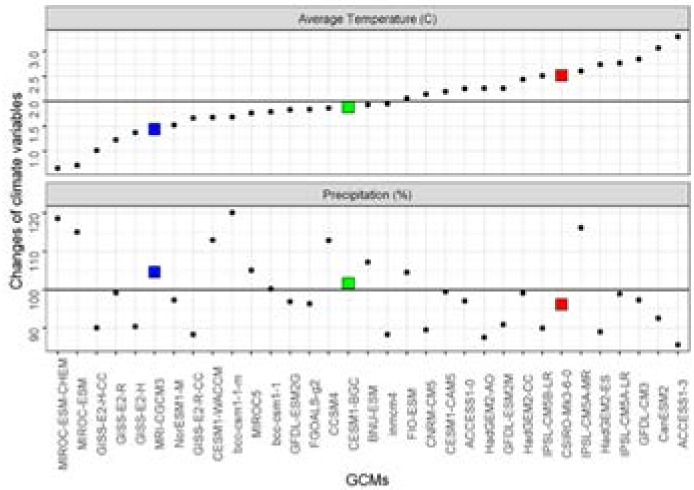

Figure 2. Change in October through March mean temperature (°C) and precipitation (%) in north-eastern Australia by 2050 relative to 1990 base predicted by 33 general circulation models (GCMs). Horizontal lines indicate +2°C shift in mean temperature and no change (100%) in mean precipitation. The GCMs are arranged from left to right in order of increasing predicted shift in

temperature. Coloured squares indicate the three GCMs selected to represent optimistic (blue), central (green), and pessimistic (red) scenarios used in this study.

Crop simulations were performed using current and projected climates for a broad range of sowing dates, antecedent soil moisture, crop management (row configuration, plant density), and genotype attributes (maturity, tillering, high temperature tolerance). Simulated yields were used to generate average yield vs risk plots. Risk was assessed as the frequency of occasions that yield fell below a "break-even" threshold, which was set here as 1.5 t/ha.

Current and future effects of water and high temperature stresses

While water as a limiting factor to crop yield remained a key feature of the sorghum production environment in future climates, it was only under the pessimistic climate projection scenario that any increase in severity was likely to occur (data not shown). This result reflects the interacting negative and positive effects on the crop water balance of increased temperature via increased VPD, projected changes in precipitation, and the increased crop water use efficiency associated with increased CO_2 concentration.

In contrast, the frequencies of high-temperature stress effects were predicted to increase substantially for 2050 climate conditions (Figure 3). As expected, the projected warming by 2050 increased the frequency of exposure to damaging temperatures around flowering causing increased incidence of yield loss independent of the degree of high temperature tolerance assumed. A high-temperature-tolerance threshold of at least 36°C was required to minimise the incidence of high temperature stress in 2050 climate scenarios.

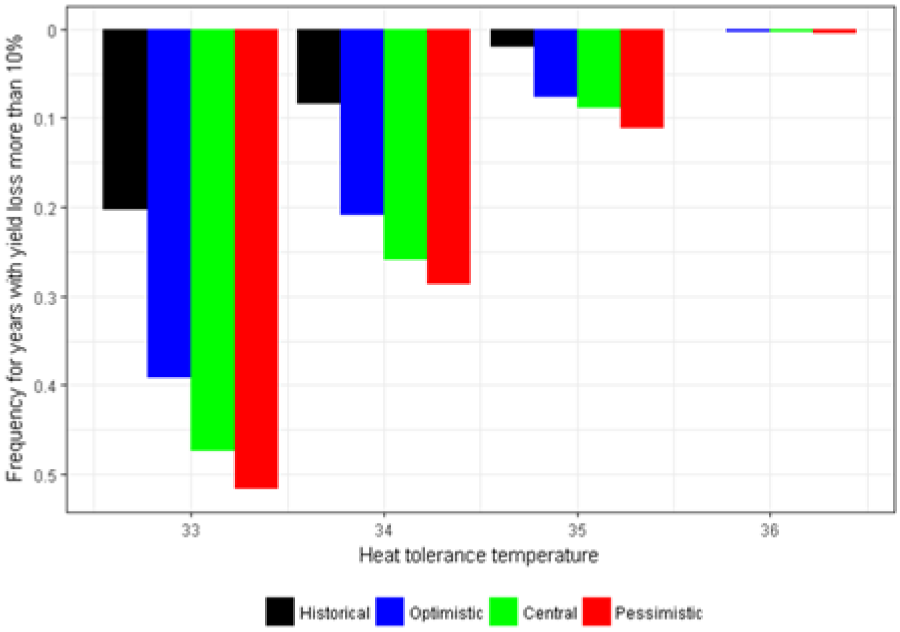

Figure 3. Frequencies of cases with simulated yield loss >10% due to the occurrence of high-temperature events around flowering for historical climate (black bars) and future (2050) climate generated by three general climate models selected to represent optimistic (blue), central (green), and pessimistic (red) for genotypes varying in their threshold maximum temperature tolerance from 33°C (susceptible) to 36°C (tolerant)

Crop adaptation under current and future climates

Broad adaptation

Broad adaptation for the entire region was examined using a yield–risk plot for average simulated yields across all production environments (Figure 4) using standard management (solid 1-m rows, density 5 plants m^{-2}) for the range of genotype factors affecting crop canopy dynamics and water balance (i.e. maturity and tillering combinations). There was a clear trade-off between productivity and production risk among the genotype combinations for the historical climate scenario (Figure 4(a)). The technology frontier on the yield–risk plot is represented by those points with greatest yield at a given risk up to the point where average yield starts to decrease as risk increases, that is, for the points on the frontier where there is no outcome with greater yield at the given risk level nor lesser risk at the given yield level. The peak of this frontier (circled on Figure 4(a)) was populated with early maturing and high tillering types.

(a)

(b)

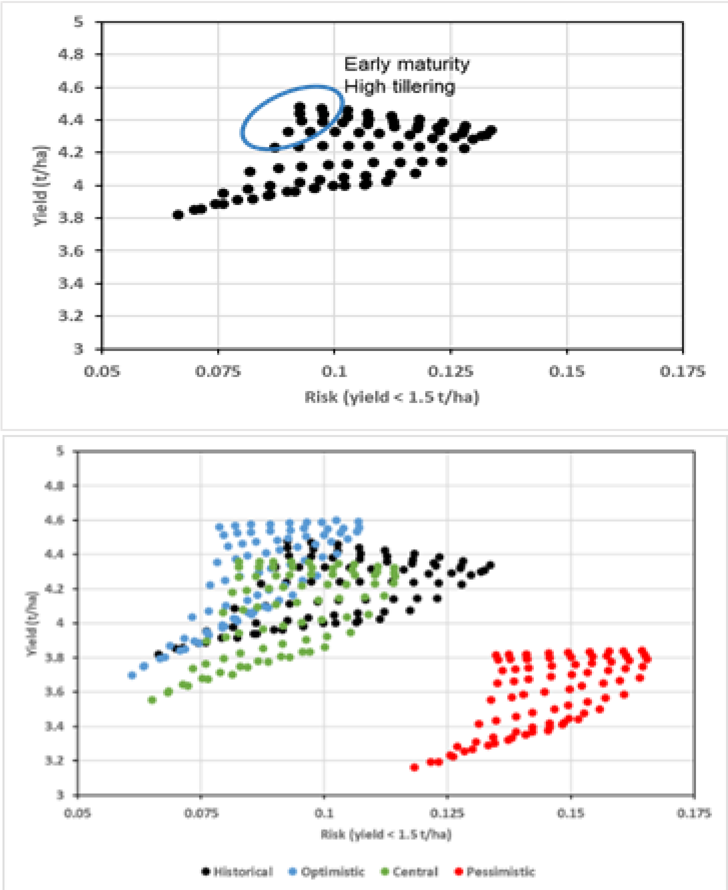

Figure 4. (a) Simulated average yield–risk trade-off for the historical climate scenario for genotypes varying in maturity and tillering grown with standard agronomy. Average yield for each genotype is derived from simulations over all environments (sites, seasons, soils, times of sowing, antecedent moisture levels) sampled in the production region. Production risk for each putative genotype is quantified as the frequency of occasions in which simulated yield falls below 1.5 t/ha.
(b) Simulated average yield–risk trade-off for genotypes varying in maturity and tillering grown with standard agronomy (as in (a)) but for the four climate scenarios used in this study: historical (black), optimistic (blue), central (green), and pessimistic (red).

Yield–risk plots were also generated across all relevant environments using standard management to examine broad adaptation within each future (2050) climate scenario (Figure 4(b)). In all cases, the nature of the technology frontier was not affected so that the early maturing and high tillering types remained preferred. However, there were significant shifts in average yield and risk associated with each future climate scenario. There was a slight advantage associated with the optimistic scenario due to the improved water balance (i.e. higher rainfall and CO_2 fertilisation effects). However, for the pessimistic future climate scenario, average yield was substantially reduced, and production risk was substantially increased. This reflects a tipping point in the crop water balance as the slightly reduced rainfall and increase in VPD (via temperature increase) impose negative consequences sufficient to outweigh the enhanced crop water use efficiency from CO_2 fertilisation.

These general effects on broad adaptation across the entire north-eastern Australian sorghum production region were also maintained in the patterns of response evident at subregional levels, although there were differences in average yield and risk levels among subregions (data not shown). It is clear that avenues for broad adaptation in sorghum in these production environments based on modifying canopy development and water use dynamics via changes in maturity and tillering cannot counter the negative effects anticipated in future climates once global warming of ~2°C is reached.

Specific adaptation

Specific adaptation was examined at subregion level by considering management options beyond the standard management used for the analysis of broad adaptation. Yield–risk plots for simulations of all possible G×M combinations affecting canopy dynamics were generated across all relevant environments within each current or future climate scenario for sites in each subregion. The yield–risk plots in Darling Downs East (DDE – Pittsworth, Dalby, Miles) and South-West (DDSW - Goondiwindi, Moree) showed potentially advantageous shifts on the technology frontiers (Figure 5). In all cases, this was associated with simultaneous reduction in both population density and tillering (and skip row in DDSW), which would generate a reduced canopy size relative to the broad adaptation combination. However, for the favourable, higher-yielding environment (DDE), the shift from the standard broad adaptation practice was only minor, as risk in this situation was generally low. It involved only a small reduction in risk that was associated with some trade-off in reduced yield. However, for the less favourable, lower-yielding environment (DDSW), the reduction in risk with specific adaptation was greater and could be obtained with little or no trade-off in yield depending on climate scenario.

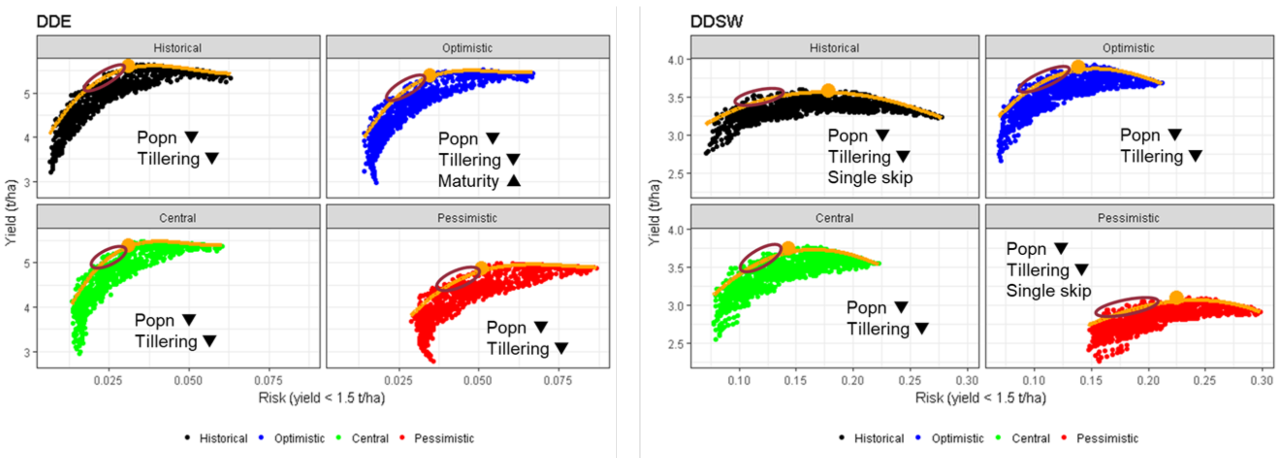

Figure 5. Simulated average yield–risk trade-off for all combinations of genotype (G) and management (M) attributes for the Darling Downs East (DDE) and Darling Downs Southwest (DDSW) subregions for the four climate scenarios used: historical (black), optimistic (blue), central (green), and pessimistic (red). The solid line indicates the technology frontier of superior G×M combinations. The filled circle indicates the position of the optimal G with standard M (broad adaptation combination). The ellipse indicates potentially superior combinations of G×M associated with the

indicated directional shifts in factors relative to the broad adaptation case. Note that scales differ for the two subregions, as the risk is generally low for the higher-yielding subregion (DDE)

While the genotype and management strategies needed to cope with all three climate scenarios were similar, options to adapt sorghum to these future production environments based on modifying canopy development and water use dynamics via t changes in both G×M attributes included in this analysis cannot counter the negative effects anticipated in future climates once global warming of ~2°C is reached.

Conclusions

Anthropogenic global warming contributes another dimension to the existing climate risks affecting crop productivity in sorghum. The results in this case study indicate the urgent need for high-temperature tolerance to mitigate effects on seed set and address increasing high temperature risk. Further, existing approaches to adapting traits and management (G×M) for effective use of water through the crop cycle will not be adequate to maintain productivity once global warming of ~2°C is reached and the positive effects of CO_2 fertilization are counterbalanced. Novel approaches seeking improvement in crop water use efficiency will be required. These are the focus of current research.

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Dryland and irrigated winter-sown sorghum

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Key words

frost tolerance, GxExM, grain sorghum, heat stress, soil temperature

GRDC code

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Take home messages

- Winter sowing sorghum didn't penalise yields in eight trials sites from Liverpool plains to Central Queensland and across two seasons
- In dryland cropping, winter sown sorghum provides additional sowing opportunities, reduces the chances of heat stress, and increases the chances of double cropping a winter crop
- In irrigated cropping, ratooned winter sown sorghum can compete with cotton on profits and is less risky
- Commercially available hybrids can successfully germinate and emerge in cooler soils than previously recommended, though the seed must be tested for vigour at low temperatures
- Sorghum seedlings can withstand mild frost, though so far, we haven't been able to frost kill a crop, meaning that frost risk is unknown.

Background

Water stress and extreme heat at flowering are common stresses limiting yield in sorghum across the Northern Grains Region. Earlier sowing of sorghum could avoid heat and water stress at flowering. However earlier sowing or winter sowing of sorghum in southern Queensland requires the crop to be sown into soil moisture in cold soils.

Dryland farmers are already successfully sowing maize and sorghum earlier than recommended, though the benefits for yield and the cropping system and the likely risks are not known. Previous research by Muchow, et al., (1994) identified that winter sown sorghum crops show high yield potentials with increased frost risk and a larger canopy increasing water stress risk. However, these risks require re-evaluation because frost risk thresholds (thresholds were assumed in previous research) are unknown and modern hybrids have a smaller canopy.

In irrigated systems, sorghum is a profitable option when irrigation water is limited, though it is often assumed to be a less profitable option than cotton in fully irrigated systems. Winter-sowing and opportunistically ratooning sorghum allows growers to manage risk when water supply is limiting at the beginning of the season and intensify production and profits if rainfall is greater than expected.

Previous research shows that ratooned irrigated sorghum crops yield 80% of the sown crop yield on average (Gerik et al., 1990). Growers in Central Queensland successfully ratoon irrigated sorghum crops, though questions remain on the suitability of the system in southern regions and crop sequences.

Here we report on irrigated and dryland trials conducted by UQ-QAAFI in the 2018-2019 seasons. This series of trials is part of the multi-environment sorghum agronomy experiment in collaboration with DAFQ and NSW DPI. The experiment was designed to develop a data set to support the present trend in advancing sowing times of sorghum and assess potential benefits and risks from adopting the strategy at the crop and cropping system levels.

Trial details

Two trials were sown in the 2018-2019 season at Surat and Warra, Qld. Trials included three times of sowing, four plant populations and nine commercial hybrids (Table 1). In addition, after the harvest of the second time of sowing at Surat, the crop residues were mulched, fertilised, irrigated and allowed to ratoon into a second harvest. A third time of sowing occurred at the same time when sowing 2 was ratooned (Table 1). This allowed us to also compare the yield of the ratooned sorghum crop with the yield of a sown crop.

Table 1. Winter-sown sorghum agronomy trial locations and treatments

Time of sowing (TOS)	Sowing date	Target plant population (pl/m^2)	Hybrids
"Austin Downs" Surat, Qld (irrigated)		3, 6, 9, 12	MR Buster, MR Apollo, MR Taurus, Agitator, Cracker, HGS 114, A66, G33, G44
1	8th August 2018		
2	28th August 2018 & ratooned		
3	24th January 2019		
"Wywurrie", Warra, Qld (dryland)			
1	27th July 2018		
2	19th October 2018		
3	9th November 2018		

Results and discussion

Optimum flowering windows

Crop growth conditions around flowering are important in determining final grain number and grain yield. At flowering, grain number can be reduced by temperature extremes, both heat and chilling (i.e. cold but non-freezing temperatures). Analyses of long-term climate records (see CliMate App), can be used to quantify the likelihood of these stresses around flowering and identify ideal flowering windows.

For example, Figure 1A shows that chilling or heat stress temperatures are least likely in narrow and regionally specific windows during spring and autumn. These windows have a lower likelihood of heat (>38°C) and chilling (<13°C) events in a 10-day period corresponding to the sensitive flowering phase. However, the impacts of extreme temperatures on yield depend on duration of the heat/chilling exposure, crop water status and cultivar. Research on the relationships between extreme temperatures and the yield of early sown sorghum will continue throughout the GRDC funded project "Optimising Sorghum Agronomy".

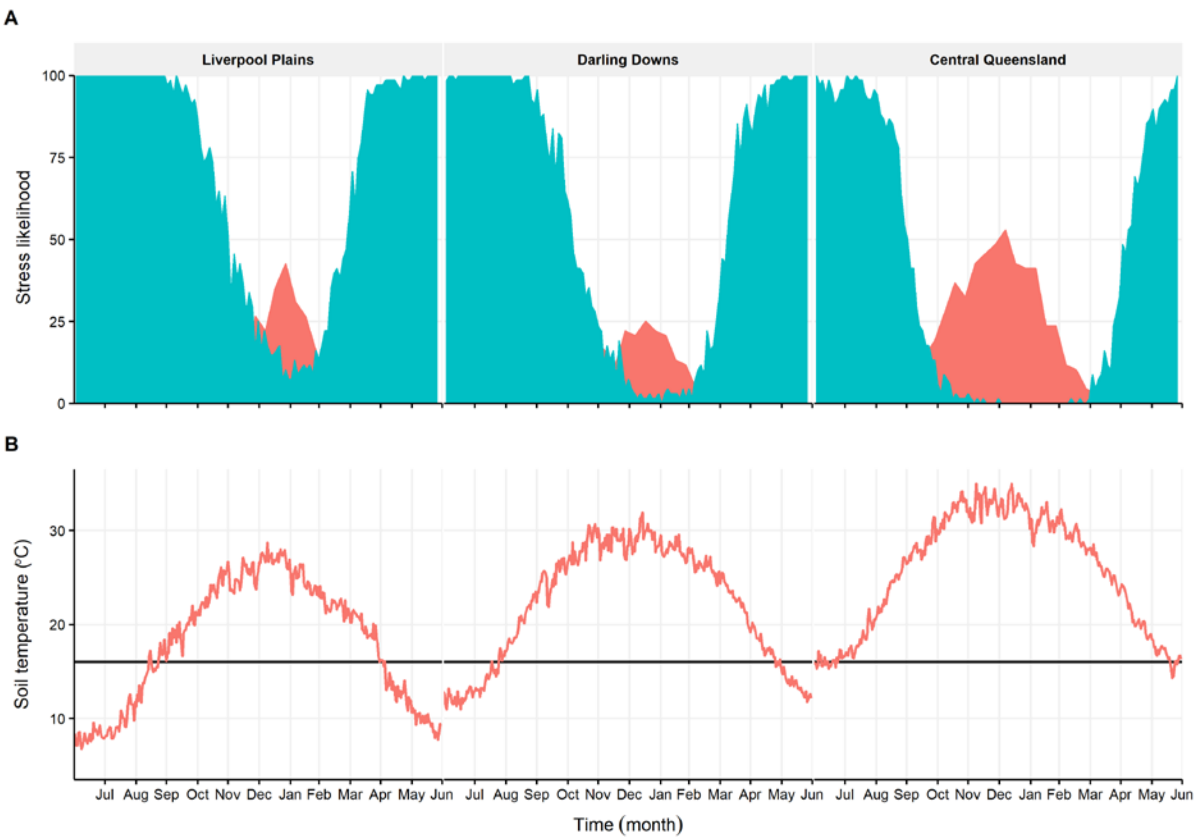

Figure 1. The likelihood or percentage of seasons exposed to heat (>38°C; **red**) or chilling (<13°C; **blue**) during a 10-day temperature sensitive period around flowering (A); and (B) the mean 9:00 am soil temperature measured at 50 mm depth in three sorghum growing regions, the Liverpool Plains, Darling Downs and Central Queensland. The horizontal line in Figure 3B shows the recommended minimum seeding depth temperature threshold for sorghum. (Note: 9:00am soil temperatures are shown because high quality long-term data for the conventional 8:00 am or minimum daily 100 mm deep soil temperatures were not available).

Targeting optimum flowering windows

The easiest way for growers to move the flowering window is to plant at a different time to their standard sowing time or to select a quicker maturity hybrid. As there is limited variation in maturity type among the commercial hybrids, moving the sowing window is the more effective option. This means sowing sorghum crops much earlier than normal, potentially moving sowing into the months of July and August depending on local climate. Soil temperatures during this period are cooler than the recommended (>16-18°C measured at sowing depth during the coolest period of the day or 8:00am; Figure 1B). Long-term trends show that July to August soil temperatures are coldest in the southern regions of Darling Downs and Liverpool Plains. However, time of sowing decisions require information on each field because of varying weather, topography, soil type, water content and ground cover, all of which strongly influence seedbed temperature.

Regardless of the sowing time, achieving rapid and uniform crop establishment is also required to realise yield potential. The decision on sowing time will then need to evaluate the trade-off between likely benefits of reducing heat stress around flowering, with the higher risk of early frost damage, higher establishment losses and potential for less even crop canopy uniformity.

Temperature effects on sorghum germination in 2018-2019

Planting sorghum into moist soils at extremely low or high temperatures can reduce crop establishment and reduce crop uniformity. Crop establishment is the result of several distinct plant development stages including seed germination, emergence, root proliferation and leaf growth. Here we studied the impact of extreme temperatures on the germination for a range of commercial sorghum hybrids in the lab.

Results showed that the lowest and highest observed seedbed temperatures from Figure 1B, reduced the proportion of sorghum seeds that successfully germinated in the lab (Figure 2).

Eight of the ten most widely grown sorghum hybrids showed germination values greater than 90%, when incubated with ideal moisture and at constant temperatures between 13 and 32.1°C (Figure 2). At 9.4°C, two of the ten tested hybrid seedlots still showed germination values larger than 90%.

Higher temperatures (≥34.9°C) reduced the germination of five out of the ten tested seedlots, yet three hybrids showed germination rates greater than 90% at extreme hot temperatures (39.5°C).

In these experiments, seeds were exposed to constant high temperatures for multiple days, whereas in the field, seedbed temperatures fluctuate diurnally. Maximum daily seedbed temperatures of 45°C were recorded during the 2018-2019 sorghum agronomy trial at Emerald, though those temperatures only exceeded the high thresholds for a short period each day (< 1 hour).

Seed production, storage, handling, seed treatment and genetics will all determine the germination rate for each hybrid-seedlot. Therefore, germination must be evaluated every year for each hybrid-seedlot. Understanding the drivers for low germination in Australian germplasm remains a priority research question.

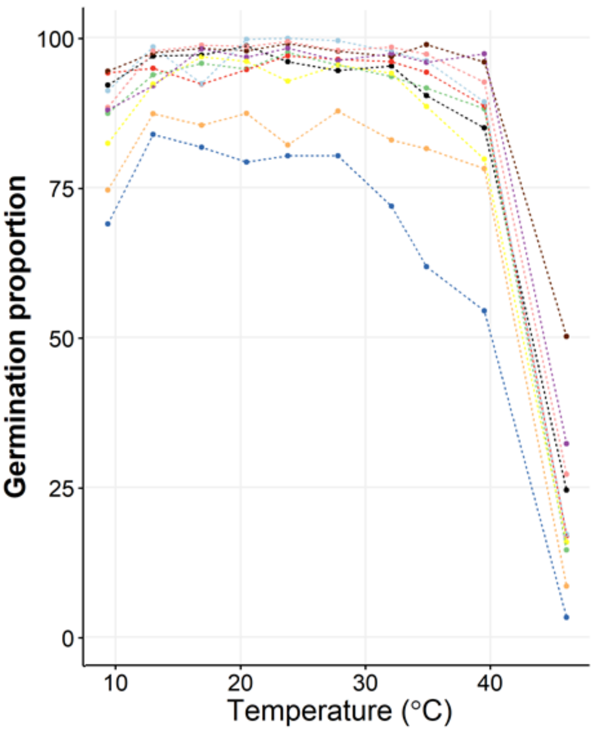

Figure 2. The proportion of sorghum seeds that successfully germinated when incubated at constant temperatures. Each colour represents one hybrid seedlot but they are not identified as the experiment doesn't differentiate if the result is due to genetic, seed production or storage factors.

__2018-2019 temperature effects on predicted time required for successful sorghum germination__

Low temperatures delay the period from sowing to germination and emergence. Therefore, quantifying the number of growing degree days is important. Growing degree days (GDD) are a measure of the accumulation heat and are used to predict plant development. GDD = ∑(Tmax – Tmin)/2 – Tbase. Tmax and Tmin are the daily maximum and minimum temperatures. Tbase is a crop specific minimum temperature for development. Here we estimated the required number of cumulative heat units for ten commercial hybrid seedlots under a controlled temperature environment. The results show that the first 10% of seeds germinate with 5 days but it took 9 days to achieve >90% germination at Surat in 2018 (Figure. 3). Results also show that germination time is similar across diverse sites on some dates, but germination timing is also highly variable for different sowing dates at any site (Figure. 3).

This means that July-August soil temperatures ≥9.4°C do not limit germination of commercially available sorghum hybrid-seedlots. However, germination will take a long time and will be spread over several days, meaning that the seedbed must remain moist for at least 9 days for successful germination and longer for emergence.

Investigations into the impacts of low seedbed temperatures on emergence continue in 2019-2020 through the GRDC funded project “Optimising Sorghum Agronomy”.

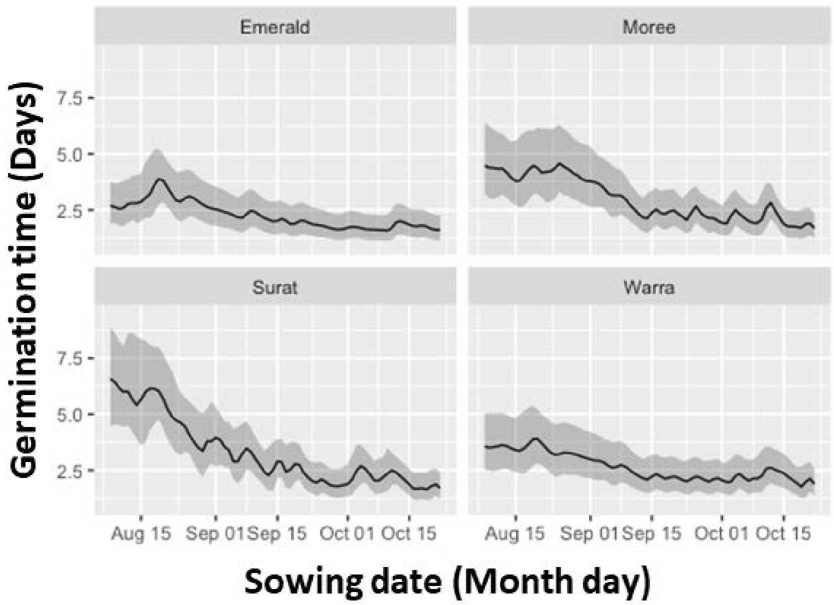

Figure 3. The predicted number of days from sowing until germination for sowing dates between 1st August and November 2018 based on seedbed temperatures recorded at four on-farm trial sites. Black line shows 50% seed germination and the grey shading shows the spread from 10 to 90% germinated seeds. (Note: data is for seed germination and not for crop emergence which will take far longer)

Climatic conditions for 2018-2019 trials

The 8:00am seedbed temperature at Surat for sowing time one was 8°C and it emerged 20 days later with seedbed temperatures of 10°C. Seedlings survived two mild frosts (~0°C) in late August and mid-September (Figure 1C). The earliest flowering hybrids in the first time of sowing had the highest photo-thermal quotient during flowering, meaning that growth and yield formation potential was greatest (Figure 4A). Flowering time of the latest flowering hybrids in the first time of sowing overlapped with the earliest flowering hybrids for the second time of sowing, meaning that combinations of hybrid and sowing time are required to target flowering (Figure 4A). Water was sufficiently available for all treatments, except irrigation ran out before time of sowing three finished flowering (Figure 4B). Maximum temperatures were high for all sowing times (Figure 4C).

Seedbed temperatures at 8:00 am measured at sowing depth (75mm) for the first time of sowing were 12°C and seed germinated 2 days later on the 30th July. Soil temperatures decreased to 10°C and seedlings emerged between 8 and 17th August. The first time of sowing at Warra had four consecutive frost days with minimum daily temperatures of 0, -4, -5 and -2°C without seedling death (Figure 5C). Pre-flowering rainfalls prevented water stress at flowering for time of sowing one and two, but time of sowing three was water stressed at flowering (Figure 5B). High temperatures occurred during flowering for all three sowing times (Figure 5C).

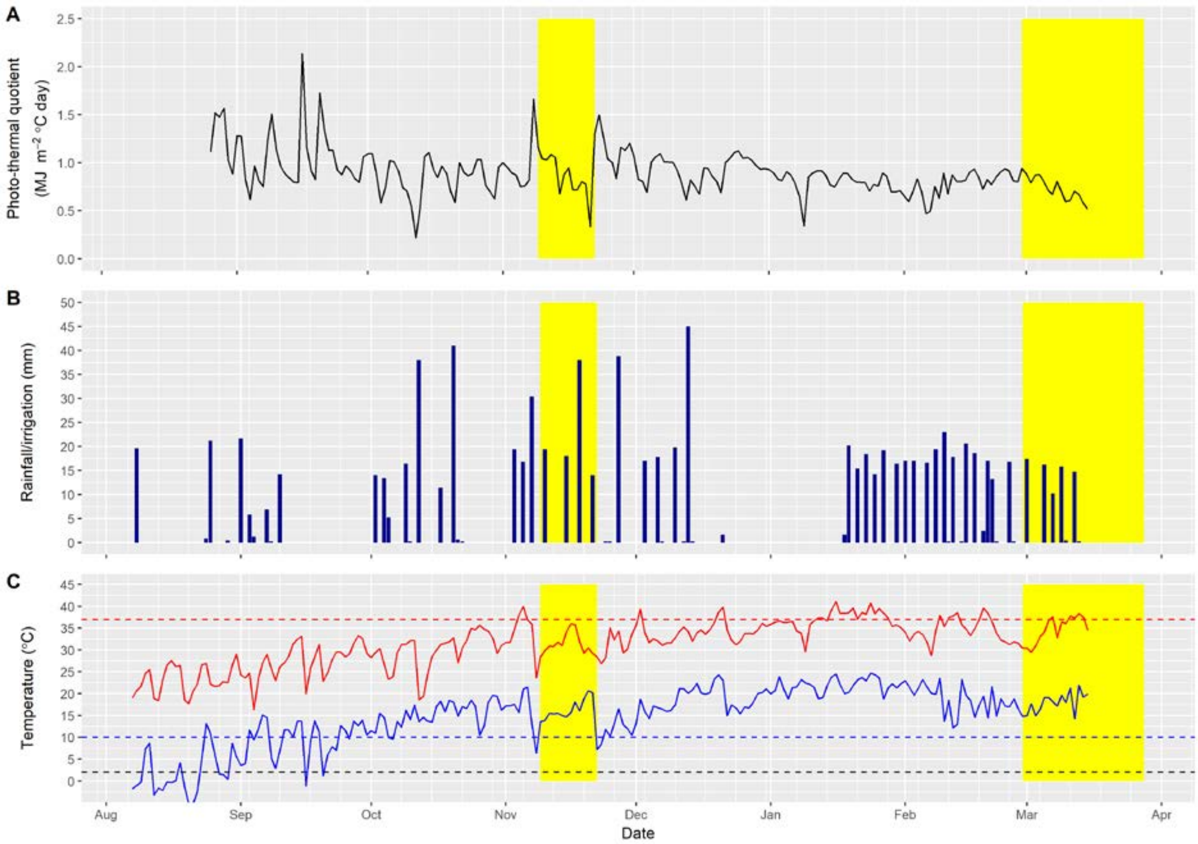

Figure 4. Photothermal quotient (A), rainfall (B) and ambient temperatures (C) at Surat, Qld for the 2018-2019 summer cropping season. The two yellow rectangles indicate the overlapping flowering timing for the 8th and 28th August 2018 sowing dates and 24th January and ratoon crop flowering dates, respectively. Solid blue and red lines represent daily maximum and minimum temperatures, respectively. Dashed horizontal represent the reported minimum (blue) and maximum (red) temperatures stress thresholds at flowering and frost (black).

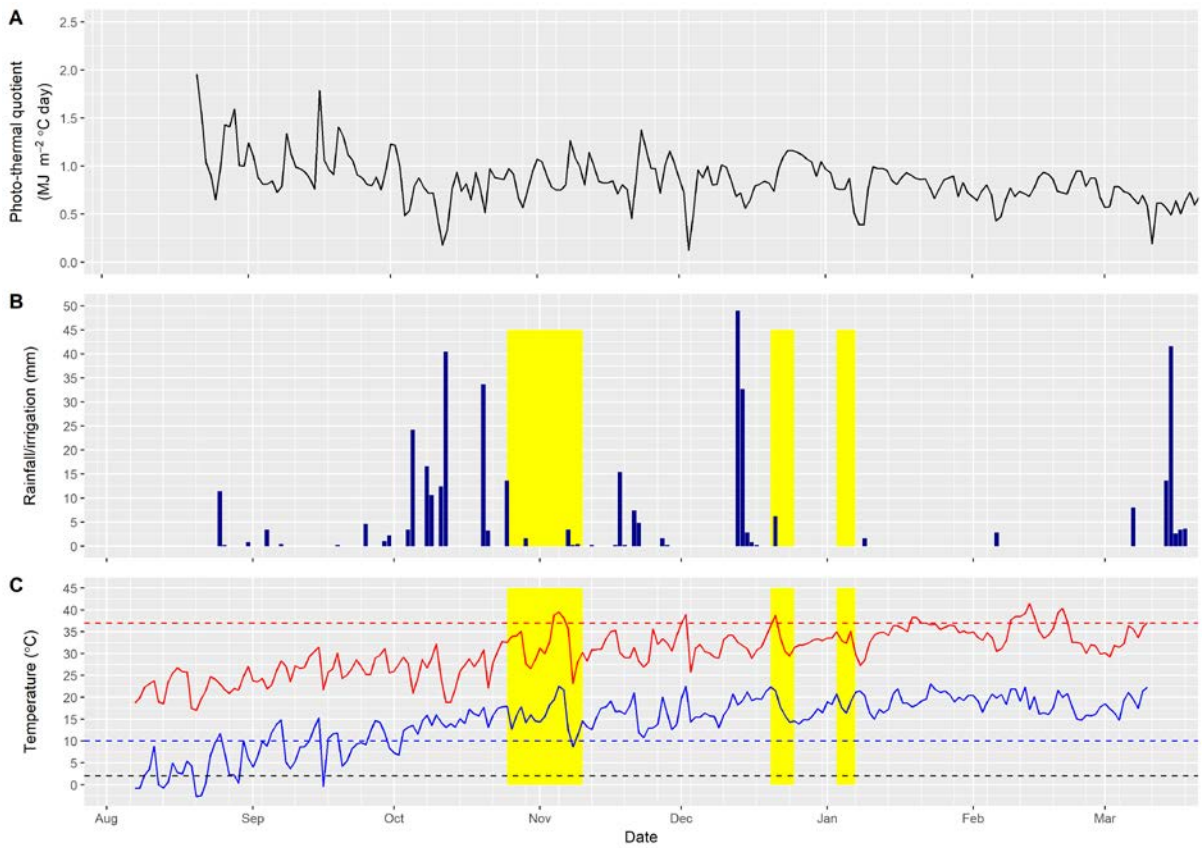

Figure 5. Photothermal quotient (A), rainfall (B) and ambient temperatures (C) at Warra, Qld for the 2018-2019 summer cropping season. The three yellow rectangles indicate flowering timing for each sowing date (see **Table 1**). Solid blue and red lines represent daily maximum and minimum temperatures, respectively. Dashed horizontal represent the reported minimum (blue) and maximum (red) temperatures stress thresholds at flowering and frost (black).

Winter sown sorghum yields

We expect high yields for early sown sorghum crops when water is sufficient, because sunny spring days with cool temperatures (high photo-thermal quotient) should maximise growth rate. However, cool non-freezing "chilling" temperatures can stress some crops and cultivars. Low temperature limits for sorghum growth and development are not characterised for modern Australian hybrids.

At Surat, grain yields averaged across all hybrids were approximately 10 t/ha (11.3 t/ha at 13% moisture content) for all plant populations sown on 8th and 28th of August (i.e. time of sowing 1 & 2; Figure 6). Lack of tillering and water stress contributed to lower yields for time of sowing three (sown 29th Jan 2019) at Surat. The ratooned time of sowing two (28th Aug 2018) crop yielded approximately 75% of the sown time of sowing two crop yield, but similar yield to time of sowing three (24th Jan 2019). The ratoon crop yields were similar to reported yield potential, but time of sowing three that grow during a similar time showed a yield gap. This result will be further analysed in the new GRDC funded project that investigates the impacts of early sowing and ratooning on root growth and water stress.

At Warra, grain yields averaged across all hybrids decreased with latter sowing dates, especially for lowest plant population densities (Fig 6) despite substantially lower pre-flowering rainfall (Figure 5C).

These results mean that sorghum crops can be sown much earlier without yield penalty, supporting 2017-2018 results. Further research on sorghum growth, development and root function at frost and chilling temperatures is required to understand early sown sorghum yield potential.

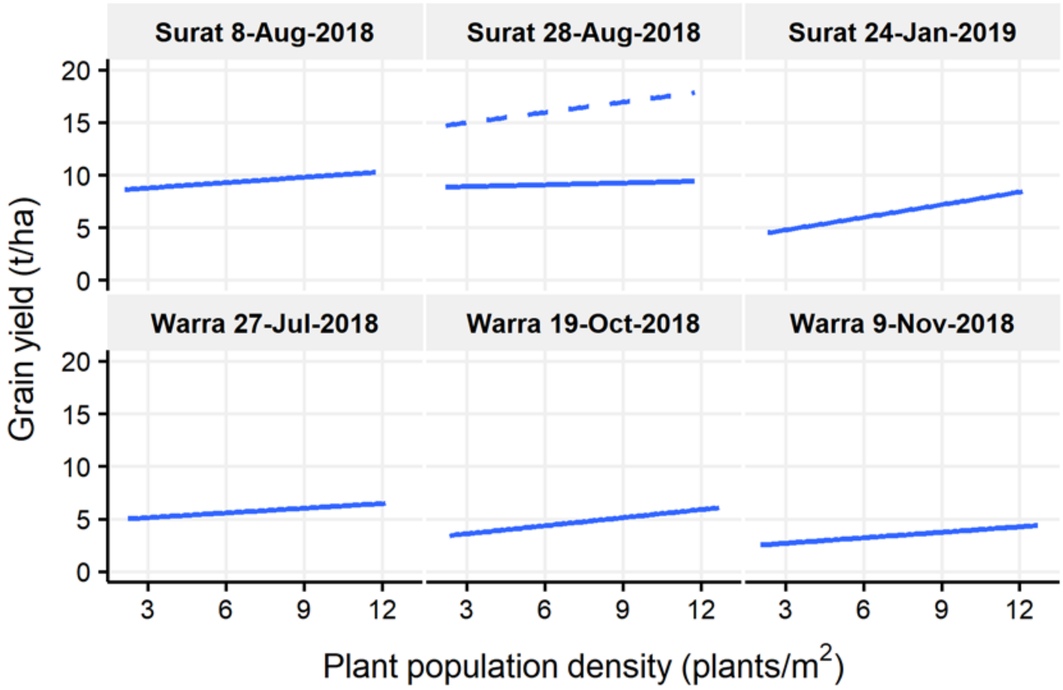

Figure 6. The effect of plant population density on sorghum grain yields averaged across all hybrids for three sowing times at Surat and Warra trial sites for the 2018-2019 summer cropping season. Solid lines indicate grain yield (dry weights) for sown crops and dashed lines show combined sown and ratoon crop yields for the Surat 28-Aug-2018 sowing.

Conclusion

Sorghum can be sown into soil moisture much earlier than recommended, but seedbed temperatures must be monitored in each field and the seed must have high germination rates at low temperatures. Treated stored seed from previous seasons should not be used.

Ratooning of sorghum provides an alternative to cotton, particularly in seasons with low water availability.

The Optimising Sorghum Agronomy project is developing agronomic packages for winter-sown sorghum. For more information follow us on Twitter @Queensland_fsr and at https://www.qld-fsr.info/

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In particular, the support of the Bidstrup, Warra and Milla, Surat families is gratefully acknowledged.

Optimising sorghum agronomy is a collaboration between the Grains Research and Development Corporation, University of Queensland, NSW Department of Primary Industries and Queensland Department of Agriculture and Fisheries.

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Improving yield reliability of grain sorghum in north-west NSW

Loretta Serafin, NSW DPI, Tamworth

Key words

sorghum, yield, risk, row configuration, plant population

GRDC code

DAN00150 Sorghum in the western zone

DAN00200 Building capacity in the northern grains region

UOQ 1808-001RTX Optimising sorghum agronomy

Take home messages

- Starting with a full profile of soil moisture is the best way to reduce the risk of crop failure in north-west NSW
- Using skip or wide row configurations can potentially reduce the risk of crop failure by saving soil water for post anthesis but can also limit yield potential. Solid plant offers more advantages in seasons where yields are likely to be above 3.0 t/ha
- Plant populations should target establishing at least 5.0 plants/m^2 to achieve average yields
- Moving the planting window earlier than currently recommended is under evaluation and may be a useful tool to manage heat and moisture stress risk associated with flowering in December
- Further interrogation of current data, in combination with simulation using APSIM, is expected to provide a more robust agronomic package for reliable production of sorghum in NW NSW.

Introduction

Grain sorghum is an important rotation crop in the northern grains region of Australia. However, the inability to provide reliable, profitable yields has prevented its inclusion as a set part of rotations in north-west NSW. The prolonged drought during this decade has further exacerbated these issues and reduced the area sown to sorghum across the region.

The north-west region is defined as the area west of the Newell Highway, stretching from the Queensland border south. This area is serviced by the regional centres of Moree, Walgett and Narrabri.

The typical farming system in this area is highly reliant on winter crop production, namely bread wheat and chickpeas with the opportunistic inclusion of summer crops, predominantly cotton but also occasionally sorghum.

The inclusion of sorghum in NW NSW cropping systems provides for rotation of herbicide chemistry to assist in the management of herbicide resistant weeds and is a non-host of the primary winter cereal disease Fusarium crown rot (*Fusarium pseudograminearum*) plus is resistant to the root lesion nematode *Pratylenchus thornei.* The inclusion of a reliable summer crop option in NW NSW would also assist with splitting of human/equipment logistics for planting and harvesting and provide more even cash flow across the year.

In NW NSW the rainfall pattern favours the summer months. In Moree more than half the average annual rainfall is expected in the months of November through to March. The dominance of summer rainfall increases northwards of Dubbo in central NSW.

The average rainfall amount reduces the further west you go from Moree to Walgett by, on average, 150mm per annum. In contrast the difference in average annual rainfall between Moree and Narrabri is only 16mm. Temperatures also increases as you move further west, with fewer frosts and increasing heat. December, January and February display elevated average maximum temperatures in NW NSW.

This combination of higher temperatures and less rainfall means that the risk of failed or uneconomic sorghum crops increases as you move west. However, there are many tools which can be used to build a package for reliable sorghum production in this region. The most difficult aspect is combining each of these decisions and their complex interactions to offer the most robust and reliable sorghum production package to growers, whilst balancing their attitude to risk.

Agronomic levers to reduce risk

Growers and advisers in NW NSW have a limited number of management levers to pull when choosing to grow sorghum as part of their dryland crop rotation. These include varying row spacing or row configuration, altering plant population, or changing their time of sowing, typically between a spring and a summer plant. There are also decisions around nutrition supply to the crop and the acceptable level of starting soil water to trigger planting which can be used to improve reliability of sorghum production.

To achieve the best possible sorghum yields, the interaction of management practices with the selected genetics (hybrid) and environment need to be at the forefront of growers and advisers' minds.

Row spacing and row configuration

Varying row spacing is a management practice which can be used to better match crop growth and development to the availability of soil water resources and/or expected seasonal conditions.

Where crop yields are likely to be > 3.0 t/ha solid plant will provide higher yields. If a grower is achieving 2.5 to 3t/ha on a skip row configuration, the data suggests it is likely that a solid plant would yield 0.5 to >1 t/ha more (Figure 1). Below 2.5 t/ha responses to varying row configuration and plant population are less obvious (Figure 2).

In summer broadacre cropping, the use of skip row technology became common place in the early 2000's firstly with cotton and later with other summer crops such as sorghum in more marginal environments like NW NSW. Initially, single (miss one row) or double skip (miss two rows) were used and later wide row spacing such 120 or 150cm rows on a solid plant came into use.

The adoption of skip or wide rows provides an area of soil water in between summer crop rows which could not physically be accessed by the plant roots until later in the season. With sorghum, it is estimated that roots growing at 2.5cm/ day will not reach the centre of a double skip area until around 60 days post-sowing. This conserves a reservoir of soil water which can possibly be used during flowering and grain fill to mitigate the risk of moisture stress.

There are trade-offs with using skip or wide row configurations. While the risk of crop failure is reduced, so is yield potential, especially in seasons with higher levels of in-crop rainfall.

Consideration must also be given to the management of the bare inter-row area including weed, nutrient, fallow and stubble management when using skip rows. Single skip leaves one third and double skip one half of the field without crop cover. This area is open to moisture loss through evaporation, invasion with weeds and potentially impacts on lateral nutrient distribution.

Plant population

The sorghum plant population established will depend on the initial target density (i.e. sowing rate), seed quality (germination/vigour and impact of any seed treatments), management (e.g. seeding depth) and environmental impacts on the germination and emergence of the seed, such as adequate soil moisture and temperature.

Trials have included plant populations from 1.5 – 7.0 plants/m^2. These populations have been maintained regardless of the row configuration.

Varying plant population is probably the easiest management lever to pull. The ideal plant population for growing sorghum in NW NSW is influenced by the yield potential and sowing date.

Generally, the higher the yield potential of the crop, the higher the plant population which can be supported. However, populations of 5 plants/m^2 can achieve yields close to 5.0 t/ha in NW NSW (i.e. Mungindi 10/11 – Figure 1), which is much higher than average yields in this environment. Populations above 5 plants/m^2 i.e. 7 plants/m^2 rarely produced statistically significant higher yields (analysis not shown) but incur increased expense due to additional hybrid seed costs.

Plant populations below 3 plants/m^2 have been lower yielding in higher yield potential seasons and are also more difficult to achieve even plant distribution across a paddock.

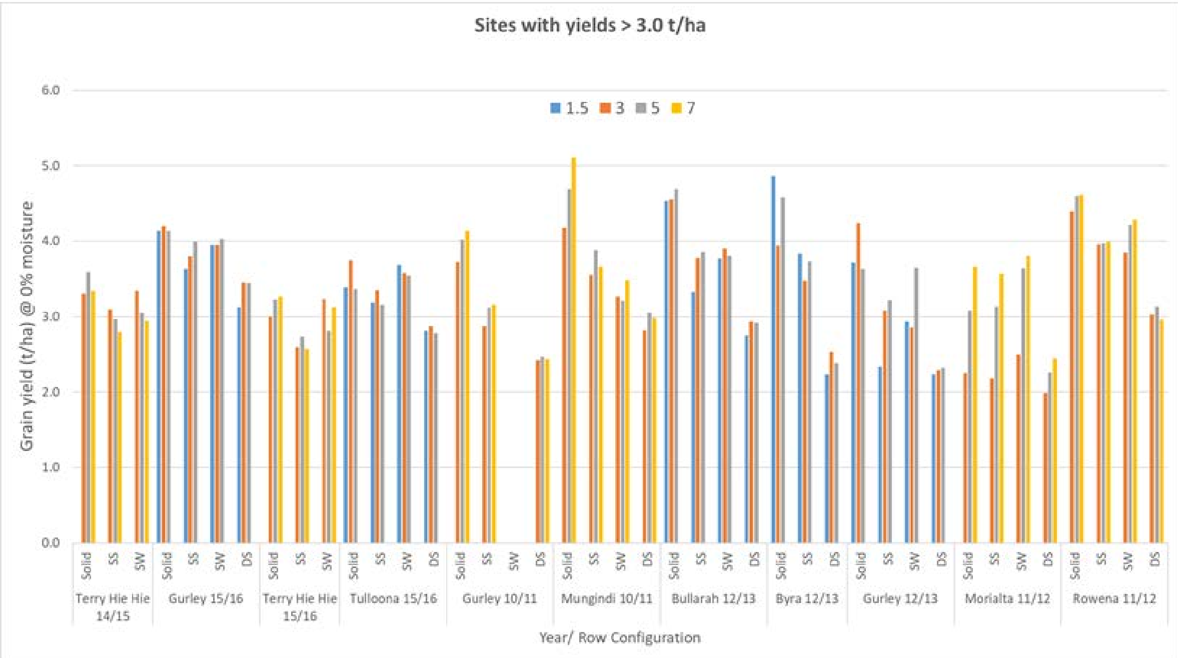

Figure 1. Trial sites with **grain yields > 3.0 t/ha**: Response to varying plant population (plants/m^2) and row configuration in sorghum across north west NSW from 2010-2016 (Solid = solid plant, SS = single skip, SW = super wide (150 cm solid) DS = double skip)

In contrast, at grain yields under 3.0 t/ha, responses to plant population and row configuration tend to be flatter (Figure 2). Some advantages have been seen from very low populations of 1.5 plants/m^2 In these environments responses to row configuration are also less than generally believed, particularly when yields are lower than 1.0 t/ha where this usually indicates terminal moisture stress.

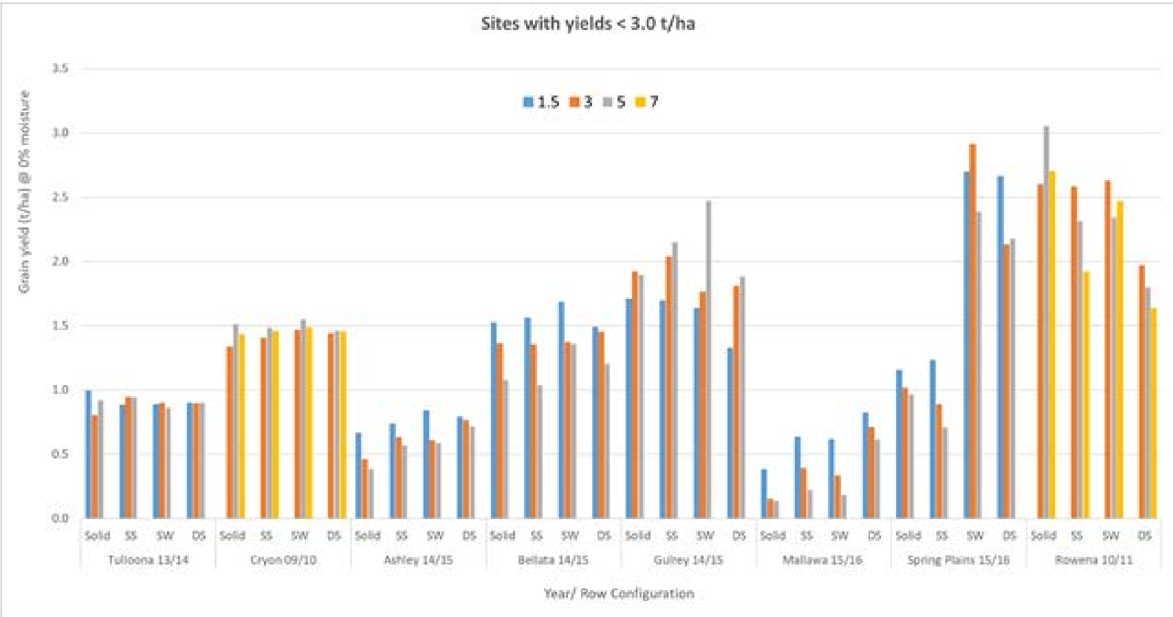

Figure 2. Trial sites with **grain yields < 3.0 t/ha:** Response to varying plant population (plants/m2) and row configuration in sorghum across north west NSW from 2010-2016 (Solid = solid plant, SS = single skip, SW = super wide (150 cm solid) DS = double skip)

Early sown crops often have reduced establishment, hence more seeds may need to be sown to achieve the target plant population. The other important point to consider when deciding on a plant population is that population alone is not responsible for crop yield. The optimum population also depends on the row configuration and the level of tillering within different hybrid sorghum varieties.

Starting soil moisture

Recommendations for sorghum in NW NSW always state that paddocks must have a full profile of soil moisture prior to sowing. Paddocks have been sown with less than a full profile, but the reality is that less moisture at sowing means a higher level of risk as there is a greater reliance on in-crop rainfall, which is known to be highly variable in this environment.

We can compare two sorghum sites (Figure 3), which did not have a full profile at sowing. The first trial had a starting plant available water (PAW) of 50 mm but received 257 mm of timely in crop rainfall resulting in yields up to 4.5 t/ha. The second site started with 100 mm of PAW but only received 15 mm of in-crop rainfall and subsequently failed. Both sites needed significant in crop rainfall to achieve profitable yields.

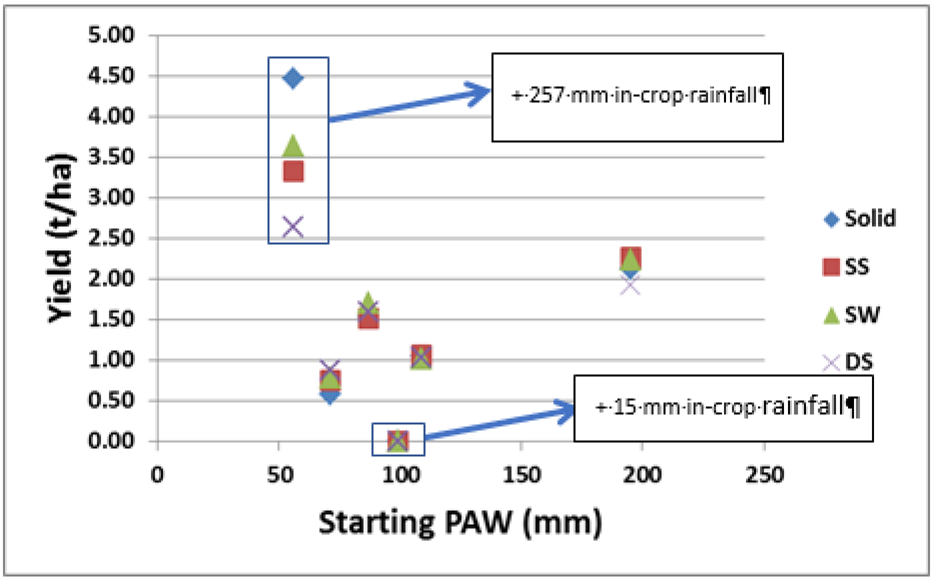

Figure 3. Effect of starting plant available water on sorghum yield at selected sites in north west NSW

If paddocks were only sown when full, they would be starting with a minimum of 150 mm of PAW or more in most soils in northern NSW. If this was combined with average summer in-crop rainfall (September – end January) at Walgett of around 200 mm, then acceptable yield could normally be expected.

There is much less risk from adopting this strategy, than sowing with a half full profile and then hoping to re-fill the deficit during the season via in-crop rainfall when evaporation and transpiration rates are high.

Planting date

Traditionally the sowing window for sorghum in NW NSW was considered to commence in mid-late September. In the last two years, research on the effect of moving sowing times up to 4 weeks earlier has been undertaken.

This results in planting when soils are much colder; a minimum of 12°C; as opposed to the recommended 16-18°C. Planting in late-September, when soil temperature is >16°C, provides rapid emergence (within around 7-10 days), while earlier planting may take 14 days or more to emerge, depending on conditions following sowing. There is often a reduction in establishment in cold soils associated with earlier planting.

However, the goal is to move the period of flowering and grain fill earlier into summer, hopefully closer to early December and away from the peak temperatures seen in late December and January.

Sowing after the end of the first week in August at Moree has enabled flowering to be moved as early as mid-November. In comparison planting in late-September results in flowering from mid-December (Figure 4).

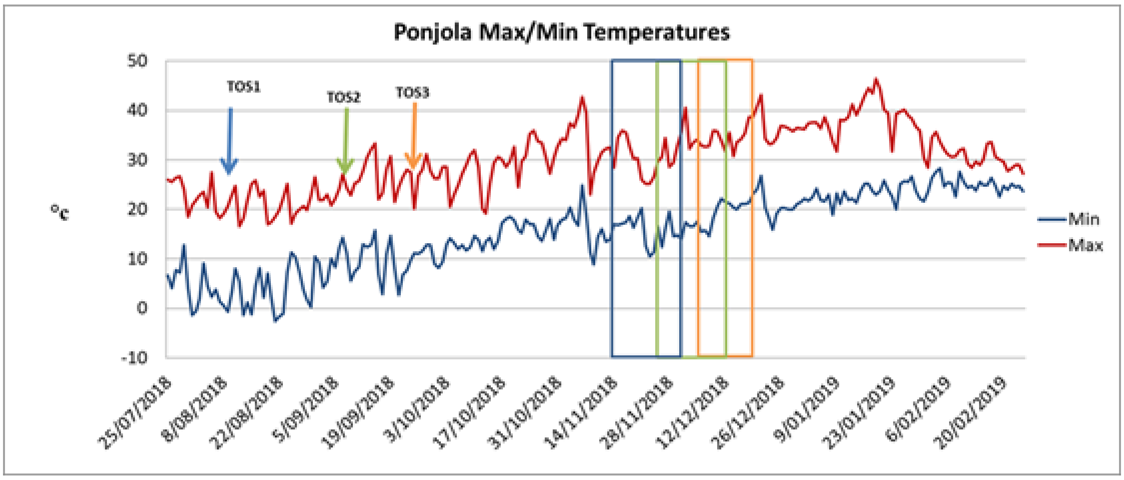

Figure 4. Sorghum flowering windows resulting from sowing 8 August, 11 September and 27 September at "Ponjola" Moree in 2018-19

Moving the sowing window forward has also resulted in improved yields in most of the trial sites such as the Moree site in 2018/19 (Figure 5). The first planting time on the 8th August was the highest yielding at 2.14 t/ha. There was no significant difference in yields achieved between the 11th and 29th September planting dates being 1.51 and 1.68 t/ha respectively.

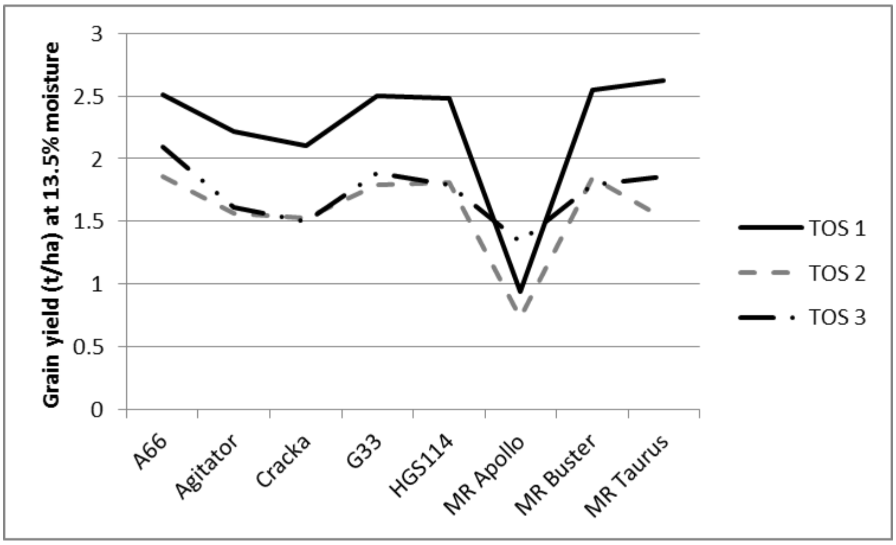

Figure 5. Grain yield at three times of sowing (TOS) at "Ponjola" Moree in 2018-19

Conclusions

Reliable and profitable sorghum production in NW NSW has not been achieved yet. A series of options for improving confidence in growing sorghum in this region have been examined. However further interrogation of this data and extrapolation over an extended period using the crop model APSIM will provide a more robust set of future recommendations.

Currently the sorghum production package for NW NSW to reduce risk is based around only planting with a full profile of soil moisture; using a double skip configuration and aiming to establish around 5 plants/m^2. This package, whilst reducing the likelihood of crop failure, also limits the top end yield potential of a sorghum crop in this region in favourable seasons.

The ideal management package will allow avoidance of the peak heat and lack of soil moisture periods in NW NSW, generate a profitable sorghum grain yield with optimised water use efficiency whilst still maintaining the system benefits such as stubble cover from a cereal crop. This is a significant challenge for the future of our industry but also a massive opportunity waiting to be exploited.

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Cover crops improve ground cover in a very dry season

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Take home messages

- Previous trials have shown cover crops can increase stored fallow water and improve crop performance and returns in northern farming systems
- A cover crop in a long fallow (14 months) in a dry season allowed improved ground cover with no net deficit in soil water. The extra ground cover improved the opportunity to deep plant wheat
- A cover crop in a short fallow had a water cost that translated to a yield penalty
- When the sorghum stopped growing in dry conditions it continued to use water, for no biomass (or cover) increase when it wasn't sprayed out.

Cover crops in the northern region

After missed or failed crops over recent seasons, ground cover is becoming increasingly important for maintaining fallow efficiency and importantly, for protection from wind and water erosion. Cover crops, sprayed out and left for ground cover, have been used to protect the soil from erosion in low stubble situations, with added benefits of returning biomass that helps maintain soil organic matter and biological activity and provide additional nitrogen when legumes are used. Cover crops also offer an opportunity to increase infiltration and fallow moisture storage for more profitable grain and cotton crops across the northern region of New South Wales (NSW) and Queensland.

Scientific rationale

Stubble and evaporation

Retained stubble provides ground cover, protects the soil from rainfall impacts and so improves infiltration to store more water in the soil. Conventional wisdom is that increased stubble loads can slow down the initial rate of evaporation, but that these gains are short-lived and often lost due to evaporation, unless follow-up rainfall occurs within several weeks. However, further rain within this period and the manipulation of stubble to concentrate stubble loads provides an opportunity to reduce total evaporation and to accumulate more plant available water.

Advances in agronomy and commercial agronomist support have seen growers better use their available soil water and improve individual crop performance. However, more effective capture and storage of rainfall across the whole farming system remain as major challenges for northern grain and cotton growers where only 20-40% of rainfall is typically transpired by dryland crops, up to 60% of rainfall is lost to evaporation, and a further 5-20% lost in runoff and deep drainage. Every 10 mm of extra stored soil water available to crops could increase dryland grain yields for growers by up to 150 kg/ha, with corresponding benefits to dryland cotton growers as well.

The GRDC funded Farming systems projects (DAQ00192/CSA00050) are assessing ways to improve this system water use, and to achieve 80% of the water and nitrogen limited yield potential in our cropping systems. Previous GRDC Eastern Farming Systems and Northern Growers Alliance trials both suggest that cover crops and increased stubble loads can reduce evaporation, increase infiltration and provide net gains in plant available water over traditional fallow periods. Consequently, cover crops have potential to be part of improved farming systems; providing increased profitability and better soil protection.

Dryland grain systems

Cover crops are used in southern Queensland and northern NSW to overcome a lack of stubble and protect the soil following low residue crops (e.g. chickpea, cotton) or following skip-row sorghum with uneven stubble and exposed soil in the 'skips'.

In long fallows leading to a winter crop, growers typically plant white French millet or sorghum, and spray them out within ~60 days, to allow recharge of the soil water extracted by the cover crop. Allowing these 'cover crops' to grow through to maturity led to significant soil water deficits and yield losses in the subsequent winter crops. However, the Eastern Farming Systems projects showed only small deficits (and even water gains) accrued to the subsequent crops when millets were sprayed out after 6 weeks, with average grain yield increases of 0.36 t/ha in subsequent crops. Furthermore, the Northern Growers Alliance showed that the addition of extra stubble (from 5-40 t/ha) after winter crop harvest appeared to further reduce evaporation, with initial studies showing between 19 mm and 87 mm increases in plant available water. These gains will be valuable if validated in further research and are able to be captured in commercial practice.

Our current project is monitoring sites intensively to quantify the impact of different stubble loads on the accumulation of rainfall, the amount of water required to grow cover crops with sufficient stubble loads, the net water gains/losses for the following crops and the impacts on their growth and yield.

Summary of previous results

Experiment 1 was a winter cover crop followed by overhead irrigated cotton near Yelarbon. Barley cover crops grew 1.2 t/ha biomass for early spray out and up to 5 t/ha for the late sprayed out barley. The early terminated barley had the most plant available water (PAW) when the cotton was planted, however, the extra resilience of the mid and late terminated barley captured more of the applied water in the soil, once irrigation of the young cotton crop commenced. Cotton yield showed a large benefit in all of the cover crop treatments over the bare fallow (control).

Experiment 2 was a spring cover crop followed by dryland wheat near Bungunya. The millet cover crops at this site produced 1.5 t/ha biomass (early terminated), and up to 4.5 t/ha for the late sprayed crop. The treatments with the most cover (and biomass) had the most stored water at the end of April. With the longer fallow after the cover crop, the early terminated cover crop broke-down before the wheat was planted. In deep planted wheat the treatments with higher ground cover established even wheat stands, while the bare fallow (control) and some treatments with fragile cover had an uneven / gappy wheat establishment. The wheat crop in the bare control yielded 1.4 t/ha, while the wheat following late terminated millet had 20 mm more PAW at planting and a more even wheat stand which enabled it to extract more of the stored water, so had an improved yield of 2.8 t/ha (net economic benefit of $280/ha).

A detailed summary of these trials can be found in Queensland grains research 2018-19: https://www.publications.qld.gov.au/dataset/queensland-grains-research/resource/3865017c-7ebf-40bc-89c9-640829b313c7

Or in a 2019 GRDC Update paper at:

https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2019/03/cover-crops-can-boost-soil-water-storage-and-crop-yields

Learnings from a dry season

This paper reports on two dryland sites in southern Queensland in the record breaking 2018/19 drought years.

The first experiment (Yagaburne) was in a long fallow from sorghum to wheat, so the cover crop was planted earlier in the season allowing earlier spray out and a longer fallow period to recharge the soil water used. This experiment had improved planting opportunities with higher ground cover, but no PAW difference at planting, so the evenly established wheat yielded the same in all treatments.

The second experiment (Billa Billa) was in a short fallow from chickpea to wheat. This cover crop was planted later in spring and had a shorter fallow period after spray out to recharge the PAW used by the cover crop. There was a PAW penalty for growing the cover crop in this season, which translated to reduced grain yield.

Experiment 3 – Yagaburne (Skip-row sorghum, long- fallowed to dryland wheat)

The Yagaburne experiment was in a long-fallow paddock following skip-row sorghum that was harvested in February 2018. This paddock was a zero till fallow, with standing sorghum and wheat stubble present. There were two times of planting for cover crops, with winter cover crops planted in July 2018 with 65 mm of PAW, and spring cover crops planted in October 2018 with 90 mm PAW. The subsequent wheat crop was planted on 30 May 2019, harvest in October 2019. Soil water was measured at key times with gravimetric soil coring, then more regularly with a neutron moisture meter and EM38. Cover crop biomass, and ground cover was measured at termination of the cover crop and periodically through the fallow. Grain yield of the wheat crop following the cover crop was measured to quantify the value of plant available water (PAW) differences between cover crop treatments.

The winter cover crop was wheat at 100 plants/m^2 and winter multispecies cover crop was half recommended rates of wheat, vetch and tillage radish (50, 30 & 20 plants/m^2). The summer cover crop was white French millet at 100 plants/m^2, sorghum cover crop was a sudan x sudan hybrid at 65 plants/m^2, and multispecies was with white French millet, lab lab and tillage radish at half recommended rates (50, 30 & 20 plants/m^2) (Table 1).

Three planned termination times matched key growth stages of the main cereal treatments: Early-termination at first node (Z31) when the crop begins stem development; Mid-termination at flag leaf emergence (Z41) when the reproductive phase begins; and Late-termination at anthesis (Z65) for peak biomass production. The site was planned to be planted to wheat in May 2019, but with no planting opportunity and no rain forecast, it was dry planted on 27 May 2019 using the growers single disc planter (33⅓ cm row spacing), with trickle irrigation applied for crop establishment.

Table 1. Cover treatments applied at the Yagaburne site prior to planting wheat, biomass at termination of each cover crop (does not include the 1700 kg/ha of residual stubble, centred mostly on the sorghum row, in all treatments including the 'bare control') and percentage ground cover at the last termination date and at the end of the fallow period.

#	Cover crop	Termination time	Biomass grown (kg/ha)	Ground cover % 5/12/2019	Ground cover % 2/05/2019
1.	Bare (control)		0	8	8
2.	Wheat	Early-sprayout	86	12	11
3.	Wheat	Mid-sprayout	410	26	24
4.	Wheat	Late-sprayout	697	45	42
5.	Wheat	Late-sprayout + roll	718	50	45
6.	Winter multi-species (wheat, vetch, radish)	Mid-sprayout	538	38	31
7.	Millet	Early-sprayout	527	62	37
8.	Millet	Mid-sprayout	1412	89	80
9.	Millet	Late-sprayout	2043	94	87
10.	Millet	Late-sprayout + roll	1945	97	84
11.	Sorghum	Mid-sprayout	2551	96	93
12.	Summer multi-species (millet, lab lab, radish)	Mid-sprayout	1117	65	46

With the late planting date of the winter cover crop the early sprayed wheat grew 86 kg/ha of biomass, which did not provide useful levels of cover (Table 1).

The mid terminated winter cover crop had 36 mm less PAW at termination than planting (Figure 2) for 400 kg/ha biomass. With 50 mm rainfall in October the late terminated wheat was 5 mm drier than at planting with 700 kg/ha of resilient straw. All winter cover crops had recovered to similar PAW as the control when the summer cover crops were planted.

With an extra 90 days and 75 mm rain in fallow, the summer cover crop had 26 mm more PAW than when the winter cover crop was planted. The early, mid and late terminated millet cover crops were 25 mm, 46 mm and 80 mm drier at termination than when they were planted (Figure 2). Biomass produced by the millet was ~ 500, 1400 and 2000 kg/ha for early, mid and late termination respectively (Table 1).

The sorghum cover crop sprayed-out at its mid termination growth stage was sprayed out on the same day as the late terminated millet and used the same volume of water and grew similar biomass as the late terminated millet.

With the dry autumn of 2019, the paddock was assessed on 14 May for the potential to plant wheat across the trial. At ten days after 8 mm rain and 45 days since the last significant rainfall, the conclusion was that only the plots with the highest levels of cover (i.e. greater than 40% cover, but more was better, Table 1), had enough surface moisture to allow an even establishment of wheat. The four treatments with the best cover (mid, late and late + rolled millet and sorghum cover crops), had good moisture for planting; three treatments were too dry (bare control, early and mid wheat cover crops) and the other five treatments would have been a marginal planting opportunity. With no rain received by the end of May and no forecast rain, it was decided to dry plant and apply trickle irrigation to the seed row for crop establishment.

When the wheat 'cash crop' was planted, the bare control had similar PAW as when the trial commenced 11 months earlier after 240 mm rain (580 mm average annual rainfall). Previous trials have shown variability in sampling of +/- 10 mm, so there was no real difference in PAW at this time with the best cover crop treatments having 10 mm more PAW than the control and the worst had 10 mm less than the control. Volumetric soil water post-harvest had a similar spread with the wheat extracting on average 61 mm of PAW from the profile. With only 17 mm of in crop rain the wheat yielded 570 kg/ha.

Two plot header runs were taken for each plot at this site: one over the previous sorghum rows and the other over the skip (Figure 1). There was a consistent yield increase for yield in header runs taken over the old sorghum rows when compared to runs taken over 'the skip row', with an extra 126 kg/ha yield measured on the old sorghum rows versus the skip (632 kg/ha vs 506 kg/ha).

Figure 1. Residual stubble at the Yagaburne site at emergence of the winter cover crop and undisturbed on the right.

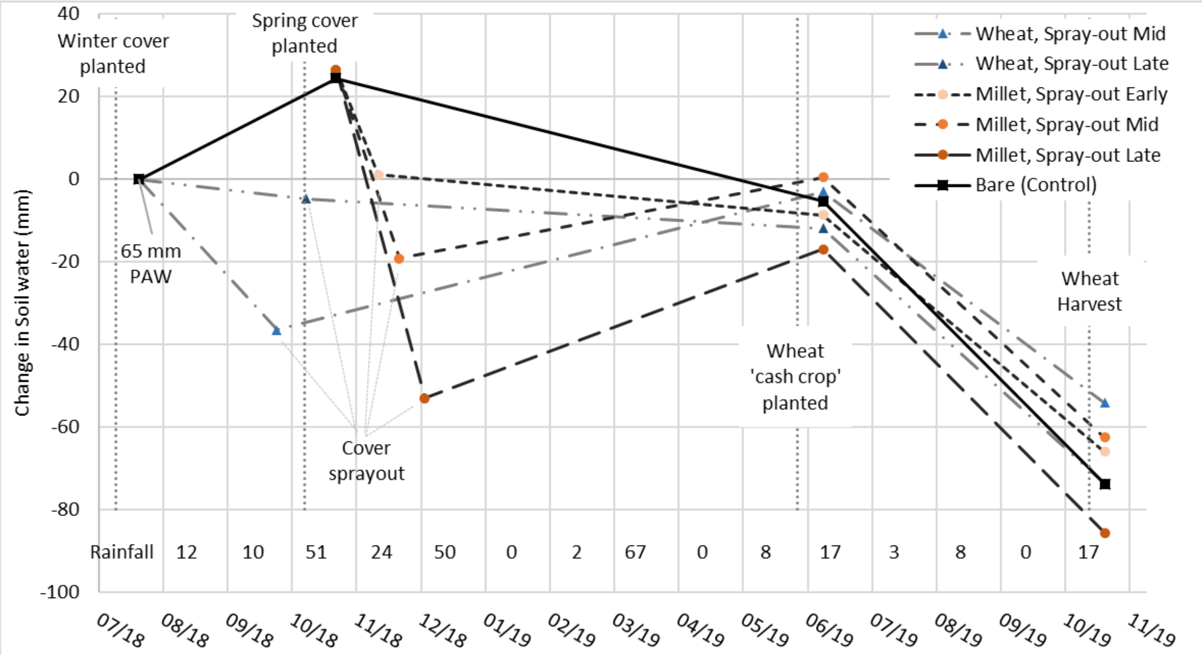

Figure 2. Change in plant available water for a range of cover crops at the Yagaburne site, measured with soil cores to 150 cm depth. Grids represent each month and numbers in the bottom row are mm rainfall for that month.

Experiment 4 – Billa Billa (Chickpea or wheat fallowed to dryland wheat)

The Billa Billa experiment had plots pre-planted to wheat or chickpeas to create areas of high and low stubble cover, with the view to grow cover crops in the low cover plots left by the chickpea crops. The wheat plots were also harvested tall (50 cm) and left standing or rolled or harvested short (25 cm) with tops removed or left as mulch (Table 2).

Wheat and chickpea were harvested on 26 October 2018 and a sudan X sudan hybrid sorghum cover crop was planted a month later with 90 mm PAW. The sorghum established over 100 plants/m^2.

Three planned termination times matched to key growth stages were planned similar to previous experiments: early, mid and late. Early termination was sprayed five weeks after planting. With no in crop rainfall and high plant populations, the crop stopped development at second node, so mid termination was sprayed three weeks after the early spray, and late termination was held off until after rain fell, being sprayed 25 March 2019 (four months after planting).

Table 2. Crops planted at the Billa Billa trial to generate different cover levels and stubble or cover crop managements imposed in the fallow period.

Preceding crop	Treatment
Wheat	Harvest high (50 cm)
Wheat	Harvest high and rolled
Wheat	Harvest low (25cm), tops spread
Wheat	Harvest low, tops removed
Chickpea	Bare (control)
Chickpea	Sorghum spray-out early
Chickpea	Sorghum spray-out mid
Chickpea	Sorghum spray-out mid + rolled
Chickpea	Sorghum spray-out late
Chickpea	Sorghum spray-out late + rolled

At planting of the cover crop, the wheat stubble plots had 34 mm more PAW than the chickpea stubble plots. From the time of cover crop planting, PAW had decreased by 59 mm to early termination; by 81 mm to mid termination and by 60 mm to late termination (Figure 3). This shows that the sorghum continued to use water after it stopped developing, with minimal increase in biomass (Table 3). Biomass produced by the cover crops averaged 1.3 t/ha for the three termination timings. Whilst this offered a significant improvement in ground cover over the bare control, the cover crops had ~1 t/ha less biomass and ~15% less ground cover than the wheat stubble plots.

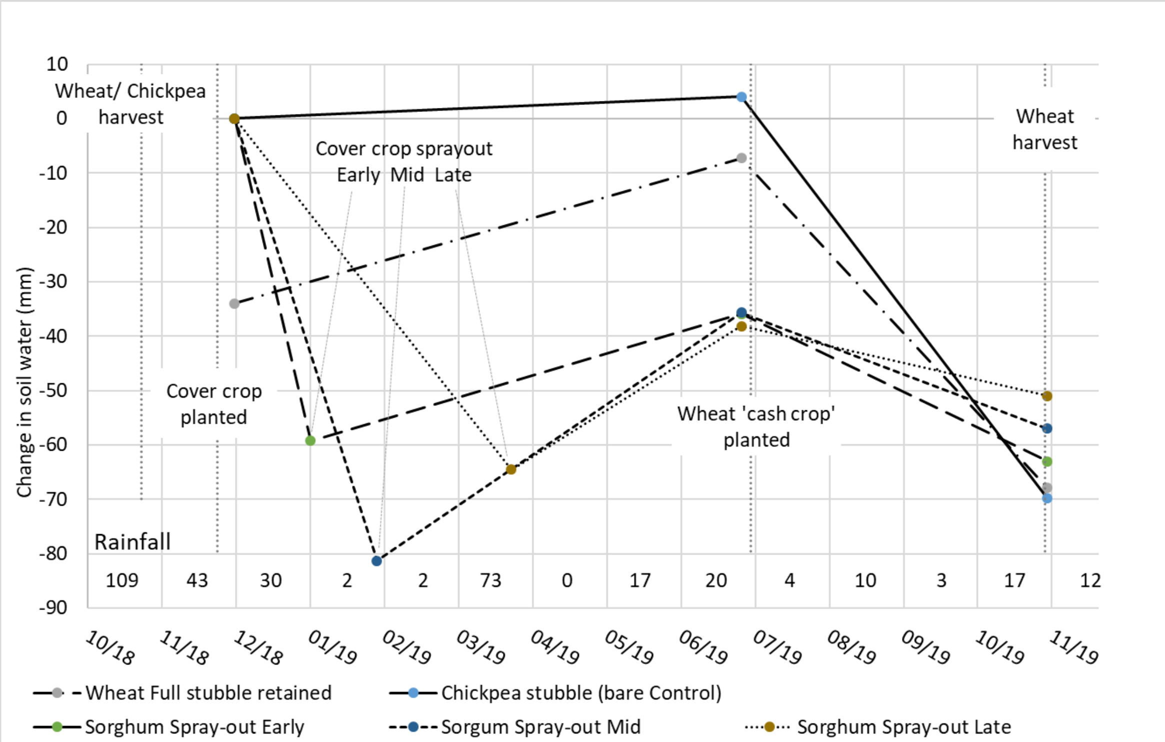

Figure 3. Change in plant available water for a range of cover crops measured with soil cores to a depth of 150 cm, at the Billa Billa site. Grids represent 30 days from the first of each month, and numbers in bottom row are mm rainfall for that month. Nb. Wheat stubble plots were 34 mm drier than ex-chickpea plots when cover crops were planted.

Table 3. Starting crop and stubble or cover crop treatment, stubble and cover crop biomass and percent ground cover at the end of the fallow period, and grain yield of the following wheat 'cash crop' at the Billa Billa site.

Preceding crop	Treatment	Biomass (kg/ha)	Cover % 2 May 2019	Wheat grain yield (kg/ha)
Wheat	Harvest high (50 cm)	2662	77	526
Wheat	Harvest high and rolled	2357	78	566
Wheat	Harvest low (25cm), tops spread	1800	82	529
Wheat	Harvest low, tops removed	1755	73	551
Chickpea	Bare (control)	267	10	727
Chickpea	Sorghum spray-out early	1270	50	364
Chickpea	Sorghum spray-out mid	1419	67	74
Chickpea	Sorghum spray-out mid + rolled	1245	57	61
Chickpea	Sorghum spray-out late	1732	66	34
Chickpea	Sorghum spray-out late + rolled	1106	66	23

With insufficient rain received in May or June and no forecast rain, it was decided to dry plant and apply trickle irrigation to the seed row for crop establishment in the last week of June.

The fallow efficiency of the wheat stubble was higher than that of the chickpea stubble (control) as wheat stubble plots accumulated 23 mm more PAW over the fallow than the control with chickpea stubble. However, with 34 mm more PAW present after chickpea harvest compared to the wheat plots, the wheat stubble still had 11 mm less PAW, when the wheat was planted in June. This trend has also been measured in the farming systems trials, where pulses leave more water at harvest than cereals, but cereals have higher fallow efficiency, and thus reduce the gap by planting of the next crop (or eliminate the gap in non-sodic soils and be ahead after long fallows).

The cover crops recovered some of the water they used with 73 mm of rain in March, but with little rain after this event, the early, mid and late sprayed sorghum cover crops were 25 mm, 44 mm and 48 mm drier than the control when the wheat crop was planted (Figure 3).

The highest wheat yield was achieved by the fallowed chickpea stubble (bare control; 727 kg/ha), followed by the wheat stubble (average 543 kg/ha) and early sprayed cover crop (364 kg/ha). The mid and late sprayed sorghum cover crops had patches of wheat die during the season for final yields of 68 kg/ha and 29 kg/ha (Table 3). Trickle tape irrigation providing even establishment across all plots and with very low rainfall in crop (34 mm) the yield outcomes were directly related to starting PAW. These yields represent an average yield reduction of 11.6 kg/ha for every mm less water the wheat crop used (i.e. planting PAW – harvest PAW + in crop rain) compared to the bare control.

Conclusions

The project has previously shown that cover crops can indeed help increase net water storage across the fallow and early crop growth in situations that have limited ground cover. We have also seen dramatic yield results for the subsequent cotton and wheat crops, which we attributed in part to more even populations established and greater water extraction.

In this dry season, improving ground cover allowed the opportunity to plant a crop, when the bare plots were too dry. At this longer fallow site (albeit dry) the cover crops recovered most of the water used, so planting with irrigation provided an even establishment and no difference in grain yield was observed.

The short fallow site had a PAW penalty for growing the cover crop and with no extra biomass growth in the later terminations, there was no advantages in persisting with the cover crop once it had stopped development. After an even establishment assisted by irrigation, the grain yield penalty to the wheat ‘cash crop’ was highly correlated to starting PAW.

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Summer crops: relative water use efficiencies and legacy impacts in farming systems

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Key words

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Take home message

- While summer crops offer rotational options in the farming system, choose the correct crop to match your available soil water and crop history
- Sorghum is a reliable performer often exceeding other options in terms of $ returned per mm used
- Cotton and maize require higher water availability and produce less reliable WUE ($/mm). However, cotton has legacy impacts on water availability for subsequent crops that should be considered
- Mungbean can produce higher $/mm in low water availability situations (<200 mm of rain + soil water). Repeated sowings of mungbeans are likely to induce yield reductions due to disease
- Sorghum crops sown with > 150 mm of plant available water will maximise crop WUE and profitability. Every extra mm at sowing could be worth as much as $35-70 extra return/ha
- Higher density sorghum crops may provide greater crop competition against weeds and potential upside yield benefits in good season. We have seen limited legacy benefits (e.g. improved ground cover) or costs (e.g. greater soil water/nutrient extraction) for soil water or nutrient availability.

Introduction

Summer crops are becoming an increasingly important component of cropping systems in the summer-dominant rainfall zone. They are often useful for providing disease or weed management benefits when in rotation with winter crop dominated systems. While it is widely recognised that summer crops are often critical for improving the system sustainability, a key challenge is transitioning between summer and winter crops or phases in the crop sequence. This requires either double cropping or introducing long-fallows (>10 months) during transitions between the summer and winter crop phases. Hence understanding how effectively different summer crop options convert available water into grain yield and ultimately profit is critical to making better decisions about when summer crops may be used in the crop sequence. Further, differences in water extraction, subsequent fallow water and nitrogen accumulation are likely to influence how subsequent crops will perform or the period of fallow time required to reach critical sowing moisture levels. So, it is important to target the right summer crop option to the system.

This paper will report on several comparisons of relative water use efficiency of different summer crops, and effects of summer crop management practices (e.g. soil water at sowing, sorghum configuration and density) and their legacy impacts in the farming system.

Relative WUE ($/mm) of summer crop options

Over the past 4 years of experiments, different summer crop options have been grown in the same season and under common previous fallow length and starting moisture. Using this data, we have calculated for these various comparisons the crop water use efficiency as $ of income generated per mm of crop water use. This was done using long-term median crop prices and inputs for each of the crops, but these relative values would shift if prices for individual crops were more/less favourable compared to others.

Across a range of seasons and growing conditions, sorghum always exceeded mungbeans in terms of $ generated per mm. This was even though on several occasions mungbean crops use less water and often left significantly more residual soil water than the sorghum crops grown in the same conditions. Sorghum was only bettered in terms of crop WUE by a cotton crop at Pampas in summer 18/19 and sunflowers when they were sown as a double crop in 17/18.

Table 1. Crop water use efficiencies ($ gross margin per mm water used) comparisons between summer crops when grown in the same season with similar starting conditions (long fallow – LF, short fallow – SF, double crop – DC).

	Pampas 16/17 (LF)	Pampas 17/18 (DC)	Pampas 17/18 (SF)	Pampas 18/19 (LF)	Pampas 18/19 (SF)	Pampas 19/20 (DC)	Pampas 19/20 (SF)	Billa Billa 16/17 (LF)	Narrabri 18/19 (LF)
Sorghum	12.0	2.82	9.4	10.1	6.1			3.4	0.7
Mungbean	7.0		3.8		5.5	2.0	12.5	1.3	0.4
Cotton	6.4			15.8					
Maize	7.3								
Sunflower		11.4							
French millet						2.7	3.0		

Figure 1 shows the relationships between crop water use and crop income generated for 100 summer crops (sorghum, mungbean, cotton, sunflower and maize) that have been grown in our farming systems research over the past 5 years. This graph demonstrates that:

- In sorghum, a strong relationship was found between crop revenue and crop water use; on average $4.50 of income generated per mm of crop water use above 200mm. That is, 200mm of available water through in-crop rain or soil water at sowing is required before a positive return is generated
- Mungbeans show a higher return per mm at lower crop water use than sorghum, particularly when available crop water is less than 250mm
- Sunflowers produced a similar return per mm to sorghum in the few seasons when they were grown. This outcome would be greatly influenced by the price obtained for sunflowers which can be highly variable
- In maize and cotton, higher variation in returns per mm were observed. In some seasons, this exceeded sorghum but was lower in others.

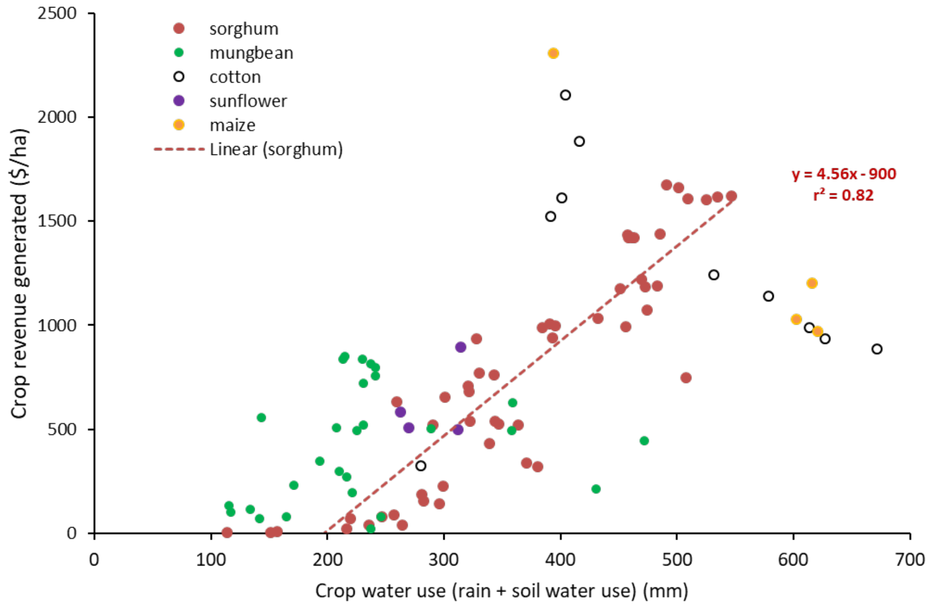

Figure 1. Relationships between crop water use (in-crop rainfall + soil water extraction) and crop revenue generated amongst 100 summer crops grown in farming systems experiments 2015-2019 (sorghum n= 51, mungbean n = 28, cotton n = 10, sunflower n = 4, maize n = 5).

Sowing soil water effects on sorghum crop performance

Soil water at sowing is critical for driving the efficiency of summer crops, especially sorghum. Here we compare the performance of sorghum crops grown in the same season with common nutrient and crop management but with significantly different soil water at sowing (Table 2). As expected, crops with higher soil water at sowing had higher grain yields. But, perhaps something less obvious was that the crops with more staring water regularly converted the available soil water more efficiently into grain and accordingly into profit. This effect was larger in seasons with limited in-crop rain, while the effect was diminished in the wetter growing season (i.e. Pampas 2016/17). This phenomenon occurs because it takes a critical amount of water to grow crop biomass, and hence when there is less available water at sowing there is less water left to efficiently convert any residual water into grain during grain filling. Hence, in wetter seasons this is less pronounced because the crop may still have enough available water to minimise this effect.

Across these studies we calculated the increase in crop return that was obtained for each extra mm of soil water available at sowing. While there was some variation in some seasons, this could be as high as $70 extra return per extra mm at sowing. These effects were largest where crops were sown on marginal soil water (< 100mm) and had limited in-crop rain (e.g. <300mm). These data clearly suggest that for sorghum to maximise its return per mm of water used, higher soil water at sowing is critical. Other analyses by Erbacher et al. (2020 Goondiwindi update paper), suggest plant available soil water at sowing of 150mm was required to optimise sorghum WUE.

Table 2. Starting soil water effects on sorghum crop performance and the marginal water use efficiency i.e. extra $ generated per mm of extra water available at sowing.

Site – year (in crop rain)	**PAW prior to sowing**	**Crop yield (t/ha)**	**Crop WUE (kg grain/mm)**	**Crop WUE ($/mm)**	**Marginal $/mm water at sowing**
Billa Billa 16 (118mm)	98	0.88	3.1	2.2	7.5
	194	1.52	4.1	3.6	
Pampas 16 (345mm)	153	6.12	13.4	12.5	7.2
	245	7.42	13.6	12.0	
Pampas 17 (230mm)	108	0.91	3.1	3.0	70.0
	163	4.52	9.4	9.8	
Pampas 18 (277mm)	62	2.70	7.9	6.1	32.4
	120	4.03	10.2	10.1	

Crop WUE and legacy effects of growing higher density sorghum crops

Integrated weed management practices involving greater in-crop competition with summer grass weeds is seeing interest in increasing sorghum density and narrowing row spacing. In addition to this weed benefit this is likely to have impacts on water and nutrient use efficiency of the crop and legacy impacts on subsequent water and nitrogen accumulation in fallows. It was hypothesised that the higher density sorghum would grow additional biomass which may or may not be converted into grain yield depending on the season. However, this greater biomass would contribute to greater and more even ground cover and improved fallow efficiency. Similarly, this may have impacts on nutrient cycling due to increased immobilisation of soil N from the higher residue with a high C:N ratio.

Across the 3 experimental comparisons we have implemented in our farming systems research, we found that consistently the higher density sorghum increased biomass production, but this was only translated into additional yield at Emerald in 17/18 (Table 3). At the other sites there was no significant yield penalty from growing this additional biomass and grain yields were comparable. Soil water extraction and crop water use was the same amongst the high and low density crops.

The higher biomass production in the higher density sorghum crops has required higher soil N extraction without an increase in grain yield and N. Hence, the nutrient use efficiency of these crops is lower. That is, such higher density crops will require a different nutrient strategy to ensure sufficient N in provided to maximise their yield potential.

Finally, while we anticipated there may be some benefits for improved soil water accumulation over the subsequent fallow following the higher density sorghum crops this was not shown resoundingly. In one season (Pampas 17/18) we did observe an extra 33mm was accumulated in the subsequent fallow after the higher density sorghum crop than the standard management. However, this was largely due to a drier soil profile at crop harvest and there was no significant difference in soil water at the end of the subsequent fallow in any of these cases. However, observations suggested there was greater uniformity of the soil water where more evenly distributed cover occurred following the narrower sorghum rows compared to wider row crops.

Table 3. Crop yield and legacy effects of growing higher density grain sorghum (i.e. 30% higher population & 0.5m compared with 1m row spacing) across 3 seasons in farming systems experiments.

Sorghum crop performance		**Emerald 17/18**	**Pampas 17/18**	**Pampas 18/19**
Sorghum grain yield (t/ha)	Standard	5.0	4.7	4.0
	High density	5.9	4.7	3.7
Sorghum biomass (t/ha)	Standard	11.6	14.1	9.1
	High Density	15.6	16.0	10.1
Sorghum WUE (kg grain/mm)	Standard	15.4	9.4	10.2
	High Density	18.4	10.4	9.6
Sorghum NUE (kg grain N/kg N used)	Standard		0.593	1.7
	High Density		0.484	1.1
Following fallow				
Soil water accumulation (mm)	Standard	+97	+63	+85
	High Density	+71	+96	+79
Mineral N accumulation (kg/ha)	Standard		+89	+107
	High Density		+116	+102

Legacy impacts of summer crop choices

Finally, here we make comparisons of the impacts of summer crops on residual soil water, accumulation during the subsequent fallow and effects on subsequent crop productivity in the sequence.

From these comparisons the legacy impacts of cotton in the farming system are clear, with lower soil water available for subsequent crops due to higher extraction and also lower fallow efficiencies (Table 4). This has translated into reductions in yield of 0.5 t/ha in sorghum and 0.3 t/ha in mungbeans when sown following cotton compared to maize.

Comparisons of sorghum with mungbean show little differences in residual soil water or soil water in the following crops. However, mungbean performance was affected by the preceding crop. 'Mungbean after mungbean' yield was 0.5 t/ha lower than 'mungbean after sorghum', despite starting with similar moisture after a long fallow (17/18). In contrast, mungbean yields were similar following short fallows out of sorghum and mungbean (18/19), even though the sorghum left less residual water. These effects are likely to be related to disease reductions rather than soil water or nutrient impacts.

Finally, a comparison between sorghum and sunflower legacy effects found little or any effects on subsequent fallow water accumulation or crop yields.

Table 4. Comparisons of legacy impacts of different summer crops on soil water accumulation and subsequent crop productivity in the crop sequence.

Crop year	Crop grown	Residual PAW (mm)	Soil water accumulation (mm)	Subsequent crop performance			
				PAW at sowing (mm)	Crop sown	Crop biomass (t/ha)	Grain yield (t/ha)
16/17	Maize	168	-6	162	Sorghum 17/18	14.1	5.37
	Cotton	149	-23	126		12.8	4.85
	Maize	168	-67	101	Mungbean 17/18	5.0	1.06
	Cotton	149	-67	82		3.4	0.75
18/19	Sorghum	2	+91	93	Not sown yet	-	-
	Cotton	-16	+64	48		-	-
17/18	Sorghum	48	+24	72	Mungbean 19/20	4.75	1.62
	Mungbean	30	+58	88		3.59	1.12
18/19	Sorghum	-10	+45	35	Mungbean 19/20	2.33	0.59
	Mungbean	-26	+112	76		2.15	0.61
17/18	Sorghum	38	+29	67	Sorghum 18/19	7.96	2.80
	Sunflower	2	+39	41		7.38	2.94
	Sorghum	41	+42	83	Mungbean 18/19	2.35	0.74
	Sunflower	3	+22	25		2.23	0.75

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Irrigation systems, designs and scheduling options

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Key words

irrigation system choices, water scheduling, water budgets, managing water across the farm, strategies for limited water, irrigation scheduling technologies

Take home message

The key message from the system research is that no single irrigation system suits every situation. Selecting and optimising the system for your farm and water reliability is the most important priority.

System choices will be impacted by water reliability, labour resourcing as well as topography and soil type.

The primary focus areas for enhanced irrigation performance are:

- Design and drainage to minimise waterlogging and deep drainage
- Irrigation scheduling to apply the right amount at the right time and optimisation of irrigation system performance.

Background

The *Smarter Irrigation for Profit Phase 1* (SIP1) project enabled the completion of valuable research in areas including irrigation system audits, irrigation scheduling, investigation of new technology, evaluation of system design and water use efficiency. The project demonstrated that improved water productivity hinged on ‘getting the basics right’. It found that participating Australian irrigators could achieve a 10-20 percent improvement in farm profitability by adopting best practice and precision irrigation technologies. This initial project has now led to phase 2.

Smarter Irrigation for Profit Phase 2 (SIP2) is a partnership between the major irrigation industries of cotton, dairy, sugar, rice and grains research organisations and farmer groups. The objective of SIP2 is to improve the profit of over 4,000 cotton, dairy, rice, grains and sugar irrigators.

Smarter Irrigation for Profit Phase 2 has 14 sub-projects covering three main components:

- Development of new irrigation technologies including new sensors, advanced analytics to improve irrigation scheduling and strategies to reduce water storage evaporation
- Cost effective, practical automated irrigation systems for cotton, rice, sugar and dairy
- A network of 36 farmer led optimised irrigation sites located on commercial farms across Australia.

This paper draws on some of the findings from SIP1 and SIP2 which will help inform grain growers of the importance of optimised irrigation to maximise irrigation water use efficiency and profitability.

Irrigation systems and designs

One of the optimised irrigation sites is located on the property “Keytah” near Moree, where over the last ten years an irrigation system comparison trial has been running. The comparison includes examples of siphon, bankless channel, lateral move, and subsurface drip, and has focused principally on cotton irrigation, although the lateral move has also been used to provide supplementary irrigations to cereal and chickpeas. The system comparison trial investigated performance on both a yield and gross production water use basis.

Definitions

Surface irrigation: water applied via siphons, small pipe through bank, bankless channel, siphon-less or bay irrigation systems where water flows over the soil surface.

Overhead irrigation: water applied via lateral move or centre pivot irrigation systems where water is applied over the top of the crop.

Subsurface drip: water applied via a drip tape buried in the soil.

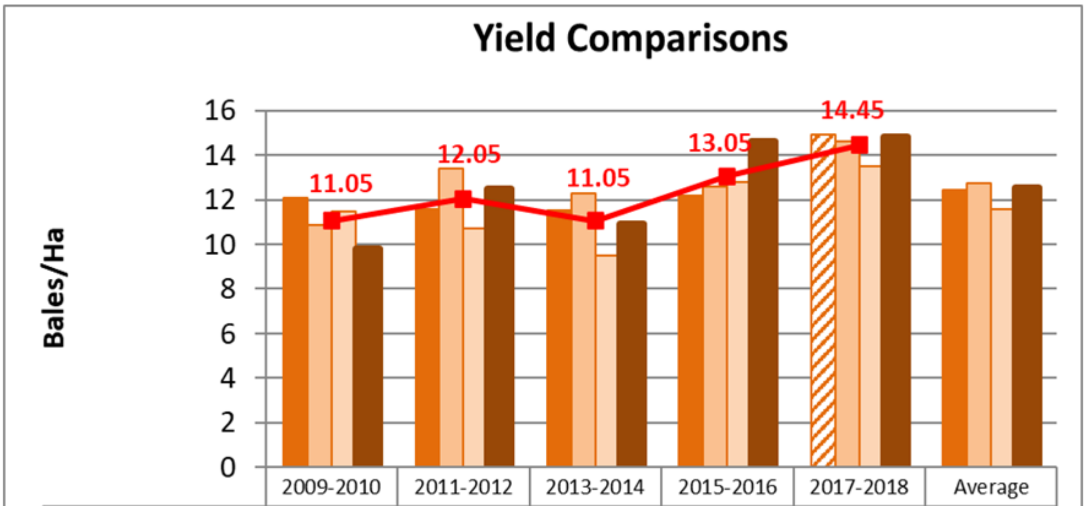
Key points to note about the trial

The trial includes a range of seasonal conditions including 2011-2012 where there were two major flood events, and 2013-2014 where there were hot dry conditions with minimal in crop rainfall during the cotton growing season. The performance of the siphon and bankless channel fields may have been impacted by variables such as flooding (siphon 2011-2012) or poor establishment due to surface crusting which meant the field had to be replanted 20 days after other fields in the trial (bankless 2009-2010), so results for these seasons should be viewed with this understanding.

The 2017-2018 season was the first set of data for the Smart Siphon (a remote-control siphon system), while the four previous seasons were irrigated with traditional siphons. Indications are that more uniform application from the smart siphon may improve performance, but additional data needs to be collected before any conclusions can be made.

System comparison results

The trial has not found that there is any one system ideally suited to every season. Figure 1 combines the yield data for the five years of the trial. There was 1.16 bales/ha difference between systems and 3.4 bales/ha difference between season. This suggests that optimising the system for the prevailing conditions is critical for producers aiming to improve productivity and ultimately profit.

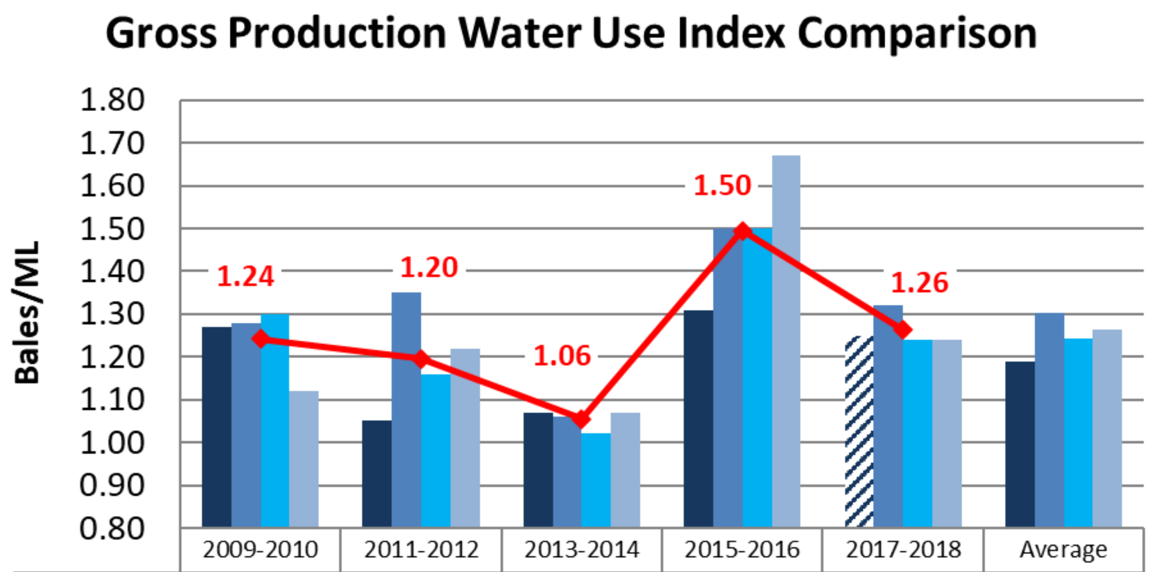


	2009-2010	2011-2012	2013-2014	2015-2016	2017-2018	Average
Siphon	12.06	11.6	11.5	12.20	14.90	12.45
Lateral Move	10.86	13.4	12.3	12.60	14.60	12.75
Subsurface Drip	11.47	10.7	9.5	12.80	13.50	11.59
Bankless Channel	9.8	12.5	10.9	14.60	14.80	12.52
Average	11.05	12.05	11.05	13.05	14.45	

Figure 1. Seasonal yield comparison in bales/ha cotton from 2009/10 to 2017/18 using different irrigation delivery systems at "Keytah" Moree. (Striped column in 2017-18 is the 'Siphon' treatment Smart Siphon system)

In the wet 2011-2012 season it was easier to manage irrigation volumes and minimise waterlogging despite extreme rain events with the lateral move. In contrast in the hot dry 2013-2014 season, irrigation scheduling needed to be intensely monitored to ensure crop water demands were met, especially with the overhead lateral move and drip systems. Having these systems set up with the appropriate system capacity, and attention to repairs and maintenance is essential, as any breakdowns where application volumes are just meeting crop requirements could have dramatic consequences.

In addition to yield, the project considered the water use efficiency of the systems. The metric used was Gross Production Water Use Index (GPWUI) which includes measures of area, yield, irrigation water applied, used soil reserves and the in-season effective rainfall. GPWUI provides the most realistic index to make comparisons between systems and between seasons. The higher the GPWUI, the more productive all water used by the crop has been.



	2009-2010	2011-2012	2013-2014	2015-2016	2017-2018	Average
Siphon	1.27	1.05	1.07	1.31	1.25	1.19
Lateral	1.28	1.35	1.06	1.50	1.32	1.30
Drip	1.30	1.16	1.02	1.50	1.24	1.24
Bankless	1.12	1.22	1.07	1.67	1.24	1.26
Average	1.24	1.20	1.06	1.50	1.26	

Figure 2. Seasonal Gross Production Water Use Index in bales of cotton per mega litre of water applied from 2009/10 to 2017/18 using different irrigation delivery systems at "Keytah" Moree. (Striped column in 2017-18 is Smart Siphon system)

The average GPWUI over the five seasons varied from 1.06 bales per megalitre (ML) in 2013-2014, a warm to hot season with almost no rainfall, to 1.50 bales per megalitre in 2015-2016, a more typical season. There were similar trends in the individual systems over each of the seasons, except in 2011-2012, where the lateral proved to be a standout in a wet overcast season.

Variation between seasons (0.44 bales/ML) have been found to be greater than the variation between systems (0.11 bales/ML). This reaffirms the yield findings, as optimising the irrigation system and management for the seasonal conditions is going to be the best way to enhance productivity and profitability.

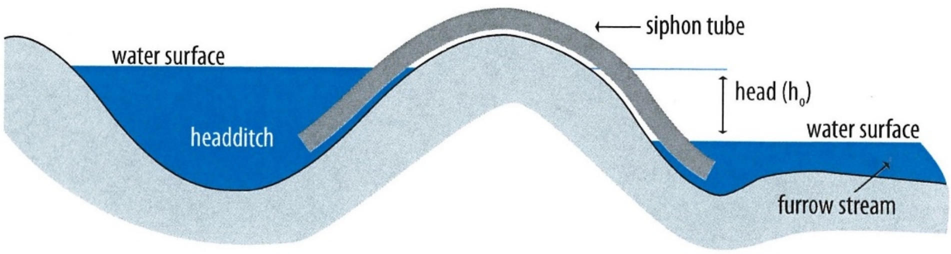
The commercial research into automated siphons and automated bankless channel systems is continuing at Keytah in 2020-2021 as part of SIP2.

The key message from the system research is that no single system suits every situation. Selecting and optimising the system for your farm and water reliability is the most important focus for irrigators. Surface irrigation systems such as siphon, small pipe through bank or bankless channel (siphon-less) typically entail lower capital to set up, although bankless designs can involve significant earth movement. Irrigators who have low water reliability will tend towards lower capital cost systems such as the traditional siphon but will then have high labour resourcing costs during operation. Those facing difficulty with labour resourcing have tended to transition towards bankless channel or siphon-less systems. Additionally, some producers have made investment in automated siphon systems to manage labour resourcing challenges. Where water reliability is higher, investment in overhead or drip systems is more feasible as the initial capital costs can more easily be recouped over a greater number of productive seasons.

In recent years there has been more detailed investigation of siphon-less or bankless channel systems. In 2018-2019 the GVIA (supported by the CRDC) worked with NSW DPI and CottonInfo to host a Siphon-less field day and developed a siphon-less booklet, which includes case studies of various designs being utilised by producers. To date however, we have limited information on the water use efficiency of the large number of designs being utilised by producers. The Smart Irrigation project being managed by Deakin University as part of SIP2 is utilising wireless sensor networks to collect field and crop data in bankless channel systems. Linkages between sensors, forecasting systems and automated irrigation infrastructure will enable precise delivery of water to crops as and when required. This will support irrigators to maximise productivity of water and optimise labour resourcing in these systems.

Optimisation

It can be difficult to optimise traditional siphons as siphon placement, furrow entry conditions, and supply head height will impact flow rates. Flow through siphons increases as head increases and decreases as head decreases.



Source: J Purcell

Figure 3. Siphon placement

Transitioning to permanent small pipe through bank will help ensure more even flow rates as siphon outlets and head height will be more consistent and controllable. This will assist irrigation managers to improve irrigation application efficiency and distribution uniformity, both of which are important to improve irrigation water use efficiency.

There are two commonly recognised configurations which utilise permanent small pipe through bank; the Waverley double head ditch design, and the smart siphon.

- The Waverley design manages the irrigation of siphon sets with a second field head ditch filled from the main head ditch. Water is delivered into the field head ditch to irrigate each siphon set.

Research into the automation of the Waverley site was included in SIP1 and SIP2 managed by the University of Southern Qld (USQ), Centre for Agricultural Engineering (CAE). It provides a commercial example of optimisation and autonomous broad-acre irrigation. The system utilises water level sensors, automated gate control, and modelling techniques which operate synchronously and autonomously from Taggle IrriMATE advance sensors using SISCOweb. These products are now available for improved manual or remote control of broad-acre irrigation, representing interim steps toward fully autonomous optimised irrigation control.

- The Smart Siphon is an elbow fitted to the head ditch side of the small pipe through bank. This elbow is turned on via a pulley in sets of up to 150 siphons by lowering the elbow into the water. The siphon sets can be remotely controlled via a smart phone app, and work is continuing to integrate information from water level sensors and water advance meters to manage irrigations.

Both these small pipe through bank set ups can be initially installed as manually controlled systems, with the potential to transition to more automated or autonomous control over time. There have been continuous improvements in the cost and availability of connected sensor technologies for remote monitoring of irrigation, and improved measurement will inform management, allowing better use of valuable water resources for agricultural production. Commercial scale deployment of remote-controlled furrow irrigation is now common for less than $800/ha. Furrow irrigation optimisation under the USQ project has shown an average 10 to 15% water saving per irrigation event.

Overhead and drip systems readily lend themselves to optimised application through remote control, automation, and autonomous irrigation. Care must be taken to ensure that the managed system capacity is sufficient to deliver to the peak crop water demand. For optimised irrigation it is also essential to conduct regular system audits to ensure accurate application and even distribution across the whole system.

In addition to the investigation of autonomous furrow irrigation, the USQ SIP1 and SIP2 projects have also investigated autonomous broad-acre pivot irrigation systems for cotton and dairy pasture. The autonomous pivot cotton project is at Jondaryan on the Darling Downs. It involves ongoing development of VARIwise cotton yield prediction. VARIwise controlled cotton irrigation has led to a 6% yield improvement and 14% more efficient water use. The VARIwise Yield Predictor has regularly predicted final cotton yield to within 3% of actual yield six weeks prior to picking.

These overhead or drip systems do work well for opportunistic irrigation of either summer or winter cereals. This is especially true for lateral moves, as the crop is generally planted on the flat, meaning there is no requirement to adjust land preparation techniques to transition from cotton to a cereal. Keytah has utilised the lateral, to supplementary irrigate cereals and a chickpea crop.

Observations from southern NSW

Monitoring of commercial irrigated cereal crops in the Murray and Murrumbidgee Valley's over three years from 2014-2016 found that 38% achieved at least 80% of their water limited yield potential. Grower surveys found that average and 'best ever' yields in 2015 were 5t/ha and in 2016 7t/ha, 25% of those surveyed reported best ever yield approaching the calculated mean physiological potential of 9t/ha.

Observations from this monitoring showed that management issues such as waterlogging or water stress at flowering coupled with seasonal conditions, including high temperatures or scalding from water being present during warmer conditions, may have contributed to crops not reaching their full water limited yield potential. Wetter years, or seasons with milder conditions during grain fill seem to produce higher yields.

Smarter irrigation for profit key learning sites - southern NSW

This project includes four key learning sites at Condobolin, Kerang, Darlington Point and Finley. The project is looking at a range of irrigated cropping systems to investigate options to maximise profit per megalitre.

Results from the 2019 winter season at the Irrigated Cropping Council (ICC) site near Kerang provided information on different irrigation approaches and different wheat varieties. The irrigation approaches included were one spring irrigation, a pre-irrigation followed by one spring irrigation, a full spring irrigation consisting of three applications and a pre-irrigation followed by three in-crop irrigations. There were some varietal differences, and the conclusion was that the best result was from the first irrigation in spring, however it was important that the crop was sufficiently developed, either with adequate biomass or tiller numbers to respond. The irrigation had to be timed to crop growth stage and the crop not subject to moisture stress. The decision on whether to pre-irrigate or not and on how many in-crop irrigations are justified will be impacted by water availability, price and seasonal conditions.

Table 1. Results ICC trial Kerang 2019 (wheat)

	Irrigation (ML)			Yield (t/ha)	IWUE (t/ML)
	Pre	Spring	Total		
No pre-irrigation + 1 spring	0	1.5	1.5	3.62	2.41
No pre-irrigation + 3 spring	0	3.4	3.4	5.00	1.47
Pre-irrigation + 1 spring	1.75	1.0	2.75	4.95	1.80
Pre-irrigation + 3 spring	1.75	2.9	4.65	6.15	1.32

IWUE = Irrigation Water Use Index measure yield per megalitre of applied irrigation water

The project is continuing in 2020 with the ICC demonstration this year aiming to highlight the importance of timing when partially irrigating. Treatments will include no irrigation, pre-irrigation only, pre-irrigation plus an irrigation at GS47, pre-irrigation plus two in crop irrigations at GS47 and GS65, pre-irrigation plus three in crop irrigations at GS47, GS65 and GS85, and a final treatment where irrigations are based on soil moisture sensors.

Getting the basics right

Getting the basics right was one of the take home messages associated with SIP1. As a general rule, there is always opportunity to make improvements to irrigation performance, this entails some key steps.

1. Irrigation design and drainage: Surface irrigation is the most common system due to the low capital cost and low energy requirements. Well-designed and managed surface irrigation can achieve application efficiencies of 95%, but efficiency comes from design and management. The focus should be on minimising potential for waterlogging and reducing losses from deep drainage.

   Application efficiencies can be improved by better design with research cited in the reference document 'Soils Under an Irrigated Environment' noting that, excessive deep drainage on self-mulching clay resulted in 1.2ML/ha increase in irrigation water use over two irrigations when water was ponded for extended periods. Additionally, waterlogging during winter and early spring especially on heavy clays with low permeability or sodicity was found to reduce tiller numbers.

2. Scheduling irrigations at the right time and the right volume to optimise plant performance (correct depth, correct position, and correct timing) remains critical regardless of the crop

type. An understanding of what is happening in the soil and the plant is important and monitoring is essential for accurate scheduling. The use of a range of sensors, as automated or autonomous systems can be extremely beneficial, enabling not only the optimal starting time, but critically also the optimal finishing time. Cut-off times suited to convenience or labour, lead to potential waterlogging, deep drainage, and yield loss.

For cereals, scheduling irrigations to ensure there is no water stress from booting GS40-49 through to grain fill (GS70-89) is important. The period from GS30 to GS39 is stem elongation and it is at this time when yield potential is being established, so avoidance of water stress at this time is equally important. Water stress can be both too little and too much water. Many of the irrigation crops monitored in the Soils Under an Irrigated Environment program suffered from drought stress before the first spring irrigation reducing the yield potential of the crop. Additionally, wheat is susceptible to 'scalding' when high temperatures coincide with water on the surface.

3. Optimised irrigation involves maximising the systems irrigation water use efficiency. As identified, no system is perfect, but by optimising whichever system is available, the productivity per megalitre can be improved. Efficiency comes from design and management and is not an inherent characteristic of the system itself.

   With overhead or drip systems, growers should perform regular audits to check application uniformity, and system capacity. Couple this with regular repairs and maintenance to pumps, supply lines and filters to maximise irrigation water use efficiency. The audits conducted as part of SIP1 showed that many irrigators could save money and improve productivity by running periodic checks or audits and giving attention to maintenance.

   Start and stop surface irrigation events at the right time, avoid stressing the crop from too much or too little water. Monitor the supply head height to ensure even flow rates from siphons and check siphon placement is uniform so that flow rates are more consistent.

   Very often the use of sensors such as soil moisture monitors, channel level sensors or water advance systems will help inform these decisions and are invaluable in the process of optimising irrigation systems. Investment in automation or autonomous systems are further steps that will allow easier optimisation of every irrigation event.

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Optimising use of limited irrigation water on grain crops - getting the biggest bang per megalitre

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Take home messages

- Here we document a calculator called '*WaterCan Profit*' that is being developed with growers and advisors to support tactical and strategic economic decision-making associated with rainfed and irrigated crops
- Three case studies relevant to south-eastern Queensland are presented. Due diligence is warranted when extrapolating these results to other regions.
- On a per hectare basis, cotton and soybeans were most profitable up to a water price of $170/ML, after which cotton and rainfed wheat were generally more profitable.
- In terms of gross margin per megalitre of irrigation applied ($/ML), cotton, mungbeans and maize were generally the most profitable options.
- The second case study optimised the use of irrigation water for a farm at Surat (500 km west of Brisbane). For a summer with average rainfall, the most profitable use of water over summer was irrigated mungbeans and cotton. During winter, the most profitable use of irrigation water was on chickpeas (in both $/ha and $/ML).
- For a low rainfall summer, the most profitable use of water over summer was mungbeans; the most profitable use of water in the following winter was again chickpeas
- Conserving irrigation water for summer was more profitable than using irrigation water in dry winters or springs
- The third case study examined long-term profitability as a result of investment in furrow, overhead lateral or drip irrigation for a farm in the Darling Downs, QLD. The net present value (NPV) and future wealth was greatest for the overhead lateral system, even though initial investment in this system was greater than that of furrow or drip irrigation systems.
- The long term internal rate of return variability (risk) associated with the overhead lateral was lower, because this system generally required less water and allowed irrigation on a timelier basis. In the long run, these factors collectively resulted in higher and less variable yields.

Background

In any given season, irrigated crop growers are faced with multiple and competing decisions. Profitability is a function of crop management decisions (sowing time, crop type, the amount and rate of irrigation water applied, fertiliser rate and timing), crop revenue (grain yield and grain price), variable input costs (water price, fertiliser, fuel and labour) and a number of other factors. Highly volatile climatic conditions, water costs and water allocations (often linked to the seasonal and political context) demand more informed crop and irrigation choices at the outset of the growing season.

While decision-makers often focus on tactical decisions such as crop management and irrigation and fertiliser scheduling, forethought and planning of longer-term strategic decisions can be overlooked. An example of this is an appraisal of the value of irrigation infrastructure over its productive life, for instance the investment worth of a flood-based system compared with an overhead lateral or pivot system. Economic assessments of this kind are often fraught with uncertainty as they are at the nexus of many agronomic, climatic, financial and social factors that are changing dynamically over time. To provide irrigated grain growers and advisors with a decision framework that accounts for these factors, we are developing a 'calculator' to be hosted on desktop and mobile apps. The calculator will allow users to answer questions such as:

1. How does water price and seasonal irrigation requirement affect crop choice and crop gross margin?
2. How do commodity prices affect crop choices for a given water price?
3. What is the optimal use of irrigation water and crop area given seasonal and agronomic conditions?
4. How does irrigation system (e.g. overhead laterals, flood irrigation, trickle) affect crop gross margins ($/ha) for varying water prices?
5. What is the relative probability that the predicted economic outcome will occur, i.e. what is the risk or confidence associated with various scenarios?

With funding from GRDC and in concert with the Irrigated Cropping Council, Southern Growers and FAR Australia, this project uses a participatory approach wherein end-users decide on the economic questions to be addressed by the calculator. Through an iterative participative method, we have designed a prototype calculator called '*WaterCan Profit'*. The calculator has been tested with eight grower groups spread throughout the Murray-Darling Basin, South Australia, northern Victoria and Tasmania.

At the time of writing, *WaterCan Profit* is under development. A link to *WaterCan Profit* can be obtained on request from Matthew Harrison at matthew.harrison@utas.edu.au

Methods

WaterCan Profit: background

Three sections comprise *WaterCan Profit*:

(1) a 'Water Price' section that facilitates simple comparison of how yields, water price, crop price and variable costs influence crop gross margin, showing how changes in water price affect crop gross margins,

(2) an 'Optimiser' section that allows users to enter their irrigation type, farm areas, rainfall, soil type, crop and water prices, and expected yields accounting for expected seasonal outlook (dry, moderate or wet) specific to farm location, and

(3) an 'Investment' section that allows comparison of the effects of changes in irrigation infrastructure, and more broadly, farm capital investment. This section also accounts for water and grain prices, crop variable costs and farm overhead costs associated with irrigation (machinery, fuel, repairs and maintenance, council rates), other initial capital costs (e.g. earthworks), area of crop sown, interest rates on loans and water-use efficiency of irrigation infrastructure.

The Water Price and Optimiser sections of the calculator consider tactical questions, such as the economic viability of crop choices given water price, providing outputs that allow determination of the most profitable crop for the next growing season (e.g. summer irrigation) or year (i.e. crop choices for both summer and winter seasons). In contrast, the Investment section is designed for strategic analyses through computation of long-term profit (net present value, return on assets, wealth) over the life of the investment (e.g. 20 years).

Case study 1: Profit by water price comparison of irrigated crops

The first case study was designed to show trade-offs between grain prices, water and variable costs, and water applied for a range of irrigated crops on a case study farm in the Darling Downs, QLD, Australia. The Water Price section of *WaterCan Profit* was designed such that gross margins could be simply compared without the need for extensive farming systems information. Inputs used for the case study were derived from Brennan Kellar et al. (2013). Long term commodity prices and price ranges were sourced from https://www.indexmundi.com/ [Accessed 7 June 2020]. Queensland Government 'AgBiz' tools were used to derive representative ranges of crop variable costs.

Table 1. Grain yields, irrigation water applied, grain prices and variable costs for an irrigated farm in the Darling Downs, QLD (case study 1).

	Yield (t/ha or bales/ha)[1]			Water applied (ML/ha)			Grain price ($/t or $/bale)[2]			Variable costs ($/ha)		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Maize	10	11.5	12.5	2.9	4	6.1	260	280	320	1800	1965	2215
Chickpea	2.5	3	3.5	2.6	3.3	4.4	455	510	560	745	910	1075
Cotton	13	13	13	8	9	10	500	500	500	1900	2100	2250
Mungbean	1.5	1.5	2	1.7	2.2	2.6	800	1100	1500	580	770	910
Rice	9	9.5	10.5	4.4	5.1	6.4	260	330	445	1515	1710	1875
Sorghum	5.5	7.5	8.5	2.6	3.9	5.3	250	300	310	1130	1255	1460
Soybean	2.5	3	3.5	3.7	4.4	6.2	430	510	600	1050	1200	1310
Wheat	4.5	5	5.5	2.2	3.1	5.2	255	320	385	840	970	1090
Rainfed wheat	1.5	2.5	3	0	0	0	255	320	385	200	200	200

[1] Yield for all crops except cotton shown in tonne/ha. Cotton yield is shown as bales/ha.
[2] Prices for all crops except cotton are in $/tonne. Cotton price is shown as $/bale.

Case study 2: Optimisation of gross margins on an area ($/ha) or irrigation water ($/ML) basis

For case study 2, the optimiser section of *WaterCan Profit* was used to examine profitability on an area and ML basis for a farmer at Surat, approximately 500 km west of Brisbane, Australia. *WaterCan Profit* was used at the end of spring to make tactical decisions on the proportion of the farm to sow with different crops for the forthcoming growing season over summer (i.e. cropping area or irrigation allocation optimisation) and following winter cropping season. Based on a typical cropping rotation, in summer the farmer had a choice of irrigating cotton, mungbeans or sorghum. Sorghum could be sown early and harvested by early January, then harvested again after ratooning. Previous experience suggested a yield potential from the combined sorghum crops of 20 t/ha. After ratooning, the stubble could also be baled, given the high volume of biomass produced by a ratooned crop. During winter, the farmer had a choice of growing dryland or irrigated wheat, faba beans or chickpeas. The farming system details for the Surat property are shown in Tables 2-4. The analysis was conducted assuming summer rainfall would be either average or dry relative to long-term rainfall records for Surat (in all cases, winter rainfall was assumed to be average).

Table 2. Water price, paddock size and soil characteristics of the Surat farm used in case study 2

Variable	Value
Water price ($/ML)	90
Paddock area (ha)	400
Plant available water capacity (mm)	147
Soil depth (cm)	122
Soil type	Heavy mixed alluvial
Irrigation infrastructure	Centre pivot (sprinklers)

Table 3. Long-term seasonal variation in rainfall, irrigation water allocation and initial soil water of the Surat farm used in case study 2

	Dry season	Moderate season	Wet season
Summer rainfall (mm)	218	324	450
Winter rainfall (mm)	129	198	343
Irrigation water allocation (ML)	0	2000	4000
Initial soil water % (mm)	20% (29)	45% (66)	55% (81)

Table 4. Crop grain prices, yields and variable costs used in case study 2. Yields and grain prices for all crops are expressed per tonne, except for cotton, which is expressed per bale.

	Mung beans	Wheat	Cotton	Faba beans	Chick peas	Sorghum	Ratooned sorghum grain & stubble
Variable cost ($/ha)	535	585	2100	535	665	1152	2100
Grain price dry season ($/t or ($/bale)	1100	300	500	480	700	220	270
Grain price average season ($/t or ($/bale)	1000	260	500	420	600	200	250
Grain price wet season ($/t or ($/bale)	800	220	500	400	500	180	230
Yield in dry season (t/ha or bales/ha)	2.0	5.5	13.0	4.0	2.5	12.0	12.0
Yield in likely season (t/ha or bales/ha)	2.5	6.0	13.0	4.5	3.0	14.0	20.0
Yield in wet season (t/ha or bales/ha)	3.0	7.0	13.0	5.0	3.5	16.0	25.0
Minimum irrigation (ML/ha)	3.0	3.0	8.0	3.0	1.0	8.0	8.0
Maximum irrigation (ML/ha)	3.5	3.5	10.0	5.5	1.5	10.0	10.0

Case study 3: Strategic decisions: investing in irrigation infrastructure

The third case study examined strategic decisions associated with changes in irrigation infrastructure for a mixed irrigation/dryland farming enterprise in the Darling Downs, QLD, Australia, following Maraseni et al (2012), CORE (2020) and Brennan-McKellar et al. (2012). Soil types ranged from light dispersible clays to heavy black alluvial cracking clays (vertosols) with high plant available water capacity. The analysis performed in this study assumed a cotton-wheat-cotton-maize four-year rotation for all irrigation systems. Wheat and maize grain prices and yields were assumed to vary between years based on historical averages, however cotton yields were assumed constant in line with lower inter-annual variability in this crop type (*WaterCan Profit* allows either cost variability between years or constant costs for entire analyses).

Irrigation water sources were from overland flows (authorised water harvesting) diverted from an unregulated watercourse. Harvested water was stored in authorised on-farm storage and distributed to irrigated paddocks by open channels. The study examined the long-term profitability associated with irrigating an additional 180 ha with either furrow-based irrigation, overhead lateral sprinklers or drip irrigation systems. Financial viability of the investment was measured using four metrics:

- Net Present Value (NPV): the sum of future net cash flows discounted to their present value
- Investment Worth: NPV minus the initial investment cost
- Internal Rate of Return (IRR): the expected compound annual rate of return earned on an investment (or discount rate that makes the NPV of all cash flows from a particular project equal to zero), and
- Payback period: the number of years required to recoup the investment funds, or to reach break-even point.

An irrigation investment was considered viable if the present value of the benefits was greater than the present value of the costs (i.e. NPV > 0). For the sake of simplicity, commodity prices and fuel costs were assumed, and overhead costs associated with irrigation infrastructure installation were assumed constant over the period of the analysis. Irrigation water costs were computed as the product of irrigation water applied and water price (these costs are computed internally in the 'Investment' section of *WaterCan Profit*).

Cost is often seen as a barrier to adoption of new technologies; the case study farmer managed financial risk by only investing in new irrigation when previous investments were paid off (CORE 2020). At the time of the study, the capital investment cost of furrow-based system was $1464/ha (20-year lifespan), lateral-move sprinklers $4083/ha (20-year lifespan), and drip irrigation $3583/ha (15-year lifespan) (Table 5). Overhead costs associated with irrigated land were assumed constant for all systems at $500/ha.year. Variables costs were adapted from Brennan-McKellar (2012) and IWUCVC (1987), assuming labour costs were the lowest for overhead lateral and drip systems and greatest for furrow irrigation (Table 5).

Table 5. Farm systems information used in case study 3 including crop rotation, grain and water price, variable costs and grain yield in low, medium and high rainfall years (shaded columns represent crop types). Prices and yields are expressed per bale for cotton and per tonne for wheat and maize.

		Cotton (years 1, 3)			Wheat (year 2)			Maize (year 4)		
System	**Variable**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**
	Crop price ($/t or $/bale)	500	500	500	220	250	310	180	240	280
	Irrigation price ($/ML)	200	250	300	200	250	300	200	250	300
Furrow	**Yield (t/ha or bales/ha)**	10.6	10.6	10.6	6.0	6.5	6.5	9.0	10.0	13.0
	Irrigation water cost ($/ha)	1300	1625	1950	400	750	1050	600	875	1200
	Other variable costs ($/ha)	1200	1500	2000	200	250	300	850	1100	1300
	Total variable costs ($/ha)	2500	3125	3950	600	1000	1350	1450	1975	2500
	Irrigation applied (ML/ha)	6.5	6.5	6.5	2.0	3.0	3.5	3.0	3.5	4.0
Overhead lateral	**Yield (t/ha or bales/ha)**	13.0	13.0	13.0	6.0	7.0	8.0	10.0	12.0	15.0
	Irrigation water cost ($/ha)	900	1125	1350	300	450	450	500	575	600
	Other variable costs ($/ha)	840	1050	1400	140	175	210	595	770	910
	Total variable costs ($/ha)	1740	2175	2750	440	625	660	1095	1345	1510
	Irrigation applied (ML/ha)	4.5	4.5	4.5	1.5	1.8	1.5	2.5	2.3	2.0
Drip	**Yield (t/ha or bales/ha)**	11.0	11.0	11.0	6.0	6.5	6.5	9.0	10.0	13.0
	Irrigation water cost ($/ha)	1000	1250	1500	200	375	450	400	500	600
	Other variable costs ($/ha)	840	1050	1400	140	175	210	595	770	910
	Total variable costs ($/ha)	1840	2300	2900	340	550	660	995	1270	1510
	Irrigation applied (ML/ha)	5.0	5.0	5.0	1.0	1.5	1.5	2.0	2.0	2.0

Results

Case study 1: Profit by water price comparison of irrigated crops

On a per hectare basis, cotton and soybeans were most profitable up to a water price of $170/ML, after which cotton and rainfed wheat were generally more profitable (Figure 1). Irrigated wheat and chickpeas were generally least profitable on a per hectare basis ($/ha). *WaterCan Profit* stacks gross margins in the graphical user interface (GUI) wherever the mouse is held (see vertical line in Figure 1). In terms of gross margin per megalitre of irrigation applied ($/ML), cotton, mungbeans and maize were the most profitable options (Figure 2). Most crops became unprofitable above a water price of $350/ML.

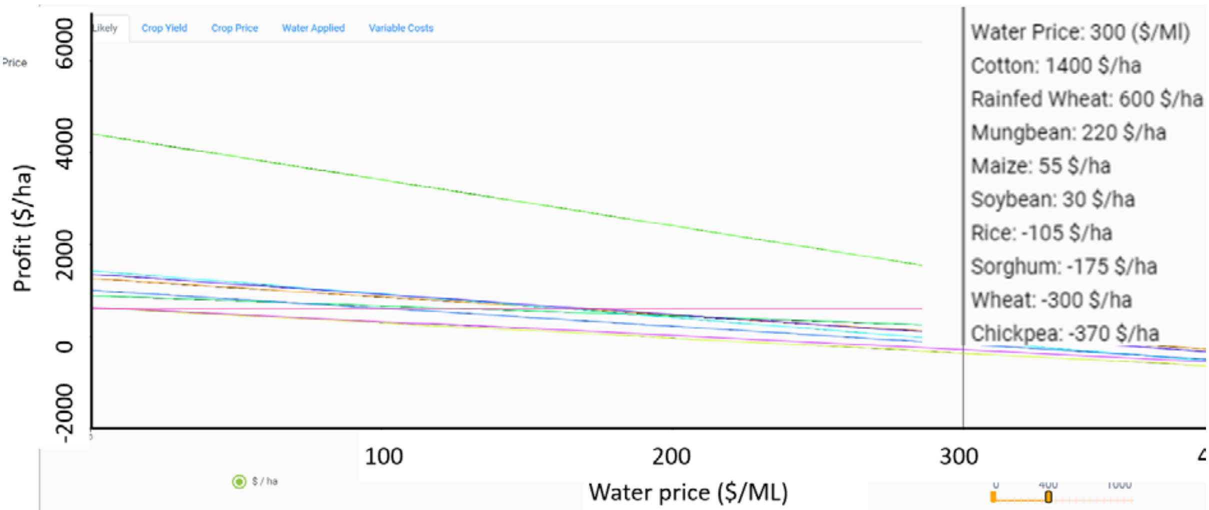

Figure 1. *WaterCan Profit* gross margin per hectare ($/ha) by water price ($/ML, x-axis) comparisons for several crops. Mouse-over 'hover' (shown by vertical line) allows simple comparison of crop profitability for a range of water prices. The above example is where the mouse was hovered over a water price of $300/ML and the corresponding crop profitability is automatically shown in descending order.

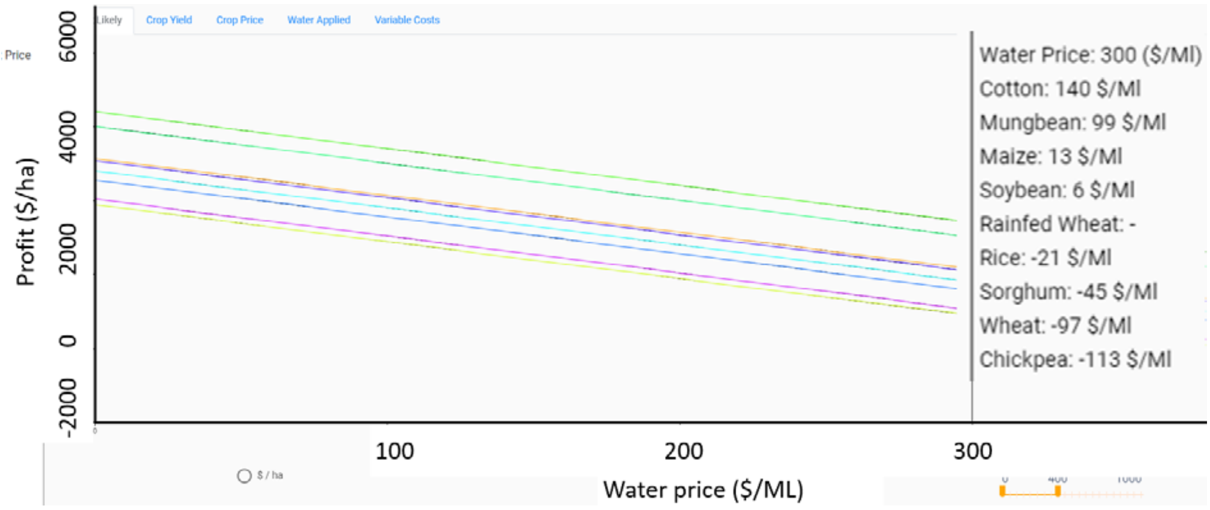

Figure 2. *WaterCan Profit* gross margin per megalitre ($/ML) by water price ($/ML, x-axis) comparisons for several crops. Mouse-over 'hover' allows simple comparison of crop profitability for a range of water prices. The above example is where the mouse was hovered over a water price of $300/ML and the corresponding crop profitability is automatically shown in descending order.

Case study 2: Optimisation of gross margins on an area ($/ha) or water ($/ML) basis

On either an area or irrigation water basis in a year with average rainfall, results from *WaterCan Profit* suggested that the most profitable use of water would be irrigated mungbeans and cotton (Table 6). The calculator includes outputs for the most profitable cropping area (e.g. 86% for mungbeans) and the most profitable use of water (e.g. 51% of water used on mungbeans). In winter, *WaterCan Profit* suggested that the most profitable crop would be chickpeas, although only 20% of the annual water allocation was suggested to be used on this crop. Across the summer and winter irrigation seasons, applying irrigation in summer would be more profitable than applying irrigation in winter.

Table 6. Optimal cropping areas computed using *WaterCan Profit* for the case study farm at Surat, QLD in an average rainfall year. The most profitable crop combination was irrigated mungbeans and cotton in summer, and irrigated chickpeas in winter (bold columns). Percentages in parentheses indicate either proportion of water applied across the farm (ML/ha) or optimal cropping areas (ha). Brown and blue columns denote summer and winter irrigation seasons, respectively.

	Mung beans	**Ratooned sorghum**	**Cotton**	**Ratooned sorghum & stubble**	**Wheat**	**Faba beans**	**Chick peas**	**Total**
Price ($/t or $/bale)	**1,000**	200	**500**	250	260	420	**600**	
Yield (t/ha or bales/ha)	**2.4**	14	**14.1**	20	6	4.5	**2.8**	
Variable cost ($/ha)	**535**	1,152	**2,100**	2,100	585	535	**665**	
Water cost ($/ha)	**90**	90	**90**	90	90	90	**90**	
Water applied (ML/ha)	**3 (51%)**	9.0	**10 (29%)**	9.0	3.0	3.0	**1 (20%)**	2000 ML
Irrigation cost ($/ha)	**270**	810	**900**	810	292	292	**90**	
Gross margin ($/ha)	**1,597**	838	**4,035**	2,090	682	1,062	**920**	
Gross margin ($/ML)	**532**	93	**403**	232	210	327	**920**	
Optimal area (ha)	**343 (86%)**	0 (0%)	**57 (14%)**	0 (0%)	0 (0%)	0 (0%)	**400 (100%)**	
Profit ($)	**547,897**	-	**229,990**	-	-	-	**367,882**	1,145,769

For a season with lower than average summer rainfall (but average winter rainfall), profit was diminished compared with a summer with average rainfall (cf. Tables 6 and 7). In such seasons, mungbeans were the most profitable summer crop, but restrictions on water allocations meant that no more than 50% of the paddock area could be sown (Table 7). In winter, *WaterCan Profit* again suggested that chickpeas would be the most profitable option (on both a $/ha and $/ML basis). The calculator suggested that 60% of irrigation water would be best used in summer, and the remainder in winter.

Table 7. Optimal cropping areas computed using *WaterCan Profit* for the case study farm at Surat, QLD in a summer with low rainfall. The most profitable combination of crops was irrigated mungbeans in summer (50% of farm area) and irrigated chickpeas in winter (100% of farm area), as shown by bold columns. Percentages in parentheses indicate either allocation of water applied across the farm (ML/ha) or optimal cropping areas (ha). Brown and blue columns denote summer and winter irrigation seasons, respectively.

	Mung beans	**Ratooned sorghum**	**Cotton**	**Ratooned sorghum & stubble**	**Wheat**	**Faba beans**	**Chick peas**	**Total**
Price ($/t)	**1,100**	220	500	270	260	420	**600**	
Yield (t/ha)	**1.9**	11	13	11.5	6	4.5	**2.8**	
Variable cost ($/ha)	**535**	1,152	2,100	2,100	585	535	**665**	
Water cost ($/ha)	**90**	90	90	90	90	90	**90**	
Water applied (ML/ha)	**3 (60%)**	9.0	9.0	9.0	3.0	3.0	**1 (40%)**	1000 ML
Irrigation cost ($/ha)	**270**	810	810	810	292	292	**90**	
Gross margin ($/ha)	**1,284**	458	3,590	195	682	1,062	**920**	
Gross margin ($/ML)	**428**	51	399	22	210	327	**920**	
Optimal area (ha)	**200 (50%)**	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	**400 (100%)**	
Profit ($)	**256,885**	-	-	-	-	-	**367,882**	624,767

Case study 3: Strategic investments in irrigation infrastructure

The net present value was greater for the overhead lateral system compared with drip and furrow irrigation. This demonstrates that - using the input prices for the case study conducted here - the overhead lateral system would be the most profitable in the long term, while furrow irrigation would be the least profitable (Table 8, Figure 3). Investment worth followed similar patterns to those in NPV. Payback periods (or time to reach positive cumulative net cash flow) are calculated in *WaterCan Profit* using the mean of 1000 random samples. Payback periods were lowest for furrow irrigation, because cash flows of cotton sown in the first year were in excess of the net cost of the investment. Lower payback periods for furrow irrigation are reflected in a high internal rate of return (Table 8). Payback periods were the longest (and internal rates of return the lowest) for the drip irrigation system, due to relatively lower yields and shorter life associated with this form of irrigation.

Table 8. Net present value, investment worth, internal rate of return on investment and payback time associated with investment in furrow, overhead lateral or drip irrigation for a case study farm in the Darling Downs, QLD

	Furrow	Overhead lateral	Drip
Net present value ($/ha)	12,479	28,647	16,717
Investment worth ($/ha)	11,015	24,565	13,134
Internal rate of return (%)	77	58	44
Payback period (years)	1	3	4

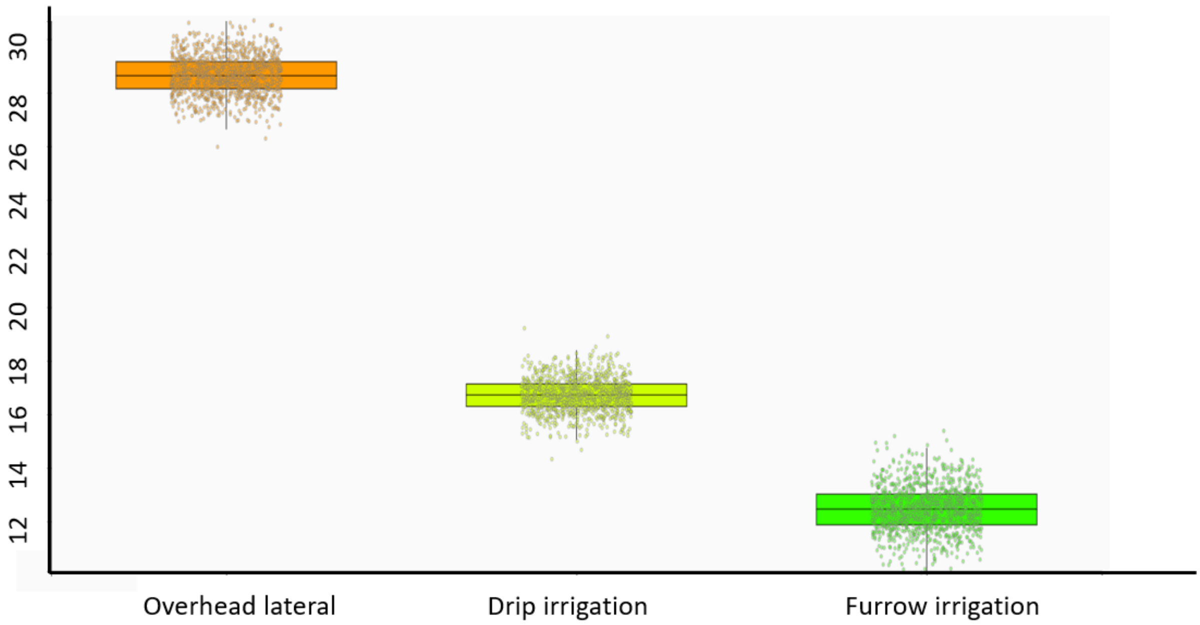

Figure 3. Net present value associated with investment in overhead lateral, drip or furrow irrigation for a case study farm in the Darling Downs, QLD. Y-axis is shown in ×$1,000/ha. Horizontal lines in boxplots indicate 75th (upper), 50th (mid) and 25th (lower) percentiles; points show individual data.

Over the life of each investment, the furrow irrigation system the greatest median internal rate of return (IRR, i.e. the expected compound annual rate of return that will be earned on an investment), but the IRR variability of the furrow system was much greater than that for both other systems. The variability associated with the overhead lateral and drip irrigation systems were lower, as these systems generally required less water, allowing irrigation on a timelier basis, which in the long run resulted in higher yields. The IRR of the drip irrigation system was less than that for the other systems due to (1) lower lifespan (15 compared with 20 years for the other systems) and (2) lower yields and income relative to the initial financial outlay.

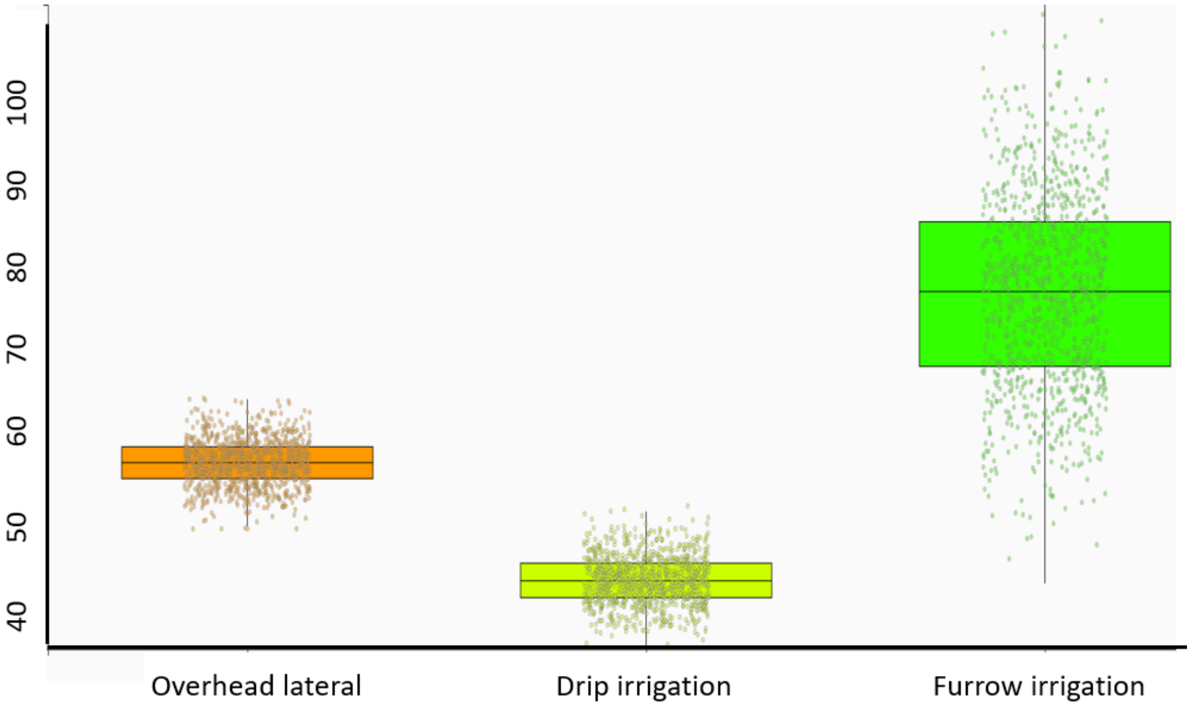

Figure 4. Percentage internal rate of return associated with investment in overhead lateral, drip or furrow irrigation for a case study farm in the Darling Downs, QLD. Horizontal lines in boxplots indicate 75th (upper), 50th (mid) and 25th (lower) percentiles; points show individual data.

Discussion

Which part of WaterCan Profit should you use?

The first and second sections of *WaterCan Profit* deal with tactical questions. For simple comparisons in the absence of farm systems and management information, the Water Price section of the calculator is most appropriate. For tactical (seasonal) questions regarding optimal use of water on a ML or area basis, the Optimiser section is most appropriate. Both the Water Price and Optimiser sections could be used on a mobile device, as they engender questions that users may wish to answer in the field. In contrast, the Investment section allows contrasting of strategic investment decisions. As this part of the calculator deals with much larger finance quanta compared with the Water Price and Optimiser sections, such strategic analysis may be less suited to a mobile device and more suited to a desktop or office analysis.

For all parts of the calculator, users are strongly encouraged to contrast multiple scenarios and test multiple input values. In this way, users can gauge sensitive variables that have a larger effect on gross margin (in contrast to those variables that have little effect).

For any decision-support tool (or similar), the magnitude (or absolute value) of any output is of lesser importance; it is the relative difference between scenarios that is important. We have facilitated such comparison in the Investment section by showing plots of several investments concurrently. In future, we aim to enable such comparison in the other parts of the calculator.

Case study 2: optimal water or area usage?

A fundamental attribute to the successful use of any decision-support calculator is how to mimic a real situation. Before applying the calculator, users should identify the output they would like to contrast. Data for irrigated ratooned sorghum and sorghum stubble in Table 4 were entered as a single crop in the Optimiser section: variable costs, yields and irrigation water were entered as the sum of each variable for the two crops. If the ratooned sorghum stubble were entered separately, *WaterCan Profit* calculated that the irrigated ratooned stubble was more profitable than the grain from the sorghum crop. Of course, in reality sorghum stubble will not be available without having first sown a sorghum crop. Note that grain prices used here for sorghum may be greater than long-term averages due to the recent drought conditions experienced in south-eastern Queensland.

It was shown that 'optimal profitability' depended on whether the metric was assessed on a $/ha or $/ML basis. In our interviews with farmers and advisors in NSW, QLD, Victoria, SA and Tasmania, we found that most irrigators compute profitability in terms of $/ML. Nonetheless, to account for different decision-making preferences, *WaterCan Profit* has options for optimising water use on either an area or irrigation water basis. In case study 2, both optimal water and area pointed to the same cropping system when the climatic outlook was the same. For example: for a summer with moderate rainfall, irrigated mungbeans and irrigated cotton were most profitable in terms of $/ha and $/ML. However, in a dry summer, mungbeans were the most profitable crop, followed by irrigated chickpeas in winter. The key point here is that the most profitable cropping system will vary depending on climatic outlook (i.e. whether the forthcoming season will be wet or dry); *WaterCan Profit* users are encouraged to contrast climatic scenarios to help inform their decisions.

In all cases tested here, the most profitable use of irrigation water was over summer, with the Optimiser section of *WaterCan Profit* suggesting that 60-80% of an annual water allocation should be used for irrigation during summer. This is a key take-home message.

Case study 3: Strategic irrigation infrastructure investment decisions

Many models or apps are built to support tactical decision-making at the farm level. In contrast, *WaterCan Profit* allows both tactical and strategic decision making, the latter comprising a scenario analyses of investment in irrigation infrastructure. While the main output metrics of *WaterCan Profit* are economic/financial, profit is only one of several variables a farmer may consider in deciding whether or not to invest in irrigation infrastructure. Indeed, the third case study farmer intended to invest in surface irrigation (drip or overhead lateral) to allow greater flexibility, increased cropping intensity, reduced labour, improved water-use efficiency, fewer paddock passes and greater terms of trade (CORE 2020). Variation in soil type, land topography, availability and sources of water, lifetime of irrigation infrastructure, on farm storage capacity, size of area being irrigated also need consideration (AgVIC 2020). For case study 3, it was shown that investment in lateral move systems allowed higher water-use efficiency than flood irrigation through greater ability to water when required and to a specified amount (Montgomery 2020), which can have implications for crop quality (e.g. better cotton fibre quality eventuates when crops are maintained under irrigation for longer periods such as that allowed by the overhead lateral system).

The case study farmer also speculated that nitrogen-use efficiency was improved for the overhead lateral and drip systems compared with the furrowed system, though data related to N were anecdotal (CORE 2020). While *WaterCan Profit* can account for many of these factors (e.g. differences in labour, variable costs, crop rotation, double cropping etc), the calculator cannot account for all the above factors. Indeed, no model or decision-support tool can account for every factor: if it did, it would not be a model, but would be reality.

Here it was shown that overall lateral irrigation systems had the greatest NPV, followed by drip irrigation systems. Although drip irrigation systems generally have higher irrigation efficiency than flood or sprinkler systems, their flow rates are relatively low (IWUCVC 1987). As well, the case study farmer suggested that such systems have relatively short lifespan due to damage by pests (mice and crickets) and soil movement of self-mulching clays (CORE 2020).

Conclusions

Through three targeted case studies with real farms in south-eastern QLD, this paper has shown that:

- For a gross margin calculation in the absence of detailed farm systems information (i.e. using the Water Price section of *WaterCan Profit*) cotton and soybeans were most profitable on a per hectare basis up to a water price of $170/ML, after which cotton and rainfed wheat were generally more profitable
- For the case study farm at Surat in a summer with average rainfall, the most profitable use of water over summer was irrigated mungbeans and cotton, while the most profitable use of water in winter was on chickpeas (on both a $/ha and $/ML basis). For a low rainfall summer, the most profitable use of water over summer was mungbeans; the most profitable use of water in the following winter was chickpeas
- Conserving irrigation water for summer was generally more profitable than using irrigation water in dry winters or springs
- Investment in overhead lateral systems was generally more profitable than investment in either drip or furrow-based systems, and long-term variability in internal rate of return of the overhead lateral system was lower because this system generally used less water and allowed irrigation on a more timely basis
- Users of *WaterCan Profit* are strongly encouraged to use the calculator with real case studies and considered input values.

Where to next?

We will continue to engage farmers and further refine *WaterCan Profit* such that it is designed to meet the needs of irrigated grain growers in Australia. Interactive training online sessions will be held in late 2020, where end-users will bring their mobile devices and own scenarios as case studies. This approach will help users understand how to use the calculator but will also provide developers within insights into deficits in functionality, bugs and counterintuitive parts of the calculator. In this way, we will develop a series of real-life case studies and use these as defaults in the new release of *WaterCan Profit*.

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Critical period of moisture vulnerability in mungbeans

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Drought, stress timing, phenology, yield determination, pod-fill

GRDC code

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Take home messages

- Mungbeans are most vulnerable to drought stress during the pod filling phase. It is critical to ensure adequate moisture is available or has been applied by irrigation during this period
- Drought stress during pod filling reduces the number of grains per pod and the overall number of pods per plant
- Yield decreased in response to drought stress by 10-33% during vegetative growth, 5-27% during flowering and 53-75% from early-pod fill compared with well-watered. Yield response to drought differed between varieties
- Mungbeans compensate for lower pod number by increasing carbon allocation to remaining pods - increasing individual grain weight and partially offsetting yield losses for stress occurring during flowering
- Optimising sowing time or irrigation timing to avoid drought stress during pod-fill will improve grain yield stability.

Background

One of the major challenges facing the mungbean industry has been meeting current and projected demand for the crop when yields can be unpredictable and fluctuate considerably from season to season. Abiotic stress, mostly high temperatures and drought stress limit mungbean (*Vigna radiata* L. Wilzcek) growth and production potential, particularly when stress occurs during flowering and pod filling. Mungbeans in the Northern Grains Region are traditionally planted from September through to November for a spring planting, or from December to January for a late summer plant, exposing them to periods of heat and moisture stress. Mungbeans are typically grown under rainfed situations due to their short duration and lower water use compared with other summer crops. Dry conditions through the crop cycle are common meaning crops are often planted on low stored soil moisture (<90mm plant available water) with little in-crop rain, resulting in terminal drought stress or drought stress during the later stages of reproductive growth. Chauhan and Rachaputi (2014) found that mungbeans experience drought in 58-68% of years depending on the location and soil plant available water (PAW), and also reported up to 55% of growing areas can be affected by mid-season or severe terminal drought stress with water availability declining approximately a week before flowering.

Crop response to water deficits are largely based on the stage of development when drought stress occurs. Drought stress is multidimensional and can impact the morphological and physiological processes that drive crop growth, productivity and grain quality (Bangar et al., 2019). While mungbeans are tolerant of drought conditions compared with other crops, the timing of water deficits can still have a significant impact on crop productivity. Robertson (1934) defined the critical period for yield determination as the physiological stage in which abiotic stressors have the largest impact on yield determination. The reproductive phase of most legumes, including mungbeans is considered the critical period for yield determination (Lake & Sadras, 2014). However, the impact of abiotic stress, particularly water deficits, during this period in comparison with other development stages is largely unknown.

The aim of this experiment was to investigate the critical period for moisture stress vulnerability and the impact of drought stress at different phenological stages on the final grain yield of mungbeans. The outcomes of this experiment will help to develop a deeper understanding of how mungbeans respond to drought stress and how we can improve our agronomic management to maximise grain yields.

Method

A pot trial was established in a lysimeter facility at The University of Queensland, Gatton Campus. The lysimeter system is housed in a shade house covered by Solarweave® material that excludes rain and some direct solar radiation (Chenu et al., 2018). Individual lysimeters consist of a large 51 L pot placed on a load cell enabling automatic weighing and watering every 10 minutes (Figure 1). Target pot weights were consistent across all lysimeters, allowing for water deficits to be controlled. Each pot was lined with a plastic garbage-bin liner and filled with a 1:3 mix of black vertosol and washed river sand to facilitate adequate soil drying and covered with insulation material cut to the same diameter of the pots to reduce surface evaporation. A basal fertiliser treatment of Granulock® at an adjusted rate of 25kg/ha was applied to each pot pre-planting. A second application of Granulock® Z was made at the appearance of first flower to avoid any nutrient deficiencies. Three varieties of mungbeans; Jade-AU⦶, Crystal⦶ and Celera II-AU⦶ were inoculated using Group I peat (*Bradyrhizobium* spp.) inoculant and planted on 10 February 2020 in a randomised complete block design with four replications and four treatments. The treatments were: well-watered to 80% field capacity for the duration of the experiment (WW), drought stress during the vegetative growth phase (V), drought stress during flowering (F) and drought stress during pod-filling (PF). Pots undergoing a drought stress treatment were not watered during the treatment period unless soil moisture dropped below 40% field capacity. Soil dry down was progressive during the stress period (Figure 2). The plants were harvested when ~90% of the pods were dark brown to black and separated into harvest components (leaves, stems and pods) and dried at 65°C for five days to obtain dry weight (DW) of each component.

Figure 1. Lysimeter pot set-up for mungbeans.

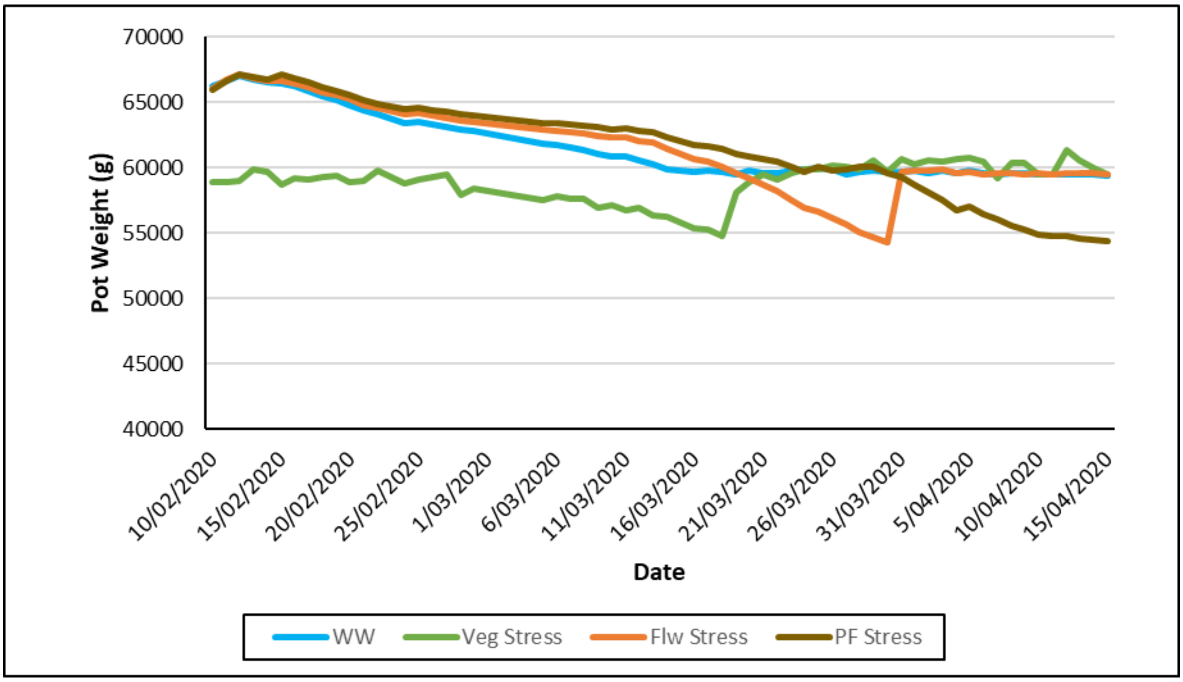

Figure 2. Average lysimeter pot weights (g) measured for the duration of the experiment. The initial peak in weight occurred from the watering up process. The vegetative stress treatment (green line) was not initially watered to field capacity to facilitate adequate dry down while water demand was low during the vegetative growth phase.

Results and discussion

Weather conditions

Daily minimum and maximum temperatures during were relatively mild with no significant heat events (>40°C) in any of the growth stages (Figure 3). The optimum temperature for mungbean growth is 28-30°C and for the duration of the experiment conditions were ideal for facilitating growth without periods of heat stress.

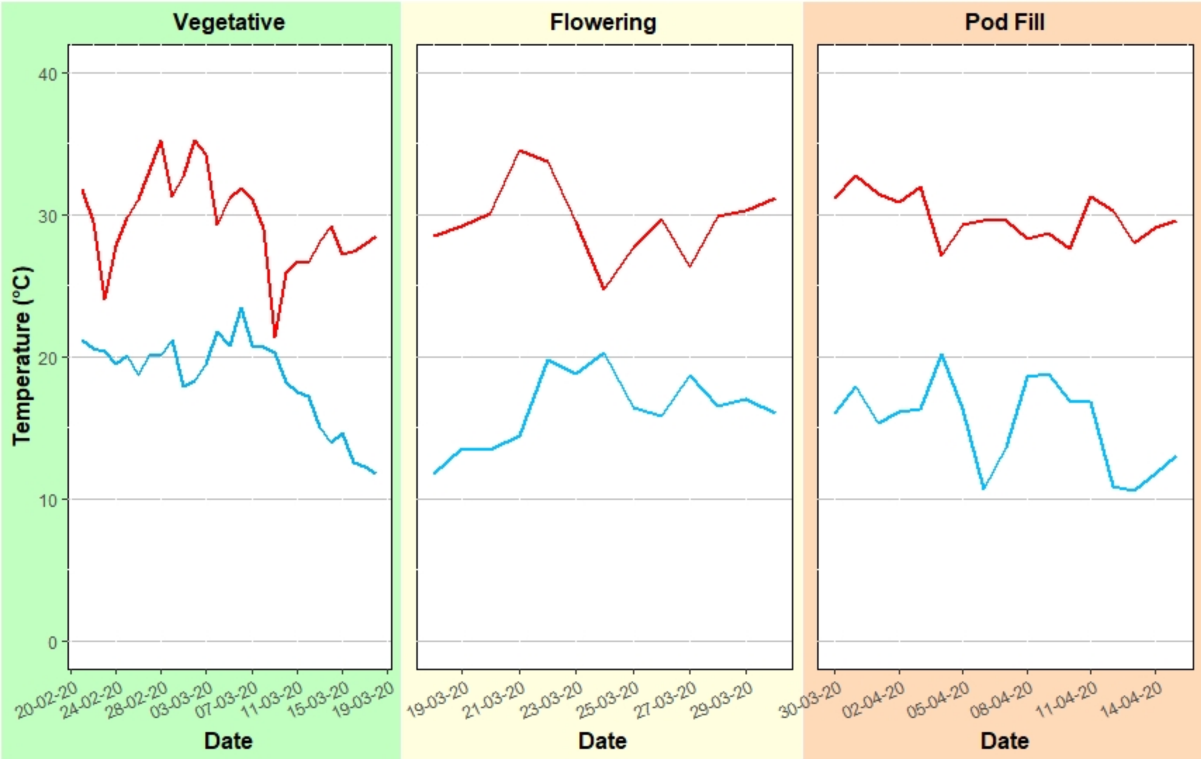

Figure 3. Maximum (red line) and minimum (blue line) temperatures (°C) from planting to the end of the pod-filling drought stress treatment.

Harvest components

Shoots and leaves

Shoot weight (weight of leaves and stems) declined significantly in response to early pod-filling water deficits compared to plants under both well-watered and vegetative/flowering stress. Shoot weight under terminal water stress (pod-fill water deficits) was affected by decreased leaf initiation/expansion and potentially increased rates of leaf senescence. Compensatory vegetative growth occurred when stress was imposed in earlier growth phases, i.e., during vegetative and flowering; however this response varied across varieties. Jade-AU⦶ produced considerably higher total shoot dry matter than Celera II-AU⦶ or Crystal⦶ (Figure 4), but was more severely affected by drought stress during pod-filling with a >20 g dm/plant dry mass reduction. Crystal⦶ and Celera II-AU⦶ had lower shoot dry mass reductions of 12 and 10 g dm/plant respectively. Shoot biomass across all three varieties was reduced during the vegetative or flowering phases by 5 g dm/plant. Contribution of assimilates supplied from the stem reserves can increase by up to 40% in drought stress situations (Sehgal et al., 2018) and combined with more rapid leaf senescence to remobilize assimilate reserves to grain may also explain the decline in shoot dry matter from the well-watered treatment to the pod filling treatment.

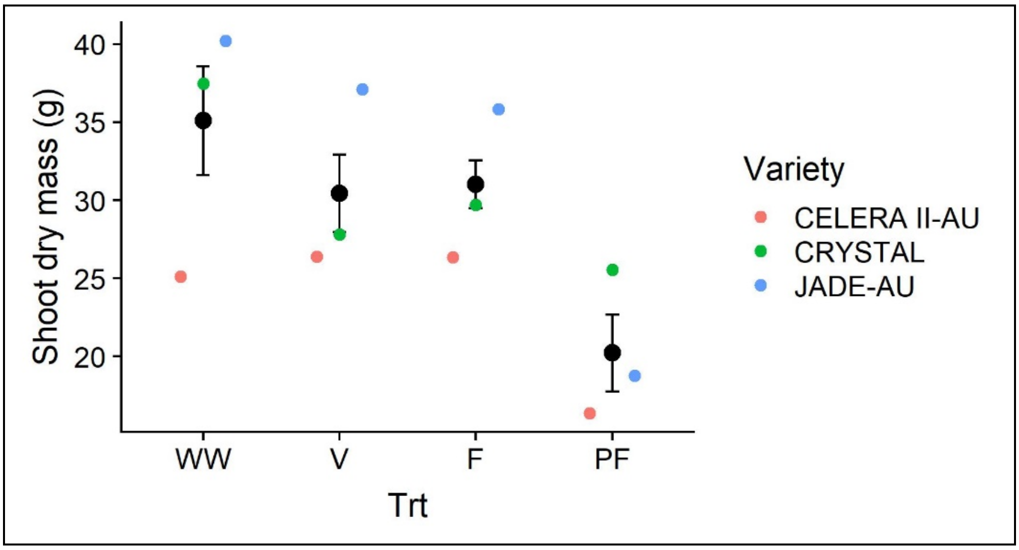

Figure 4. Total shoot dry mass for the drought stress and well-watered treatments. WW: well-watered, V: water stress during vegetative growth; F: water stress during flowering, PF: water stress during pod-fill. Black dots represent the overall treatment means across all three varieties with standard error bars; the coloured dots show the means of each variety.

Drought stress decreased new leaf production when drought was introduced in the vegetative growth period and accelerated senescence under stress in the later reproductive phases (Figure 5). Leaf appearance and growth continues after flowering in mungbeans for most commercial varieties hence the total weight and number of leaves (data not shown) in this experiment was not affected by drought stress up until early pod fill however drought stress from early pod-fill to maturity significantly affected leaf weight ($p<0.001$, Figure 5a). Leaf senescence was accelerated when plants experienced water deficits from early pod fill through to maturity (Figure 5b) compared with earlier drought stress.

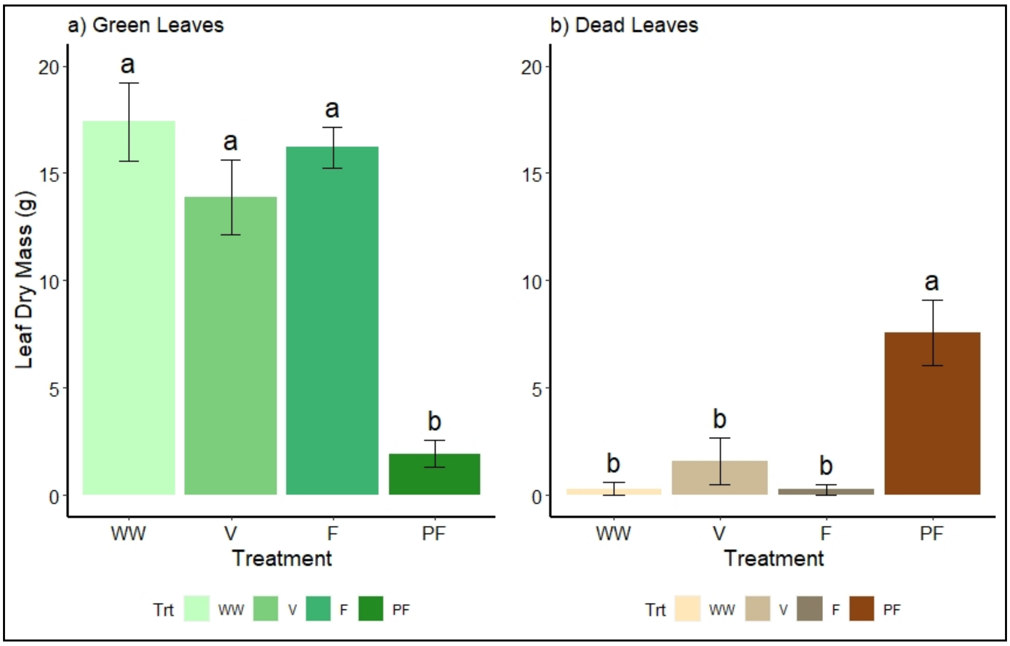

Figure 5. Contribution to total leaf dry weight by green leaves (a) and dead leaves (b) at the time of harvest (error bars are standard error) for the treatments well-watered (WW), vegetative drought stress (V), flowering drought stress (F) and pod-fill drought stress (PF). Treatments with the same letter are not significantly different at α0.05.

Pod production

Terminal drought stress can reduce the duration of flowering and pod-fill and the capacity for the plant to produce a large number of flowers and pods thereby reducing overall grain yield (Farooq et al., 2017). There was a significant decline in the number of pods produced under early pod-fill stress with a reduction of 10-35% in total pod number compared with the well-watered treatment (Figure 6). This decrease is likely due to increased rates of flower and pod abortion. Interestingly, the vegetative and flowering stress treatments set more pods than the well-watered treatment. Non-limiting water conditions can lead to prolonged vegetative growth meaning the switch from vegetative to reproductive sinks possibly was slower, resulting in fewer pods. Celera II-AU⊕ produced consistently higher numbers of pods per plant for each treatment followed by Jade-AU⊕ with Crystal⊕ producing the fewest pods.

While the goal of the experiment was to synchronise flowering across the varieties, the precise start of flowering may have varied between varieties by several days, and therefore the treatments may not have captured the full impact of drought stress on varietal development equally. In a simulation study, Muchow and Sinclair (1986) found that earlier maturing varieties can yield more than later maturing varieties by at least 40% under drought conditions despite lower biomass accumulation (Figure 4). This may explain why Celera II-AU⊕ was able to produce up to 24% more pods than Jade-AU⊕ or Crystal⊕.

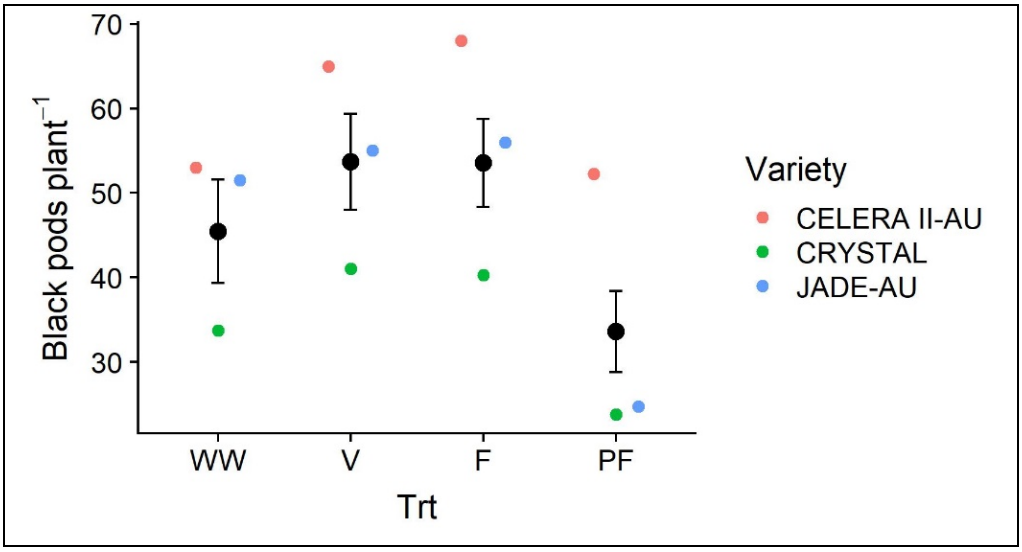

Figure 6. The number of mature (black) pods harvested from each treatment for Celera II-AU⊕, Crystal⊕ and Jade-AU⊕. WW: well-watered, V: water stress during vegetative growth; F: water stress during flowering, PF: water stress during pod-fill. Black dots represent the overall treatment means across all three varieties with standard error bars; the coloured dots show the means of each variety.

Total grain yield per plant decreased 53-75% for plants subjected to drought stress during pod-fill for all three varieties (Figure 7). Overall, Jade-AU⊕ was the highest yielding variety for the earlier stress treatments but suffered a significant yield decline (30%) with later drought stress. Crystal⊕ did not yield as well as Jade-AU⊕ however yield declines were milder from the well-watered treatment to drought stress during pod-fill. Being a smaller-seeded variety, Celera II-AU⊕ did not produce as much grain as Jade-AU⊕ or Crystal⊕ but had similar patterns of yield decline with the later season drought stress. The reduced shoot and leaf mass (Figures 4 and 5) for all three varieties in the vegetative stress treatment was reflected in the final grain yield/plant which was lower than the well-watered and flowering drought stress treatments.

Successful flowering and podding under terminal drought stress is associated with the ability for plants to store assimilate reserves in the vegetative organs (Farooq et al., 2017) in order to compensate for water-stress driven decreases in leaf photosynthesis. Physiologically grain yield is strongly linked with several factors including crop growth rate (CGR; affecting biomass and photosynthetic leaf area), presence / absence of stress affecting photosynthetic rates during grain filling periods as well as availability of stored carbohydrate reserves built up during vegetative growth. While stress in early growth phases decreases CGR, leaf area available for photosynthesis and stored carbohydrates plants can compensate via increasing leaf photosynthesis during grain fill when sink (grain) demand for carbon is high. In contrast, stress in reproductive phases, particularly post-pod fill significantly decreases photosynthetic rates and crop growth rate during a phase in which grain demand for carbon is high. Insufficient photoassimilate production (via low photosynthetic rates) and rapidly depleting stored carbohydrate reserves were insufficient to ensure yield is unaffected.

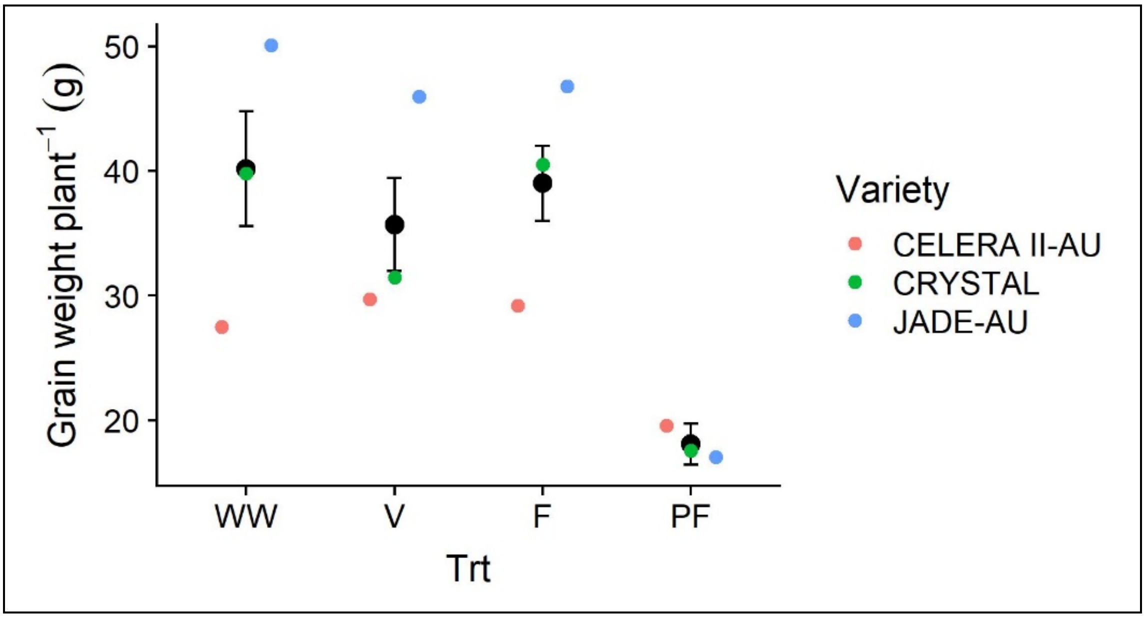

Figure 7. Grain yield/plant (g) for the three varieties across the well-watered and drought stress treatments. WW: well-watered, V: water stress during vegetative growth; F: water stress during flowering, PF: water stress during pod-fill. Black dots represent the overall treatment means across all three varieties with standard error bars and the coloured dots represent the varieties.

Individual grain weight was relatively stable for the well-watered and earlier drought stress treatments, averaging 5.0 - 5.5 g/100 seeds. However, 100 grain weight increased for Jade-AU⦶ and Crystal⦶ when drought stress was imposed during pod-filling. Pod abortion and flower shedding during early pod-fill coupled with increasing dehydration and early leaf senescence may have accelerated assimilate remobilisation from vegetative tissue and subsequent availability to developing grains. The reduced number of pods (Figure 8) produced may indicate assimilate remobilisation was redirected to the remaining pods, increasing individual grain size to compensate for grain yield lost due to lower pod and grain numbers.

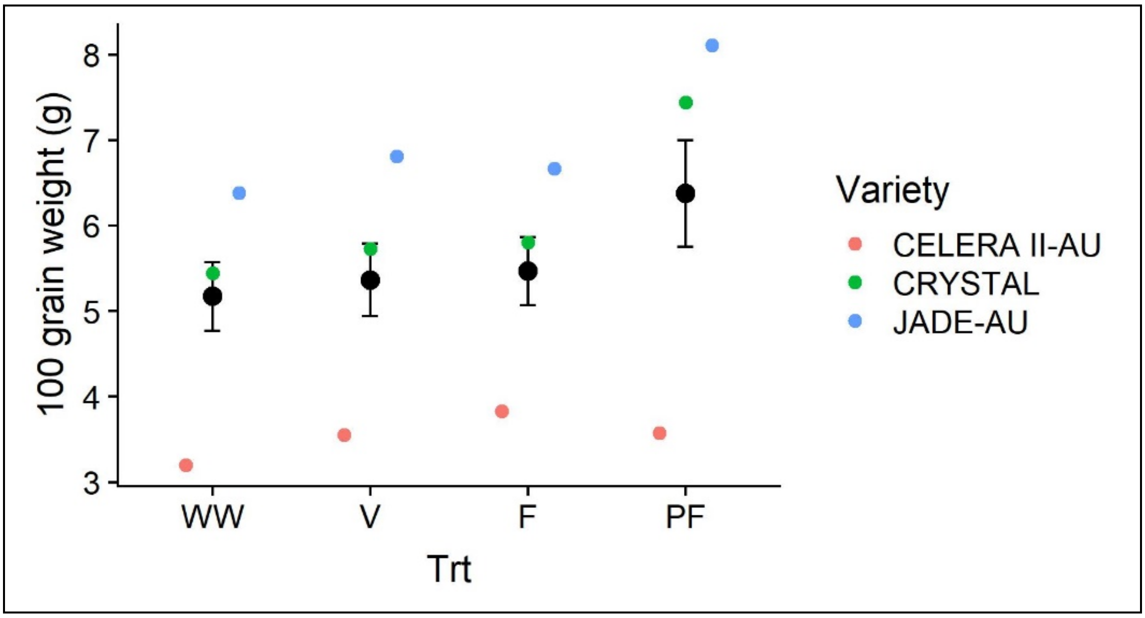

Figure 8. 100 grain weight measured for Celera II-AU⦶, Crystal⦶ and Jade-AU⦶ when subjected to drought stress during different stages of growth and development.

Grain yield was strongly driven by grain number for all three varieties with differences in seed size driving the difference in grain number/grain weight for each variety (Figure 9). Celera II-AU⦶ produces a large number of smaller sized seed therefore grain yield was not as high as the larger-seeded varieties Jade-AU⦶ and Crystal⦶. Drought stress during pod-fill reduces pod and grain number and while individual grain weight increased under drought stress (Figure 8) yield is still limited by the total number of grains produced.

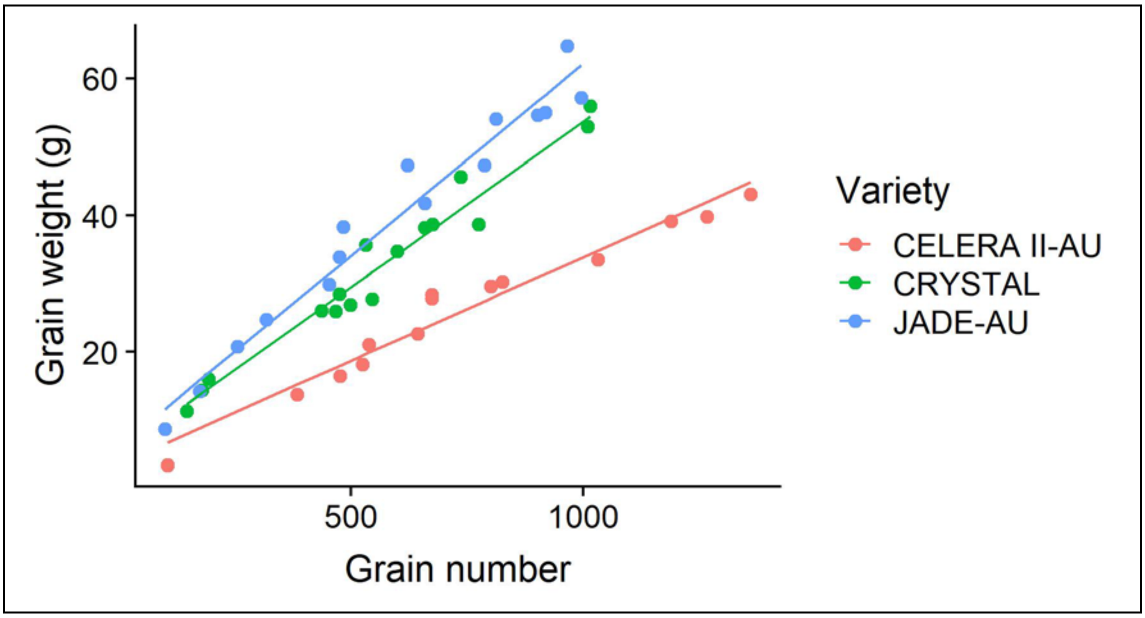

Figure 9. The relationship between grain weight (g/plant) and grain number for Celera II-AU⦶, Crystal⦶ and Jade-AU⦶.

Conclusion

- Mungbeans are tolerant of mild to moderate drought stress during the vegetative and early reproductive stages without major yield penalties.

- Drought stress during the vegetative phase can limit leaf development and biomass production which limits grain yield later in the season. However, yield is largely determined by terminal drought stress or drought stress in the later reproductive stages of development, i.e. during pod-fill.
- While the total number of harvestable pods is reduced when plants are under drought stress, drought stress during pod fill can increase individual or 100 grain weight through efficient remobilization of assimilate reserves to partially compensate for lower pod number. However, the total grain yield shortfall is still substantial.

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Yield gaps in mungbean crops across the northern grains region

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Key words

nematodes, nitrogen, flowering, heat stress, water-use-efficiency, nutrition

GRDC code

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Take home messages

- Mungbean crops with low observed yield and high yield gaps were those with a low harvest index, which was not always associated with low crop biomass
- Management factors found to significantly increase yield were narrow row spacing (<50 cm) and crops sown on a fallow rather than double cropped
- Maximum water use efficiency (WUE) of approximately 7.5 kg/ha/mm of available water (in-crop rain + starting soil water) were found across the data set. Differences in starting water at this WUE explained observed yield differences between fallow and double crop mungbeans
- 35% of crops achieved > 80% of their water-limited yields, while 36% yielded < 60% of the water-limited yield potential. Nearly half of all monitored crops had yield gaps > 500 kg/ha
- No single biotic or abiotic factor was found to be associated with low mungbean observed crop yields or high yield gaps. However, 88% of crops with a high yield gap (i.e. < 65% water-limited yield) had either *P. thornei* present at > 3/g soil, or maximum temperatures > 39°C during flowering, or soil nitrate levels below 65 kg N/ha
- Consider soil tests for nutrient status and root lesion nematodes before sowing mungbeans to avoid risks of poor crop performance.

Introduction

Mungbean crop yields in sub-tropical Australian farming systems are highly variable and the risk of low yields leads to grower perception they are a high-risk crop. The factors causing yield variability are poorly understood. A range of abiotic and biotic yield-reducing factors are likely to be important.

In this study a paddock survey approach was used to assess paddock conditions and yields across three main mungbean growing areas in the northern region. This was combined with simulation modelling to determine the water-limited yield potential and estimate yield gaps of mungbean crops across a diverse range of environments and growing conditions. The objective was to identify factors likely related to poor mungbean crop performance.

Methods

Field survey of mungbean crops

Consultants in Central Queensland (CQ), Darling Downs in southern Queensland (SQLD), northern New South Wales (NNSW; Moree and Liverpool Plains) were contracted to collect mungbean paddock survey data in season 2017-18. Supplementary data was collected from the GRDC farming systems and legume agronomy projects. Data was collected from 12 paddocks in CQ, 17 paddocks in SQLD and 13 paddocks in NNSW in addition to the supplementary data collected in the GRDC farming systems and legume agronomy projects. Paddock data including GPS latitude / longitude, soil type (if known), cropping history for past summer and winter seasons, fertiliser and herbicide applications were recorded, and in-season measurements completed. In-season measurements included starting / finishing soil water and starting soil nutrient analysis in 0-10, 10-30, 30-60 and 60-90cm soil layers, row spacing, cultivar, paddock rainfall, time of flowering, biomass and harvest cuts. In each paddock Predicta®B sampling was also completed. Crop measurements occurred across the 2017/18 season at five monitoring points (in the same location as the soil sampling) including plant counts, flowering date, biomass cuts, maturity date and harvest samples. Weeds, diseases and insects were monitored throughout the season.

Prediction of yield potential and gaps in mungbean crops

Simulation description

The APSIM-mungbean model was used to simulate the water-limited yield potential of mungbean crops corresponding to the 42 farm fields surveyed, along with 29 experimental sites obtained from either Mungbean Agronomy research (2013-2018) or Farming Systems research sites (2015-2018). Simulations for each crop, replicated crop management deployed in each field (e.g. same sowing date, configuration). Climate data was obtained from the nearest climate station available from the SILO database or from climate stations located at the experimental site. Soils used in simulations were sourced from the closest soil with the same classification in the APSoil database. Where possible, simulations were initiated with soil water and nutrient samples taken prior to or at sowing. In many cases, starting soil water was not measured or could not be reliably estimated at sowing because of uncertainties with crop lower limits on the specific soils at each site. In these cases, estimations were made by resetting plant available soil water to zero at the completion of the previous crop and allowing APSIM to model soil moisture accumulation during the fallow period leading up to mungbean sowing. The cultivar Emerald was chosen to most accurately represent Jade⍉ and Crystal⍉ in the APSIM model.

Estimation of yield gaps

In rain-fed crops, yield gaps were calculated as the difference between the water-limited yield potential (Yw) and the achieved grain yield (Ya). The water-limited yield potential is influenced by soil type, soil water status at sowing and climatic conditions over the crops growing season but is not limited by nutrients or biotic stresses. The yield gap was computed as the difference between APSIM simulated yield and the observed yield for each of the 71 mungbean crops. Hence, computed yield gaps are attributable to sub-optimal nutrient supply, biotic factors reducing grain yield or other stress events (e.g. high temperature) which are not captured in the APSIM simulation model. The model was also used to compute three separate stress indices from simulations of each crop to indicate the degree that crops are exposed to high temperature stress events, low soil moisture status and photosynthetic reductions due to moisture stress during flowering and grain filling periods.

Results

Agronomic drivers of mungbean yield - nutrition

There were limited relationships between yield and both key macro and micro-nutrients across the surveyed paddocks. Across the sites, nitrate N in 0-90cm ranged from 10-300 kg/ha with an average of 115 kg N/ha and average grain yield of 1.0 t /ha. Higher yields were associated with higher starting soil N, however, this relationship was highly variable. Vegetative biomass ranged from 0.75 – 7.0 t dry matter (DM)/ha and there was no significant correlation between grain yield / biomass and phosphorus (P), zinc (Zn), sulfur (S), magnesium (Mg) and potassium (K) in the soil. This is not to say these nutrients aren't critical for crop growth and yield, but more that they weren't singularly the key factor driving yield.

Agronomic drivers of mungbean yield – harvest Index

Unsurprisingly, grain yield was highly correlated with biomass (0.84) and harvest index (HI) at 0.68 (Figure 1). High biomass didn't guarantee high yields, with biomass being poorly correlated with harvest index (0.22). Crops with poor harvest index were strongly associated with lower yields and breeding / management factors that improve harvest index should be a future focus.

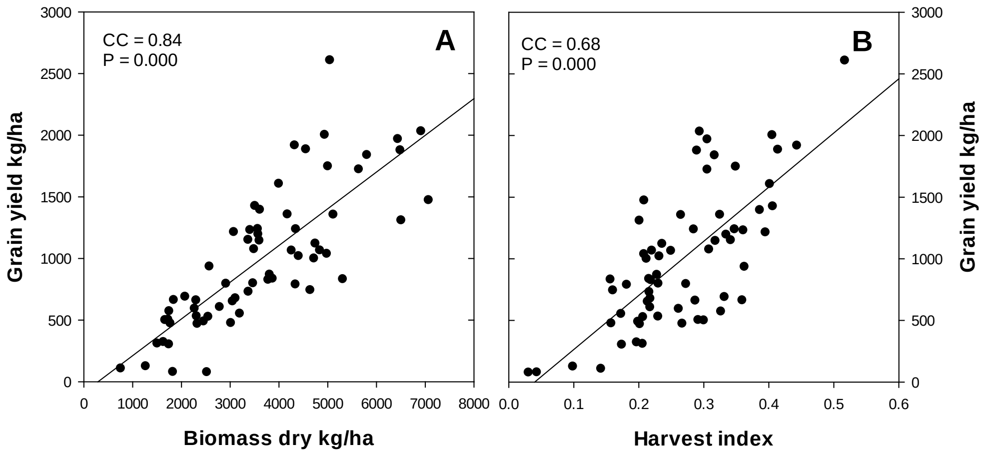

Figure 1. Relationship between grain yield (kg/ha) (A) and biomass kg DM/ha; (B) harvest index across mungbean paddocks in season 2017-18. Spearman correlation coefficient (CC) and significance indicated.

Agronomic drivers of mungbean yield – row spacing and WUE

Management factors that improved yields included narrow row spacing and planting onto fallow. Row spacing < 40 cm yielded 33% higher than crops on row spacing > 50cm, at 1.2 and 0.8 t/ha, respectively (Figure 2).

Crops achieving yields higher than 1.25 t/ha, generally required a minimum of 200 mm of available water (starting soil water + in-season rainfall) (Figure 2). Benchmark water-use efficiency of 7.1 kg/ha/mm (n = 10) was observed in the best survey paddocks, with mungbean WUE across the survey paddocks ranging from 0.2 to 9.4 kg/ha/mm with an average of 4.4 kg/ha/mm. While overall available water was not different between double-crop and fallow, mungbeans planted onto fallow had an extra 27mm water in the soil at planting (starting water after fallow averaged 133 mm and when double cropped, 106mm).

This difference in starting soil water accounts for the observed yield increase of 241 kg/ha for crop preceded by fallow compared to double-cropped. Crops preceded by fallow also had significantly higher biomass than double cropped mungbeans (4.1 and 3.0 t/ha, respectively). Crops that achieved yields over 1 t/ha generally had a minimum of 85mm water in the starting profile. However, available water wasn't the only factor driving yield, as many paddocks with over 200 mm available water also yielded poorly (Figure 2).

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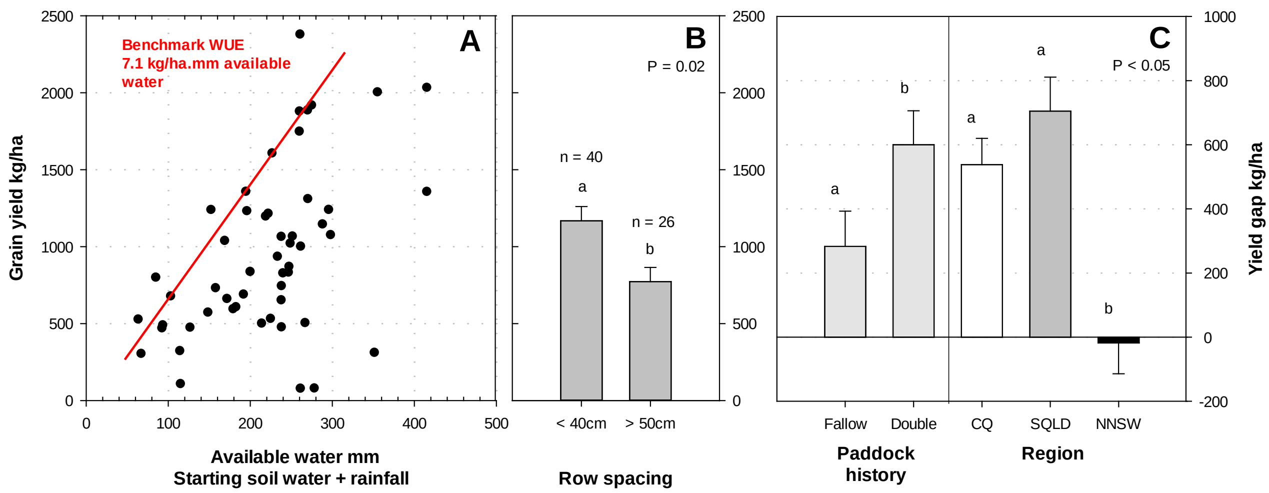

Figure 2. Relationship between grain yield and (A) available water (starting soil water and in-season rainfall mm) and (B) row spacing's across mungbean paddocks in season 2017-18. (C) Relationship between yield gap and paddock history (fallow versus double-crop) / region (CQ, SQLD and NNSW). Univariate ANOVA used to determine significance.

Regional differences in mungbean yields

Comparison of paddocks between regions (CQ, SQLD, and NNSW) found no significant differences between regions for yield, biomass, harvest index and available water (starting soil water + in-season rainfall mm). On average, paddocks across the three areas all had > 100 kg nitrate N kg/ha, > 90 mg/kg Colwell P and > 14 mg/kg Mg. NNSW had higher P, K and Zn levels compared to SQLD and CQ. While nutrient thresholds for mungbeans are currently uncertain, it appears unlikely that most sites did not have nutrient status low enough to limit yields. However, low P levels in both CQ and DD may be contributing to yield limitations based on data in other legumes. In-crop rainfall was not significantly different across the regions, however much of the crop in NNSW suffered significantly from prolonged high temperatures in January 2018. Nematode pressure was significantly higher in SQLD with > 3 nematodes/g soil. The threshold for significant yield loss in intolerant crops including mungbeans is 2 nematodes/g soil. *P. thornei* levels in other regions were well below this level and there were no differences in *P. thornei* levels between fallow and double-crop paddocks

Mungbean yield gaps

The model reasonably predicted the grain yields and harvest index of crops that achieved their potential. However, there were large differences between simulated and observed grain yields for a large number of crops analysed. These differences were used to estimate mungbean yield gaps. Across the whole dataset, simulated mungbean yields ranged from 0.5 – 2.6 t/ha across the spectrum of double-cropped following a winter crop the same year, following a short-fallow after a summer crop the previous year or where partial irrigation was provided. There were no clear differences due to location or data origin in terms of the simulated yield potentials or observed grain yields across this data set.

One third (24 of 71) of the crops analysed had no significant yield gap (< 200 kg/ha) or observed yields exceeded simulated yields (Table 1). Several observed crop yields from the both paddock surveys and mungbean agronomy datasets exceeded the simulated yield potential, but in most cases, this was within the boundaries of variation for those observed crop yields. Some uncertainties with information used to simulate these crops may also explain these differences. Forty-five % of crops had a yield gap > 500 kg/ha. Seven (10%) of the 71 crops were identified that had large yield gaps of greater than 1 t/ha (Table 1). The remaining 16 crops (22%) had yield gaps between 200 and 500 kg (Table 1). Interestingly, crops with yield gaps of different magnitudes and proportions were found across both data from experimental and paddock survey origins. As the crops grown under experimental conditions were managed using optimal weed, insect and disease control, this suggests that yield gaps are unlikely to be explained by these yield reducing factors alone.

Diagnosis of yield limiting factors

In examining possible causes of yield gaps driven by paddock nutrient and pathogen status there were weak correlations between estimated yield gap and Colwell P (R^2 = 0.11), sulfur (R^2 = 0.13), or potassium (R^2 = 0.18). Yield and biomass gap differed across the regions and paddock history with higher yield gaps (500 – 700 kg/ha) in CQ and SQLD compared to NNSW. This suggests there are factors affecting crops reaching their predicted yield potential in those regions which are not well predicted by the mungbean APSIM model. Yield gaps in double-crop mungbeans were significantly higher than in fallow mungbeans (Figure 2). The yield gap observed in double-crop mungbeans strongly suggests there are other factors or combination of factors that are playing a role in crops not reaching their yield potential.

Table 1. Percentage of crops by yield gap (absolute t/ha or proportional %) (n in brackets) for mungbean crops analysed from different sources across the subtropical grain's region of eastern Australia.

Yield Gap (t/ha)	All (*n* = 71)	Experimental (*n* = 29)	Paddock survey (*n* = 42)
< 0.2	34%	27%	38%
0.2-0.5	22%	21%	24%
0.5-1.0	34%	45%	26%
>1.0	10%	7%	12%
< 20%	35%	31%	38%
20-40%	28%	28%	28%
40-60%	21%	28%	17%
>60%	15%	14%	17%

Multiple yield reducing factors

Only 43 or the 71 crops had a full complement of corresponding soil data; these were examined in more detail in an attempt to identify critical yield reducing factors. Of these a group of 26 had relative yields of < 65% of modelled water-limited yield potential (high yield gap group) and 17 were found to have relative yields > 65% of water-limited yield potential (low yield-gap group) (Table 2).

While discrepancies in the frequency of a range of factors between these two groups were examined, only a few factors were found to occur at different levels between the groups. These were also factors found to be more important in statistical analyses, giving us confidence that they are important potential factors to consider further. The population of *P. thornei* was the most prominent single factor discriminating amongst crops in the high and low yield gap groups. Of the high yield gap group, 53% of crops had *P. thornei* levels greater than 3/g soil, while in the low yield gap group this was 23%. This factor alone was not statistically significant (Table 2), but when additional factors were added, significant differences in the populations were evident. Thus, the model that distinguished best between high and low yield gaps was when crops had either high *P. thornei* populations (> 3/g soil).

Additional factor identified as reducing mungbeans crops yield were when more than 1 day of maximum daily temperatures of over 39°C during flowering, or the crops had soil nitrate levels of less than 65 kg N/ha in the top 60 cm at sowing.

A combination of at least one of these stresses occurred in 88% of crops with a high yield gap. This set of diagnostic criteria were found to provide a significantly higher probability of occurring in the crops that had a high yield gap compared to the group with the low yield gap. Hence, a combination of one of these 3 yield reducing factors are suggested to be possible foci for further work to understand their impact on mungbean yield accumulation and in particular low harvest index.

Table 2. Frequency of crops experiencing a combination of one or more stress criteria amongst groups with a high yield gap (i.e. relative yield < 65%) or low yield gap (> 65%). *P* was calculated using a Fischer exact test, n is the number of crops in each group for which a full complement of data was available.

Stress criteria	**High YG (% group)**		**Low YG (% group)**		***p***
P. thornei > 3.0/g soil	14	(53%)	4	(23%)	0.064
+ Max. temp > 39°C during flowering	19	(73%)	7	(41%)	0.057
+ NO_3 (< 65 kg/ha)	23	(88%)	7	(41%)	0.002
n	*26*		*17*		

Conclusions

Overall, the project confirmed industry experience that there is a large proportion of mungbean crops that fail to achieve their water-limited yield potential. Crops with low observed yield and high yield gaps were those with a low harvest index, which was not always associated with low crop biomass. One third of crops achieved < 60% of the water-limited yield potential and nearly half had yield gaps > 500 kg/ha. Low mungbean yields or high yield gaps were not due to a single biotic or abiotic factor. Rather there was a multitude of factors that appear to be associated with high yield gaps (root lesion nematodes, high temperatures at flowering and soil nitrogen status). Being a single season study these findings should be interpreted with this in consideration.

Acknowledgements

The research undertaken as part of this project is made possible by the significant contributions of growers through both trial cooperation and the support of the GRDC, the author would like to thank them for their continued support. We would like to thank the consultants, Leigh Norton, Mike Balzer, Hugh Reardon-Smith, Rob Evans, Josh Bell and Jim Hunt, who collaborated by collecting soil and crop samples on the mungbean fields monitored here. We also thank the many farmers who allowed for this sampling to occur. Finally, we would recognise the contributions of previous research projects (Farming Systems CSA00050 and DAQ00192, and Mungbean Agronomy UQ00067) for provision of their experimental data.

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Exploring interactions of arbuscular mycorrhizal fungi (AMF), rhizobia and root-lesion nematode (Pratylenchus thornei) in mung bean - Could a lack of AMF be a cause of nodulation failure in mung bean?

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Key words

arbuscular mycorrhizal fungi, rhizobia, nodulation, mung bean, *Vigna radiata*, *Pratylenchus thornei,* microbiota interactions

GRDC code

USQ1912-003RSX

Take home message

- Arbuscular mycorrhizal fungi (AMF) and rhizobia act together to increase nodulation, plant biomass and seed yield in mung bean cv. Jade-AU⦶. This synergism led to an increase in uptake of nutrients, including N, P and K in the plant tops resulting from the mycorrhizal symbiosis and increased rhizobial nodulation
- Macronutrients and micronutrients essential to the nodulation process such as calcium, copper, magnesium, boron and manganese increased in the dual-inoculated plants
- Rotations with mycorrhizal associated crops to increase the levels of AMF in the soil followed by soil tests using PREDICTA®B for AMF could be beneficial prior to planting mung bean to ensure adequate nodulation by rhizobia
- Following a long fallow or non-host crop, soils are low in AMF. Build up populations of AMF using low mycorrhizal dependency crops such as wheat and oats before moving to higher mycorrhizal dependency crops like mung bean
- *P. thornei* population densities were higher on mung bean cv Jade-AU⦶ when inoculated with *P. thornei* and AMF, compared to *P. thornei* inoculated plants alone. This increase was only on inoculation with high population densities of 10 *P. thornei*/g soil and was not related to increases in root biomass by AMF inoculation. Further research is required as interactions may differ dependent on host genotype, cultivar and AMF species.

Background

Mung bean is an important summer pulse crop, with an estimated farm gate value of approximately $100 million each year. The advantages of integrating mung bean into cropping systems include its ability to fix nitrogen (N) and the added benefit as a water efficient, short season high value crop. The variety Jade-AU⦶ has a market share of approximately 60% of mung bean produced in the region (Col Douglas *pers comm*). Economic reduction and loss of yield in mung bean in the northern grain region can be attributed to bacterial and fungal pathogens causing diseases such as tan spot, halo blight, powdery mildew and other constraints such as nodulation failure (Murray & Brennan, 2012).

Arbuscular mycorrhizal fungi (AMF), previously known as vesicular arbuscular mycorrhizal fungi (VAM) are beneficial organisms found associated with the roots of 80% of terrestrial land plants including many agriculturally important crop species. They form a symbiotic relationship, exchanging the plants photosynthetic carbon for improved uptake of water and nutrients such as phosphorus (P) and zinc (Zn) from the soil (Parniske, 2008). They may also play a role as bio-protectants against fungal, bacterial, and nematode pathogens (Yang et al., 2014). There are many species of AMF fungi, which for diagnostic purposes are categorised into seven molecularly distinguished groups. Group A, which includes the species *Funneliformis mosseae* and group B, which includes the species *Claroideoglomus etunicatum* are commonly found in the northern grain region. Spore levels in the soil are higher following mycorrhizal crops than fallow or non-mycorrhizal crops like canola. Some crops have a higher mycorrhizal dependency for growth such as sorghum, maize, sunflower, faba bean, linseed, chickpea and mung bean than others such as barley and millet. Crops grown in soils with low levels of available phosphate are dependent on AMF for nutrient acquisition (Smith & Read, 2010) and for highly dependent crops extremely high rates of P fertiliser are required to offset lack of AMF.

Rhizobia are bacteria that form a symbiosis with legumes to fix N gas from the air into ammonium. The role of rhizobia in N fixation is well known and inoculation of legumes with rhizobia is currently practised in agriculture worldwide. Mung bean has the capacity to meet the N requirements for growth and yield through biological N_2 fixation (Gentry, 2010). However, previous surveys undertaken in the northern grain region indicate that the majority of mung bean crops are poorly nodulated and fix only 30% of their requirements for N (Herridge et al., 2005). Nodulation failure is a constraint to mung bean crop production that can lead to yield reductions of up to 50% (Gentry, 2010).

Nodulation failure can be ascribed to various reasons, such as incorrect inoculum application, unsuitable soil pH, high levels of soil nitrate, and deficiencies of nutrients such as phosphorus and molybdenum (Drew et al., 2012). Limitations of certain nutrients including phosphorus, calcium, boron and magnesium can affect the development and functionality of nodules and therefore productivity of the leguminous crop (O'Hara, 2001). Synergism between rhizobia and AMF can increase mineral nutrition and plant growth, nodulation levels and N fixation in other legumes (Javaid, 2017). Our hypothesis is that one cause of nodulation failure of mung bean in the northern grain region could be a lack of AMF propagules in the soil.

Also found in the soils of the northern grain region are root-lesion nematodes, *Pratylenchus* spp., which feed in and migrate through root tissue, negatively affecting root function and can lead to yield loss in intolerant host crops (Owen et al., 2019). *Pratylenchus thornei* followed by *P. neglectus* are the most important species of *Pratylenchus* found in the northern region (Thompson et al., 2008). Murray and Brennan (2009) estimated that *P. thornei* can cause AUD $104 million in potential losses annually to wheat in the sub-tropical grain region. Mung bean is a susceptible host to *P. thornei* and any increase in nematode populations can have detrimental effects on yields of subsequent intolerant crops.

Both *Pratylenchus* spp. and AMF occupy a similar ecological niche in the root cortex of the host plant. The coexistence of AMF and plant-parasitic nematodes in roots and soil has prompted a number of investigations into their interactive effects on plants. These investigations document the generally suppressive effect that AMF have on migratory nematodes (Yang et al., 2014), although some studies showed no effect or even an increase in nematode numbers after dual-inoculation with AMF (Pinochet et al., 1996; Hol & Cook, 2005). These conflicting results may be due to differences in environmental and nutritional factors, AMF species, nematode species and/or crop hosts (Gough et al., 2020).

Nematodes can also affect nodulation levels which may result in a decrease in functionality in chickpea (Castillo et al., 2008). Most research on the interaction between rhizobia, nematodes and AMF has been with root-knot nematodes *Meloidogyne* spp. and there is little information on how *Pratylenchus* spp. affect the levels or efficiency of nodulation. Hussey and Barker (1976) found *Pratylenchus penetrans* stimulated nodule formation on soybean but inhibited N fixing capacity. Synergism between AMF and rhizobia has been demonstrated in other leguminous crops such as chickpea, soybean and French bean as reviewed by Chalk et al., (2006).

The interaction between host, parasitic nematode, and beneficial symbionts is likely to be quite specific. So far, there has been no research into these interactions for mung bean in the vertosols of the northern grain region.

Methods

A glasshouse experiment with mung bean and factorial treatments of AMF, rhizobia and *P. thornei* in a randomised split plot design was conducted in 2018. The *P. thornei* susceptible mung bean cv. Jade-AU⦶ was sown in pots containing steam pasteurized Vertosol from the Darling Downs with no additional fertiliser. The experimental soil properties were as follows; pH 8.5 (1:5 water), nitrate- N 24.5 mg/kg, Colwell phosphorus 45 mg/kg, zinc 1.45 mg/kg (DTPA).

The soil temperature was maintained at ~22°C and the air temperature was maintained at ~25°C. Pots were watered with a capillary bottom watering matting system under 8 cm water tension. Inoculations at planting included three rates of *P. thornei* (0, 1 or 10 nematodes/g soil (oven dried (O.D) equivalent) and two rates of an isolate of AMF species *Funneliformis mosseae,* from the northern grains region (0 or 16 spores/g soil O.D equivalent). The *Bradyrhizobium* used was the commercially available CB1015 strain. Plants were assessed at 6 and 12 weeks after planting. Dry biomass, seed pod count, seed weight, nodule counts and root biomass from a 150 g subsample of homogenised soil and roots, *P. thornei* population, AMF % colonisation, and leaf chemical concentrations and uptakes were recorded. Data were analysed using ANOVA followed by Fishers protected l.s.d on significant values using Genstat. Data for nodulation was square root transformed and *P. thornei* numbers were log transformed prior to statistical analysis. The experiment was repeated in part of a larger factorial experiment looking into interactions of AMF, *P. thornei*, rhizobia and nutrients in 2019 using 10 *P. thornei*/g O.D soil equivalent soil and 16 spores *F. mosseae*/g soil O.D soil equivalent.

Results

AMF and rhizobia interactions increased nodulation, biomass, seed yield and nutrient uptake in mung bean cv. Jade-AU⦶

Inoculation with both AMF and rhizobia resulted in a synergistic effect (Figure 1) which significantly (P<0.001) increased nodule numbers, dry biomass, seed weight, plant uptake of nitrogen, phosphorus, potassium and zinc in mung bean cv. Jade-AU⦶ (Figure 2, Figure 3 a-b, Figure 4). The uptake of other macronutrients and micronutrients associated with rhizobia nodulation increased in the dual inoculation; macronutrients: calcium (P<0.001), magnesium (P<0.01): micronutrients: boron (P<0.001), copper (P<0.001) and manganese (P<0.01).

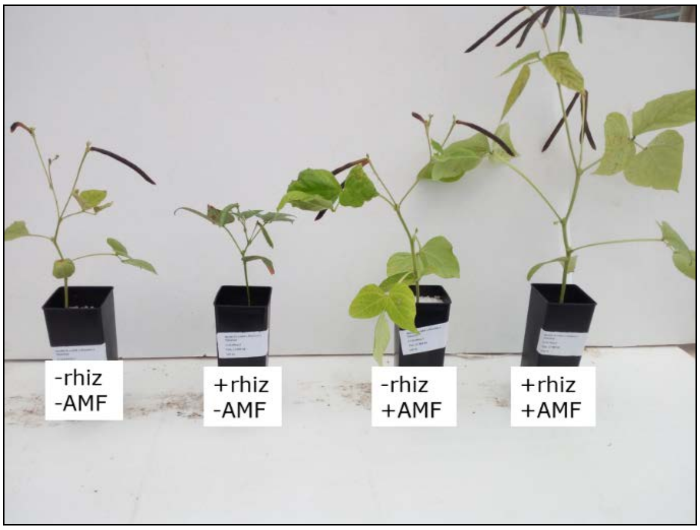

Figure 1. The addition of AMF and rhizobia to mung bean cv. Jade-AU⦶ increased plant biomass and seed yield four-fold 12 weeks after inoculation in Experiment 1.

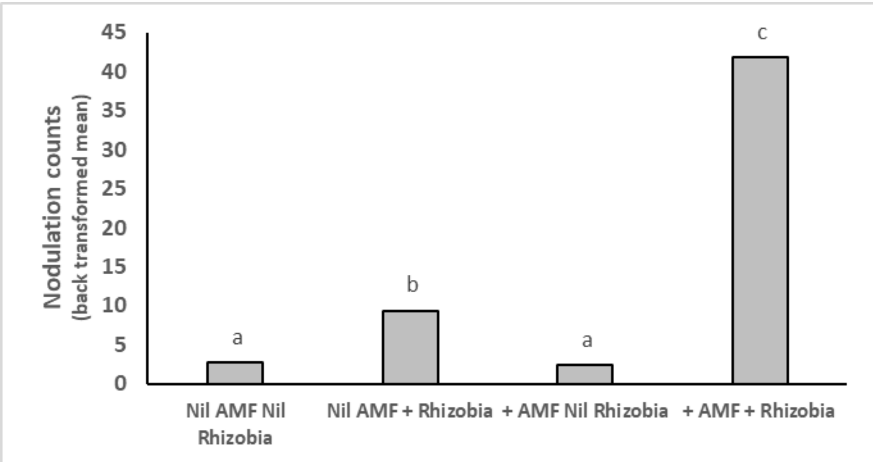

Figure 2. AMF and rhizobia increase nodulation 4.5-fold compared to rhizobia alone in mung bean cv. Jade-AU⦶. Different letters indicate significant differences at *P*=0.05.

A

B

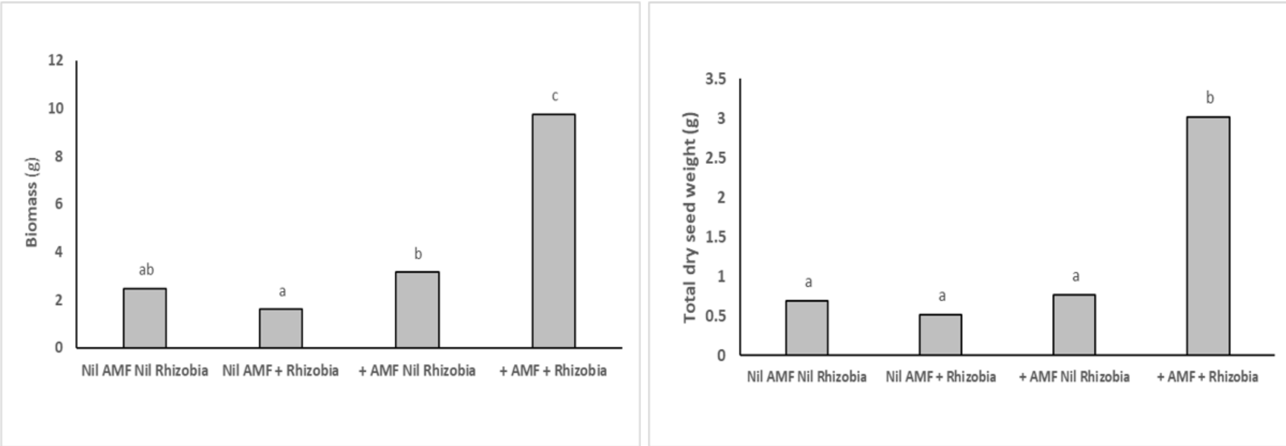

Figure 3. Synergistic effects of inoculation with both AMF and rhizobia at 12 weeks in Experiment 1 resulted in 4-fold increase in biomass (A-left) and seed weight (B-right) in mung bean cv. Jade-AU⦶. Different letters indicate significant differences at *P*=0.05

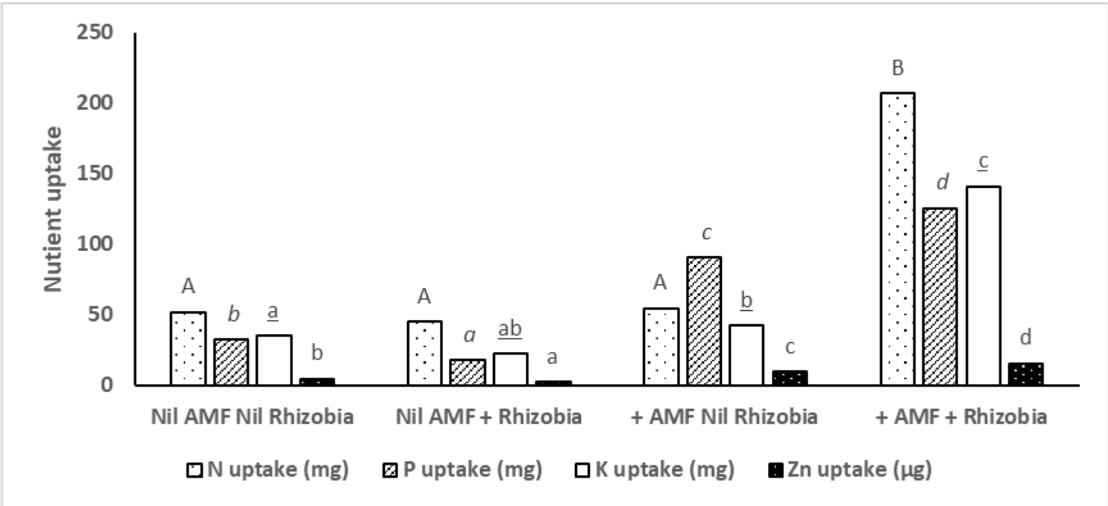

Figure 4. Synergistic effects of inoculation with both AMF and rhizobia at 12 weeks in Experiment 1, resulted in increased N uptake (mg/plant); P uptake (mg/plant); K uptake (mg/plant) and Zn uptake (µg/plant) in mung bean cv. Jade-AU⦶ Different letters indicate significant differences at *P*=0.05 and the different fonts indicate these significant differences for each nutrient analysed.

AMF and P. thornei interactions in mung bean cv. Jade-AU⦶

Plants inoculated with AMF increased the reproduction rate of *P. thornei* in the plant at high initial inoculum rates of 10 *P. thornei*/g O.D soil equivalent (*P*< 0.05) (Figure 4), but not at lower rates of 1 *P. thornei*/g O.D soil equivalent. This increase in reproduction was not as a result of increased plant above-ground biomass or root biomass (Figure 5).

Inoculation with *P. thornei* did not affect nodulation rates of rhizobia*,* mung bean biomass or seed yield of mung bean cv. Jade-AU⦶.

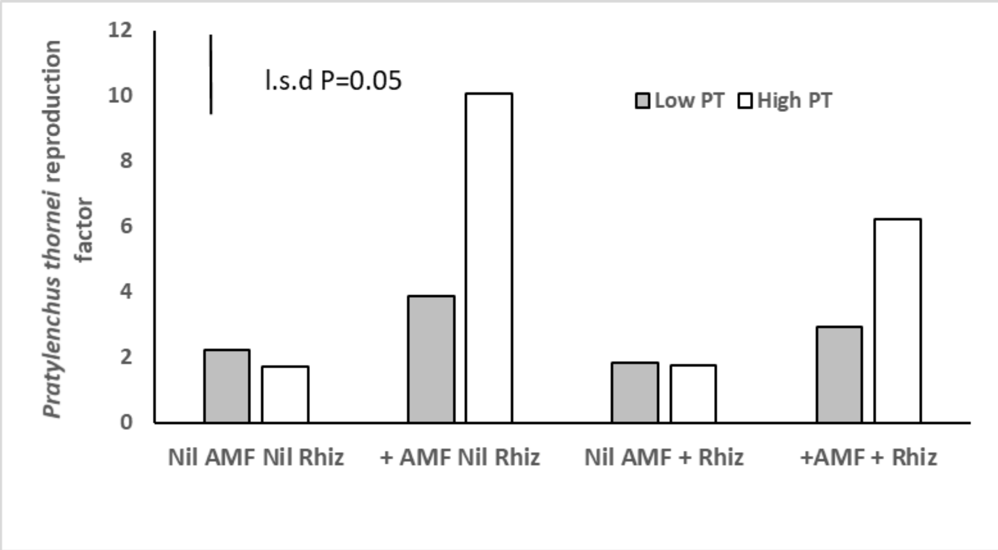

Figure 5. AMF increased reproduction of *Pratylenchus thornei* (PT) at higher rates of 10 *P. thornei*/g soil in mung bean cv. Jade-AU⦶ plants after 12 weeks growth in Experiment 1.

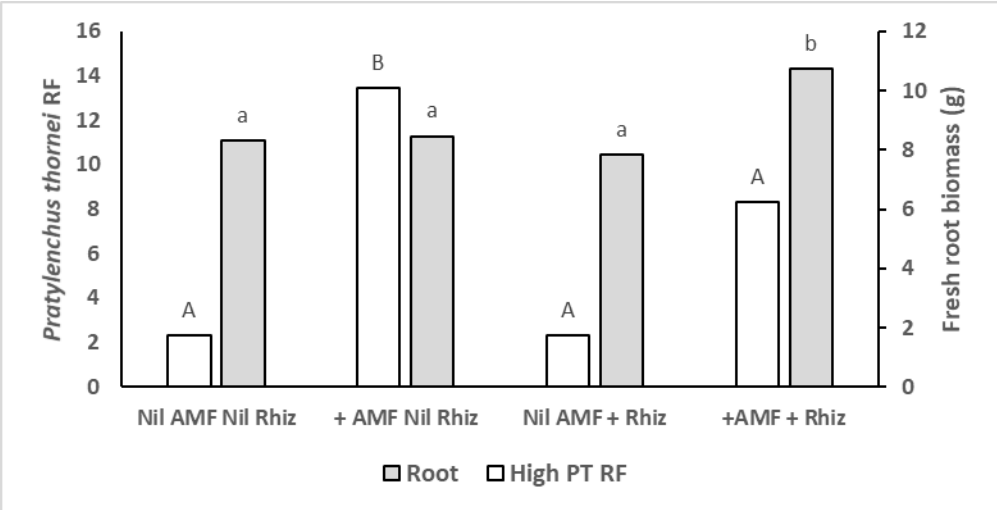

Figure 6. The higher reproduction factor (RF) of *P. thornei* was not caused by an increase in plant root biomass in mung bean cv. Jade-AU⦶. Different letters indicate significant differences at *P*=0.05. Uppercase letters represent differences in *P. thornei* RF and lowercase letters represent differences in root biomass.

Conclusions

Inoculating mung bean cv. Jade-AU⦶ with both AMF and rhizobia led to a greater increase in the number of nodules, biomass and seed yield and compared to rhizobia alone. This dual inoculation increased the uptake of nutrients N, P and K in the plant. It also increased the uptake of other nutrients essential to the metabolism of rhizobia and the establishment of an effective symbiosis such as Ca, Mg, Mn, Cu and B.

Establishing adequate levels of AMF in the soil, a soil analysis of AMF by PREDICTA®B prior to planting mung bean, and inoculation with the correct isolate of rhizobia, may lead to increased nodulation thereby increasing yield productivity of mung bean.

Management practices to establish adequate AMF levels can be achieved through rotations with crops that associate with mycorrhizae. As AMF require a living host to survive, soils after a long fallow or cultivation of a non-host crop such as canola, can reduce AMF propagules in the soil. Growing crops that have a lower mycorrhizal dependency such as wheat and oats, after a long fallow may increase the AMF propagules in the soil for a subsequent crop that has a higher mycorrhizal dependency (Thompson et al., 1997). Growing mung bean after mycorrhizal crops that are also poor hosts of *P. thornei* (Thompson 1994) would also be a good strategy.

Jade-AUⓟ plants inoculated with both AMF and *P. thornei* had an increase in the reproduction rate of *P. thornei* as compared to plants inoculated with *P. thornei* alone at high initial populations of 10 *P. thornei*/g soil. This was not related to increases in root or above-ground biomass.

However, variability in *Pratylenchus* population densities in the presence of AMF may be genotype dependent and may also be influenced by the species of AMF. AMF can increase the tolerance of plants to infestation by plant-parasitic nematodes (Schouteden et al, 2015). The increase in nutrient uptake from improved AMF colonisation, resulting in a more vigorous plant, may be a strategy to counteract the reduction in root quality and root efficiency conferring a compensatory effect against the damage done by the nematode. More research is needed on the interactions of AMF, rhizobia and *Pratylenchus* spp. in other mung bean genotypes and other host crops.

Rotations of crops to increase AMF spore densities and reduce *P. thornei* population densities are desirable in cropping systems in the northern grain region.

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Make better fungicide application decisions for mungbean powdery mildew with the new PowderyMildewMBM app

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Key words

mungbean, fungicide, powdery mildew, Decision Support System, DSS, PowderyMildewMBM

GRDC code

DAW00228

Take home message

- PowderyMildewMBM, the mungbean powdery mildew management app enables growers and advisers to explore the economics of the using fungicides to control the disease in different situations
- Good decisions are critical when making fungicide application decisions to prevent the development of fungicide resistance in the powdery mildew population; if it doesn't pay, don't spray
- Download PowderyMildewMBM for your tablet device from the Apple App Store or Google Play.

Powdery mildew of mungbean in Australia is one disease that is caused by two species of fungi, *Podosphaera xanthii*, and a second powdery mildew species, *Pseudoidium sp.*, that has not yet been fully characterised. The disease can occur at any growth stage and develops rapidly under favourable weather conditions. Mungbeans planted late in the summer growing season tend to be more exposed to the disease as the weather conditions become more favourable for the disease. Milder temperatures and higher relative humidity are conducive conditions for the fungus to infect and reproduce. Lower leaves generally show the first signs of infection as small, white, powdery patches. Later stage infections can lead to every leaf being covered in white, powdery growth with stems and pods also being infected. Yield losses in Australia have been shown to reach 40% in varieties that are highly susceptible to the disease, e.g. Berken. Losses in currently planted varieties are not as great. The moderately susceptible variety 'Jade-AU⦶', offers the best resistance to the disease. Because of the lack of resistance in currently available cultivars, fungicide treatments remain the best option for controlling this disease when it occurs.

Current control recommendations for mungbean powdery mildew are to spray at the first sign of disease with a second application two weeks later, if necessary. Although the recommendations are straightforward, many other factors enter into a decision to spray or not to spray.

Powdery mildew fungi are known to develop resistance to synthetic fungicides. In Australia, fungicide resistance in wheat and barley powdery mildew have already been identified by the Centre for Crop and Disease Management (CCDM), based at Curtin University. Overreliance on fungicides can lead to the development of fungicide resistance in powdery mildew fungi populations. Currently, only one fungicide, Custodia® (tebuconazole 200 g/L + azoxystrobin 120 g/L) has a permit allowing use on powdery mildew in mungbeans, PERMIT NUMBER – PER82104. we encourage growers and advisors to consult with the PowderyMildewMBM app to see if a spray is economically viable. If a spray is not indicated to be economically viable because the disease is not yet present or weather conditions do not favour disease development, please do not spray. Unnecessary use of fungicides is both expensive and leads to the development of fungicide resistance and as a result, should be avoided. Good stewardship of fungicide use gives the breeding program more time to develop varietal resistance and extends the usefulness of the fungicides for continued use by the mungbean industry.

PowderyMildewMBM aims to assist fungicide application decisions, when to spray or not to spray, by presenting useful information about different situations that can influence the potential financial return of fungicide applications. Users can run several different scenarios to see what the expected payback is for different combinations of fungicide applications. It allows you to compare the profitability of zero, one, and two spray management strategies, while accounting for forecasted weather, production costs, and mungbean market values.

Mungbean powdery mildew management app – PowderyMildewMBM

PowderyMildewMBM joins a family of apps; SclerotiniaCM, for controlling canola sclerotinia stem rot; and BlacklegCM, for controlling canola blackleg. PowderyMildewMBM is the first app for a summer crop grown in the GRDC northern grains region.

PowderyMildewMBM takes account of costs, yield benefits, and grain price to give you the best case, worst case, and most likely estimates of financial return. The app allows the user to tailor each simulation for a given paddock to give custom recommendations for each paddock. Users can run as many simulations as they like to help determine their best course of action.

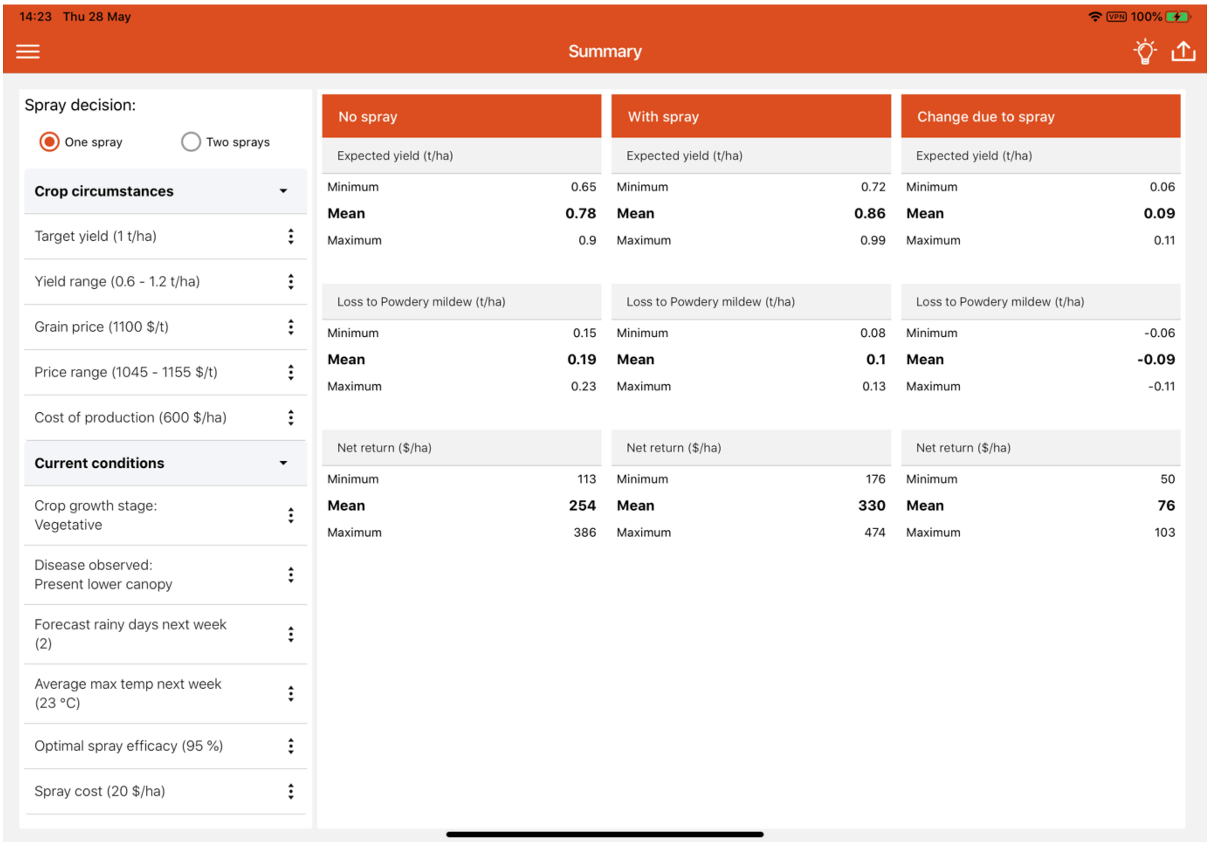

Figure 1. PowderyMildewMBM launches with a standard set of values that the user can modify to best represent their paddock's circumstances.

When the user first launches the app, it starts in the summary view (above). In this view to the far left are the parameters that can be adjusted for; 'Crop circumstances' and 'Current conditions'. To the right are three columns that display information regarding what the effects are of 'No spray', 'With spray' and the 'Change due to spray' for the currently set values.

To change values of the 'Crop circumstances' or the 'Current conditions', select the item to change, and the pop-up displays a dialogue to select the desired values. The target yield can be set from 0.5 to 4 tonnes/ha and yield range can be adjusted for wider or smaller intervals depending on experience and the current season.

In the 'Current conditions' section, the app offers several options to tailor the information to reflect the crop circumstances including the already incurred costs and estimated farm-gate price, as well as adjusting the volatility of the yield and price.

The current conditions are easily tailored for the crop growth stage, forecasted weather, and fungicide efficacy and costs.

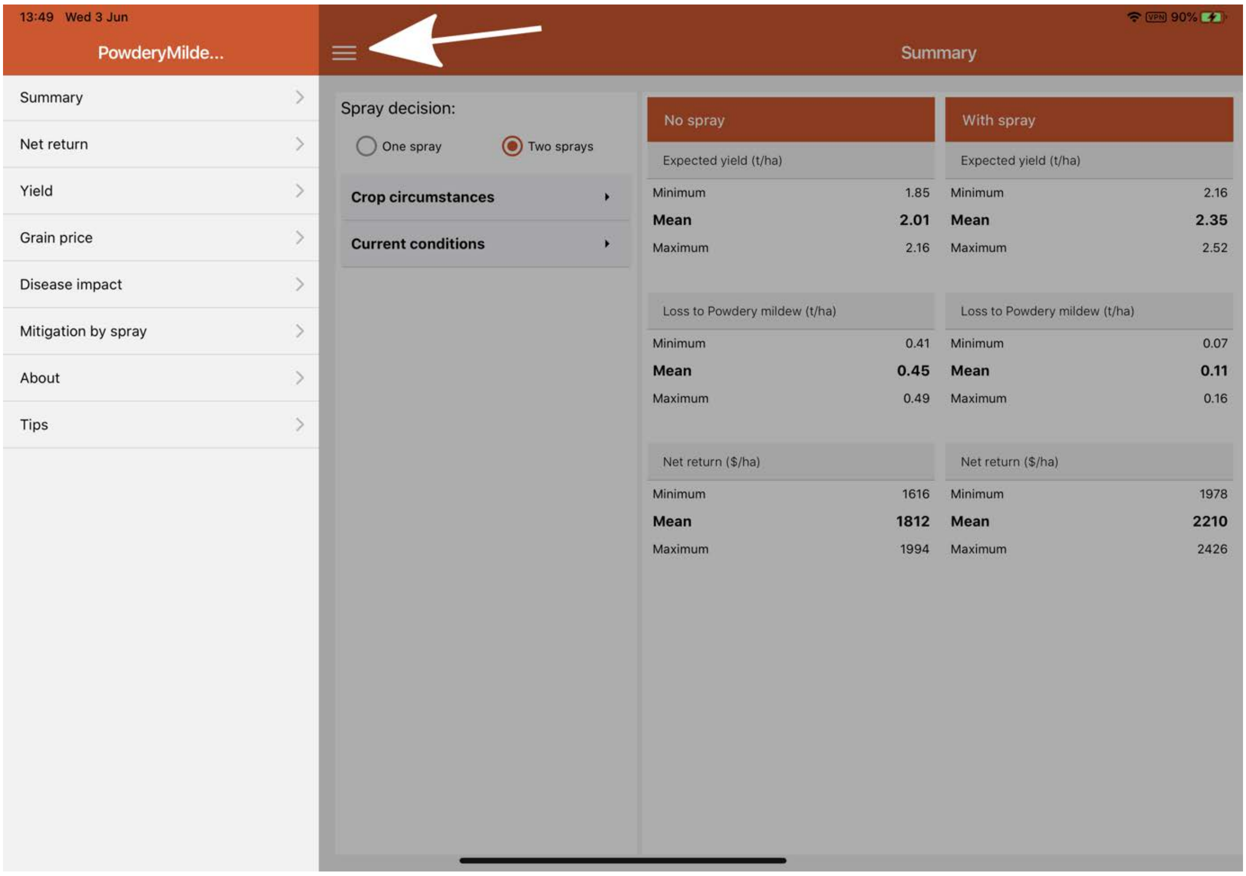

Figure 2. Clicking on the 'hamburger menu icon', indicated by the white arrow, in the upper left reveals a hidden menu to display the information in different formats.

Clicking on the hamburger menu icon to the upper left reveals a menu of options to view different interfaces. This allows users to explore the results in different sets of graphs and tables, like 'Net return', (above), 'Yield', 'Grain price', 'Disease impact' and 'Mitigation by spray' which allows users to easily find the information that they are looking for in an easily interpretable interface.

Two possible use cases

To illustrate how PowderyMildewMBM might be used to provide information to a user, two case studies are provided below. The first is where two fungicide applications will be economically viable and beneficial to save mungbean yield. The second illustrates a situation where a fungicide spray is not economically viable and should not be made.

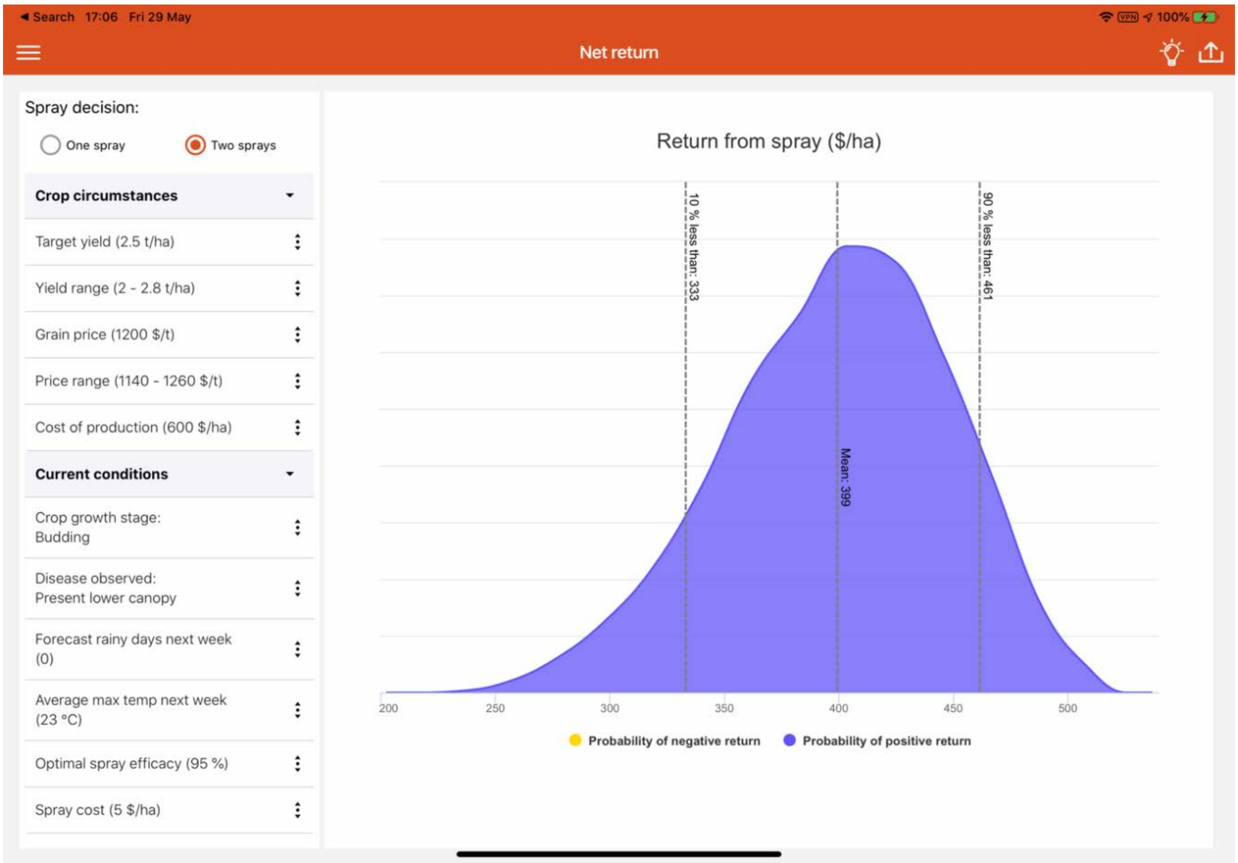

Figure 3. A possible use case showing the Net return view, showing the target (entered by the user) and expected (calculated by the app) net return resulting from zero or two fungicide applications.

Case study number 1

An app user has a paddock that will potentially yield 2.5 tonnes per hectare at a price of $1,200 per tonne. Currently, the crop is still in the vegetative stage, meaning that there is still some time left in the season for the disease to develop and the disease has been found in the lower canopy on some leaves. The app predicts that with no sprays, the mean yield would be reduced to 2.01 tonnes per hectare and with two sprays the mean net return from spraying would be $399 per hectare with no probability of a negative net return from the spray.

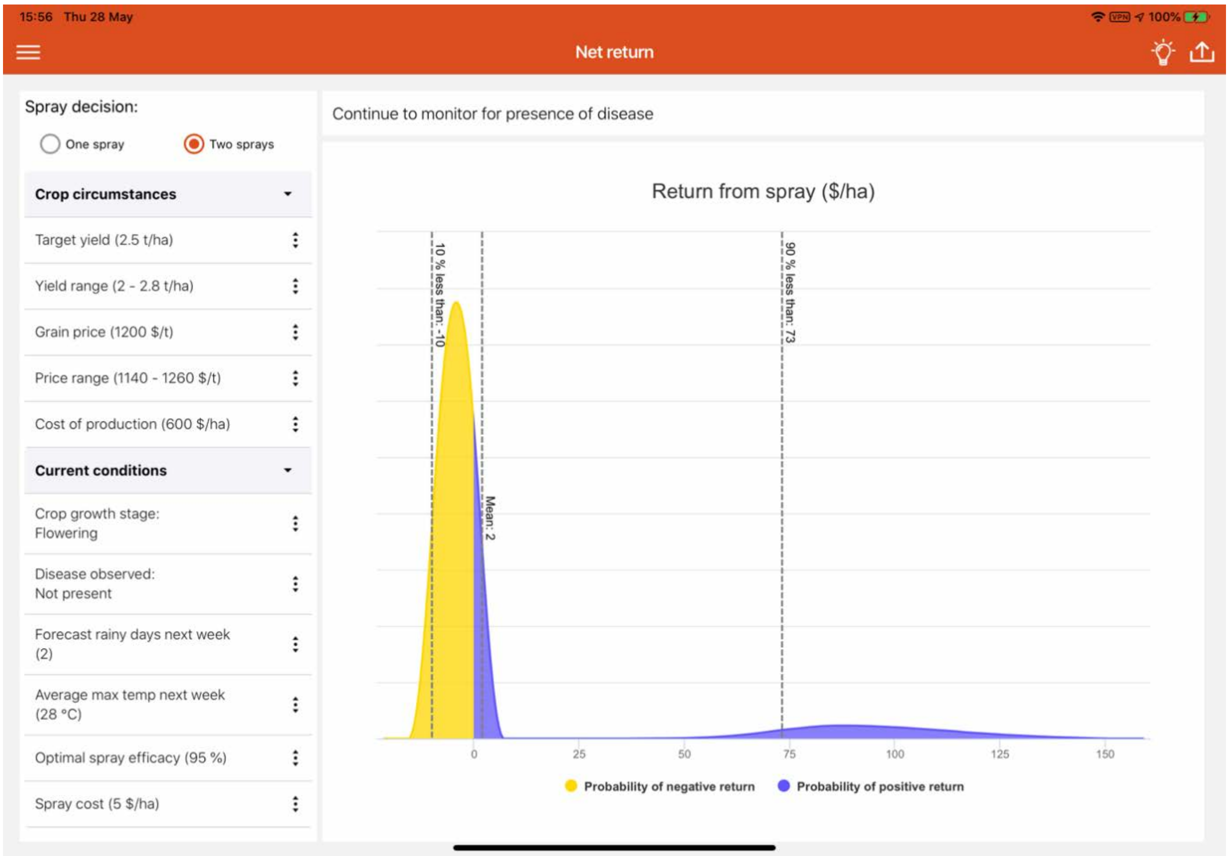

Figure 4. A possible use case showing the probability of an economic return of a fungicide treatment when no disease has yet been observed in the crop canopy of the paddock in question.

Case study number 2

An app user is having a good year, they are again expecting 2.5 tonnes per hectare, the crop is flowering and it is still fairly early in the season so the average temperatures for the next week are 28˚C and there has been no disease yet noted in the canopy. However, there is going to be an insecticide application, so the user is considering including a fungicide just for good measure.

Plugging these values into the app suggests that there is a far greater probability that even the costs of just the product (this time $5 per hectare) will not be recovered. The probability of a negative return is quickly seen in yellow versus the probability of a positive return in purple. A further risk is that of adding to the probability that fungicide resistance will develop in the fungal populations due to the overuse of fungicides through unnecessary applications and should be avoided. In this situation, no fungicide should be applied. The crop can then be re-examined later and if disease is observed, the app can be updated, and fungicide can be applied at that time if warranted.

Currently, the use of Custodia® for control of powdery mildew in mungbeans is covered by an APVMA permit (PER82104) that is valid until November 2022. Trials conducted by USQ in conjunction with DAF Queensland have previously shown this fungicide to be effective in controlling the disease under yield-limiting conditions.

The app has already seen use that is on par with the existing apps. After the initial launch in November 2019, which saw the biggest monthly spike in downloads of the app, there was a second spike in March 2020, which would coincide with the anticipated onset of the disease and continued use into the month of May. The app will assist advisers and growers determine whether or not the conditions warrant a fungicide application. PowderyMildewMBM is the result of over five years work with trials located at multiple locations. Research was conducted by the University of Southern

Queensland (USQ) and DAF Queensland (DAFQ) across northern New South Wales and Queensland. As with the existing family of management apps, PowderyMildewMBM will continue to be developed and improved with further research. Currently, research is being conducted by USQ and Queensland DAF on possible differences from the differing powdery mildew pathogens and the influence of differing mungbean cultivars. This information will be used to enhance the app's accuracy and value to end-users.

It is hoped that this app will be used to help make informed fungicide application decisions for mungbean powdery mildew that will help slow the development of fungicide resistance in the pathogen populations by reducing the number of unnecessary fungicide applications. Remember, if it doesn't pay, don't spray.

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Three new herbicide-tolerant soybean varieties will aid nutgrass control

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Key words

soybean, halosulfuron-methyl, herbicide, nutgrass

GRDC code

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Take home messages

- The only soybean varieties with tolerance to halosulfuron-methyl (i.e. Sempra®) are New Bunya HB1, Mossman HB1 and Kuranda HB1
- APVMA Permit number PER88483 for Sempra® (or other registered products containing 750g/kg halosulfuron-methyl as the only active constituent) is for the control of nutgrass (*Cyperus rotundus*) in soybean, effective from 31 March 2020 to 31 March 2023. *Note the restraints, critical use comments and withholding periods on the permit*
- Temporary maximum residue limits (tMRLs) have been established to allow treated produce to be used domestically for human and animal consumption. Growers are advised to discuss use of halosulfuron-methyl with marketers of final produce to ensure that the residue limits of importing countries are not exceeded
- Control established weeds with knockdown herbicides/ land preparation prior to planting the crop
- Ensure correct crop stage. For optimal results, apply 65–130 g/ha of a 750g/kg formulation early post-emergence to the crop (up to 1st trifoliate leaf stage), when the majority of the nutgrass is at the 3–4 leaf stage
- Coverage is important. Apply in a minimum 80 L water/ ha utilising a COARSE spray quality
- Always follow adjuvant recommendations on the label of the halosulfuron-methyl product being used. For example, Sempra® recommends application with either Supercharge® Elite (Paraffin oil 471g/L) or Banjo® (Methyl esters of canola oil 725g/L) at 1L/100 L. Some halosulfuron-methyl formulations recommend a non-ionic surfactant/wetter.
- Only ONE (1) application is permitted per season
- Read and understand the conditions of the PERMIT and the herbicide label prior to use
- It is advisable to only use ONE (1) application of a Group B herbicide per season.

The Australian Soybean Breeding Program has recently released three new soybean varieties: New Bunya HB1, Kuranda HB1 and Mossman HB1. All three varieties possess the ALS 1 gene conferring tolerance to halosulfuron-methyl, the active ingredient in Sempra®, a sulfonylurea herbicide commonly used to control nutgrass.

Sulfonylurea (SU) herbicides inhibit the acetolactate synthase (ALS) enzyme in plants. The ALS enzyme, which is responsible for manufacture of certain branch-chain amino acids, subsequent protein manufacture and plant growth, is blocked at the growing point, resulting in plant death.

Sulfonylurea herbicides are taken up by the roots, shoots and foliage. Herbicides in this group differ in whether their activity is predominantly through root and shoot uptake, or foliar uptake, or both.

Halosulfuron-methyl is a Group B herbicide that is absorbed through roots, shoots and foliage with the active ingredient being translocated through the plant to the nutgrass 'nut' (tuber) below the soil surface. Nutgrass exhibits a complicated interconnected network of tubers through underground rhizomes (stems) howeverhalosulfuron-methyl does not translocate through these rhizomes to attached tubers, so subsequent emergence from adjacent tubers may require alternative control measures.

Under APVMA permit PER88483 (which expires 31 March 2023) halosulfuron-methyl may be applied as a foliar spray to soybean early postemergence (up to the 1st trifoliate leaf stage of the crop) to target nutgrass at the 3–4 leaf stage.

Symptoms of successful weed control are a gradual yellowing of foliage and seed heads followed by desiccation. Initial symptoms may take 7 to 10 days to be noticeable, with full effects occurring 4 to 6 weeks after treatment.

Characteristics of the varieties

New Bunya HB1Ⓟ

Regional adaptation – New Bunya HB1Ⓟ is expected to have similar adaption as its parent variety BunyaⓅ. It is well-adapted to irrigated cropping across inland southern Qld and to northern NSW with planting window from late November though to mid-January. New Bunya HB1Ⓟ may also be grown as a winter season crop in the Burdekin Irrigation Area with a planting window from May through to the end of June.

Market suitability – New Bunya HB1Ⓟ, is suitable for crushing, full fat, and a wide range of human consumption markets. It is anticipated that it will be strongly sought after by tofu makers.

Breeding – New Bunya HB1Ⓟ, is largely derived from its parent variety BunyaⓅ but with tolerance to halosulfuron-methyl herbicides, resistance to powdery mildew and resistance to seed coat splitting transferred in to via by backcrossing.

Kuranda HB1Ⓟ

Regional adaptation – Kuranda HB1Ⓟ appears to be well adapted to cropping in coastal environments in Qld from around Nambour to the wet tropics and may also be grown as a winter season crop in the Burdekin Irrigation Area with a planting window from May through to the end of June.

In the southern end of the cropping range Kuranda HB1Ⓟ is best adapted to planting dates from late December though to early February as at earlier planting dates it may become excessively vegetatively vigorous.

Market suitability – Kuranda HB1Ⓟ, is suitable for crushing, full fat, and a wide range of human consumption markets.

Breeding – Kuranda HB1Ⓟ, is largely derived from its parent variety M103-22 which was a selection from MoonbiⓅ x Fraser with some parentage from a breeding line selected from StuartⓅ, x sib of CowrieⓅ. Kuranda HB1Ⓟ combines broad adaptation and high yield potential with tolerance to halosulfuron-methyl and high resistance to many diseases such as soybean rust, purple seed stain and powdery mildew.

Mossman HB1

Regional adaptation – Mossman HB1 is a grain option in the Burdekin and Atherton Tablelands or green manure option in many cropping environments due to its long duration and high biomass production.

Market suitability – It is anticipated that grain of Mossman HB1 will be accepted into most crushing, stockfeed and human consumption markets.

Breeding – Mossman HB1 is closely related to its parent variety Leichhardt but with the additional inclusion of a light hilum and herbicide tolerance derived by backcrossing.

Tolerance of HB1 soybean varieties to Halosulfuron-methyl

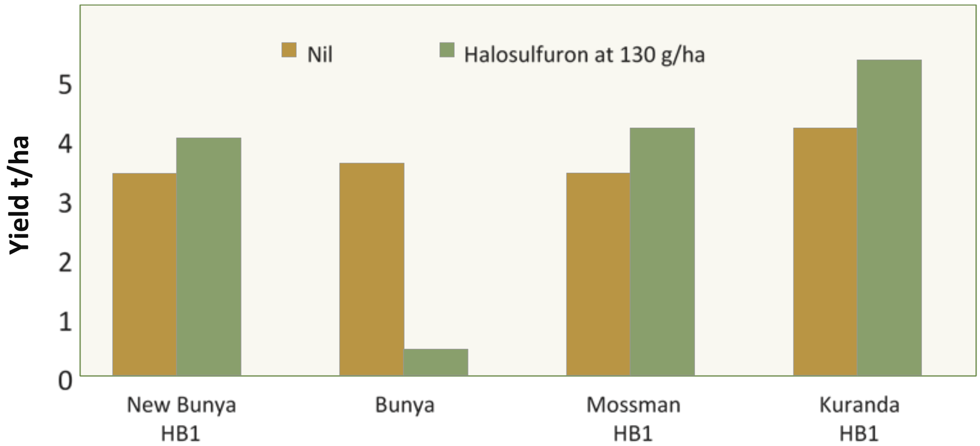

Figure 1. Yield of soybean varieties grown at Gatton in 2018 with and without a treatment of halosulfuron-methyl at 130 grams per hectare. Within a cultivar, all treatment effects were statistically significant ($P < 0.05$).

When conventional herbicides are used and direct comparisons are possible, the HB1 varieties yield similarly or higher than their recurrent parents. In instances where a treatment of halosulfuron-methyl at 130 grams per hectare was used in weed-free field trials, yields of HB1 varieties were observed to be higher in the treated plots than in plots treated with nil herbicide application (Figure 1). The cause of this apparent yield-gain requires further investigation although similar effects are reported in the USA and Brazil.

What weeds does halosulfuron-methyl control?

In Australia, there is limited data available on the efficacy of halosulfuron-methyl on weeds other than nutgrass, Navua sedge and Mullumbimby couch. It is, therefore, recommended to discuss with your agronomist complementing halosulfuron-methyl targeting nutgrass with other herbicides registered for soybean production.

Successful application

Attention to detail with application set-up is crucial to ensure desirable coverage and uptake of halosulfuron-methyl applied as a selective, post-emergence foliar spray.

For successful results it is important to ensure the following:

- Spray rig is accurately calibrated
- Apply halosulfuron-methyl in a minimum of 80L water/ha utilising a COARSE spray quality

- Add an adjuvant as per the herbicide label
- Do not spray when crop and/or weeds are stressed due to low relative humidity, temperature extremes, waterlogging, or when severe root or foliar diseases are present
- Do not spray if storms or heavy rain is anticipated within at least 48 hrs
- Crop nutrition is managed to avoid nutritional deficiencies and plant stress

Plant back periods

Pesticide residues need to be taken into consideration in determining plant back intervals to subsequent crops and resulting future cropping opportunities.

In the circumstance of a failed HB1 soybean crop where halosulfuron-methyl has already been applied to the failed crop, another HB1 soy variety (tolerant of halosulfuron-methyl) can be re-planted, however, halosulfuron-methyl must not be re-applied to the re-planted crop. If subsequent weeds germinate, manage with conventional herbicide options registered for use in soybean production, excluding other Group B herbicides (e.g. imazethapyr, imazamox, flumetsulam).

Break down in soil

Sulfonylurea herbicides are extremely active at low use rates in the soil and can be very damaging to many broadleaf rotational crops. It is essential that plant back recommendations are followed.

The primary factor for degradation of all SU herbicides in low pH to neutral pH soils is a hydrolysis chemical reaction. In alkaline soils at higher pH levels, this reaction slows or stops and breakdown reverts to a far slower microbially driven breakdown process. Soil pH is the key factor driving breakdown while maintaining soil moisture over the warmer spring/summer months is the most important factor assisting microbial degradation.

Factors important for breakdown include:

- soil moisture – increased breakdown with higher soil moisture
- soil temperature – increased breakdown with warmer soil temperature
- organic matter in cropping soil is crucial as it provides a food source for soil microbes
- soil pH –slower breakdown in alkaline (high pH) soils
- time.

No one path works in isolation. A combination of the factors above results in effective breakdown of SU herbicide residues. Always follow the product label with respect to plant back timeframes to subsequent crops and discuss your particular situation with your local agronomist.

Herbicide resistance

Sulfonylurea herbicides are historically the fastest herbicides to select for herbicide resistance, with resistance occurring in as little as 4-6 applications in some weed species. To delay herbicide resistance, only use 1 application per crop; ensure the herbicide is applied for maximum efficacy and ensure there are no survivors that are allowed to set seed.

Further information

- APVMA PERMIT PER88483 – http://permits.apvma.gov.au/PER88483.PDF
- Nufarm product information and contact details – https://nufarm.com/au/

- Soy Australia factsheets for new HB1 varieties – http://www.australianoilseeds.com/soy_australia/licensed_varieties
- NSW DPI Summer Crop Production Guide – Soybean https://www.dpi.nsw.gov.au/agriculture/broadacre-crops/summer-crops/general-information/summer-crop-management-guide
- GRDC Soybean Northern Region Grow Notes™ – https://grdc.com.au/GN-Soybeans-North

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Update of new research in peanuts to assist in-field decision making

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Key words

peanut, KairiⓅ, plant population, row configuration, nutrient management, rotations

GRDC code

DAQ00204

Take home message

- Target plant populations of 180,000 plants/ha to improve the productivity and profitability of peanut variety KairiⓅ
- Peanut variety KairiⓅ does not need a different nutrient management plan than current commercial varieties.

Introduction

Grain legume rotations are an essential component of sustainable sugarcane farming systems of the Coastal Burnett. Research conducted by the Sugar Yield Decline Joint Venture (SYDJV) demonstrated a 20% yield improvement in sugarcane productivity by breaking the monoculture with a legume crop. Factors such as the close proximity of Bundaberg and Childers to Kingaroy; access to irrigation water to ensure cropping reliability; depressed sugarcane prices and grower adoption of SYDJV recommendations to include legumes in the farming system has seen an expansion of peanut production in the Coastal Burnett. In the years 2010 – 2020, 52,584 tonnes of peanuts were grown in the Coastal Burnett and delivered to the Peanut Company of Australia, representing $46,331,102 in gross crop value being fed back into the economies of the Bundaberg, Childers and to a lesser extent, Maryborough farming communities.

Peanuts are viewed as a 'high input' crop requiring irrigation of up to 50 mm/week, regular fungicide applications (8 or more per crop) and soil sampling to apply the correct ameliorants to maximise productivity. The high reliance on protective fungicide applications in a high rainfall environment can be problematic in La Niña years, when access to the paddock can be limited by high rainfall. The National Peanut Improvement Program has improved foliar disease resistance traits as a major foci in the breeding program. KairiⓅ (previously D281-p40-236A) has high foliar disease resistance to rust.

Initial field trials conducted by DAQ00184 and DAQ00204 highlighted the superior rust resistance of KairiⓅ over HoltⓅ with the relative disease score ratings highlighted in Figures 1 and 2 for KairiⓅ and HoltⓅ respectively.

Treatments detailed in Figures 1 and 2, are labelled as follows:

ES = early start to fungicide (four weeks after sowing) program. LS = late start (eight weeks after sowing) of fungicide program. 14 DBS= there were 14 days between fungicide sprays. (21 DBS = 21 day spray intervals). Commercial means Initial fungicide application four weeks after sowing with sprays on a 10-14 day basis with two Bravo® sprays replaced by Amistar Xtra® and ES + Monitor = early start then re-initiate spray program once disease is detected. Please note that the fungicide applied in all treatments was Bravo Weather Stick® with the exception of the 'Commercial' treatment where two of the Bravo® applications were swapped out with Amistar Xtra®

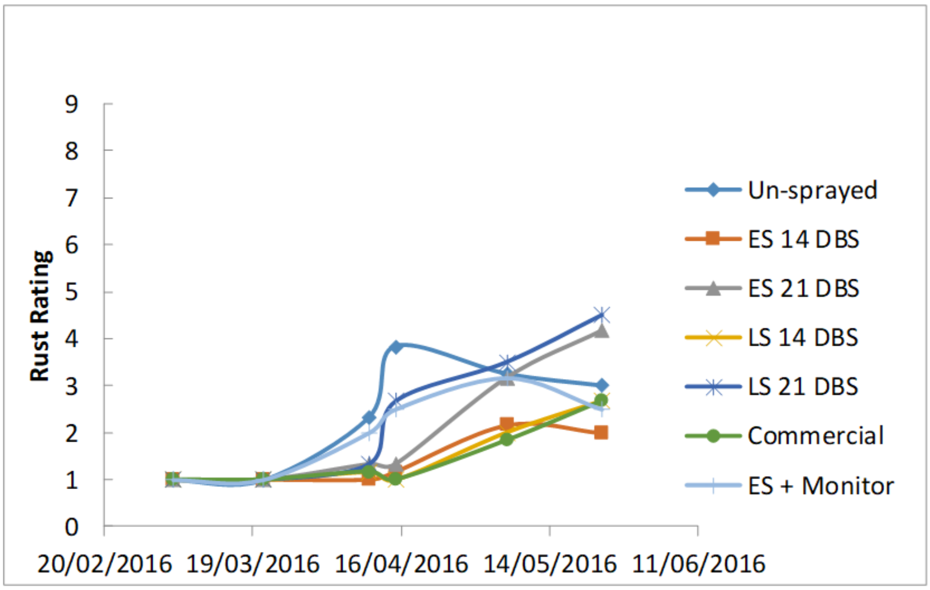

Figure 1. The impact of fungicide application strategy on the incidence of rust (*Puccinia arachidis*) on peanut variety KairiⒹ. (Rust rating where 0 = no evidence of disease 9 = complete infection resulting in defoliation)

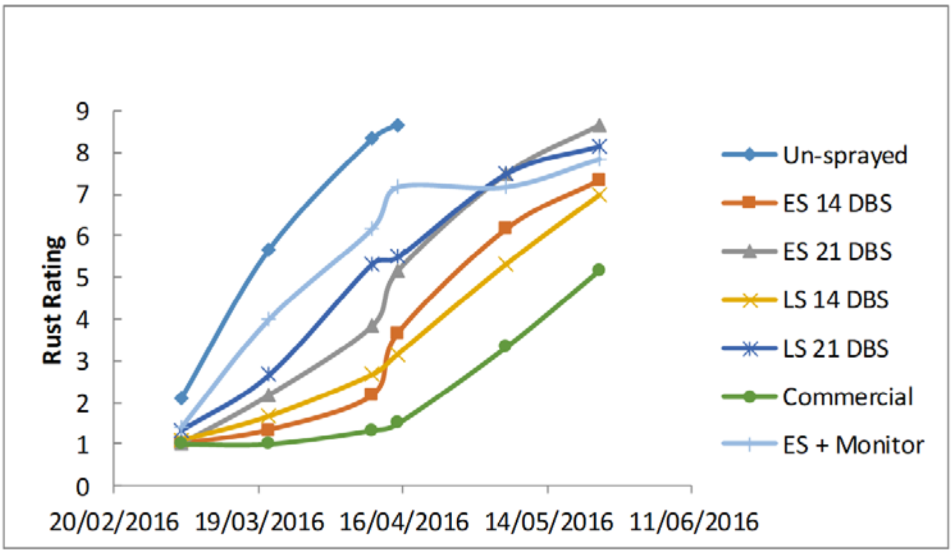

Figure 2. The impact of fungicide application strategy on the incidence of rust (*Puccinia arachidis*) on peanut variety HoltⒹ. (Rust rating where 0 = no evidence of disease 9 = complete infection resulting in defoliation)

To better illustrate the foliar disease resistance of KairiⒹ to leaf rust, Figures 3 and 4 are pictures from the late start (eight weeks after planting) and 21 days between fungicide application treatment for KairiⒹ and HoltⒹ plots respectively. This high resistance to rust resulted in a 44.8% increase in productivity of KairiⒹ over HoltⒹ in this fungicide application timing experiment.

Figure 3. Leaf canopy in the Late start, 21 days between sprays treatment in variety Kairi⑴

Figure 4. Leaf canopy in the Late start, 21 days between sprays treatment in variety Holt⑴

The soil at the end of a cane cycle (plant cane crop and three ratoons) typically is acidic and low in potassium and nitrate nitrogen. It is not uncommon for the application of 2t/ha of lime and a basal fertiliser containing 30kgN/ha, 20kgP/ha and 100kgK/ha incorporated pre-plant for peanut production in the Coastal Burnett. Natural gypsum at 1t/ha and foliar applications of boron, zinc and magnesium are generally applied in-crop.

Peanuts are unique in that the calcium and boron needed for kernel development is absorbed through the pod wall, necessitating the pod zone to have adequate calcium and boron levels. Figure 5 is a drawing of a peanut bush demonstrating above and below-ground components.

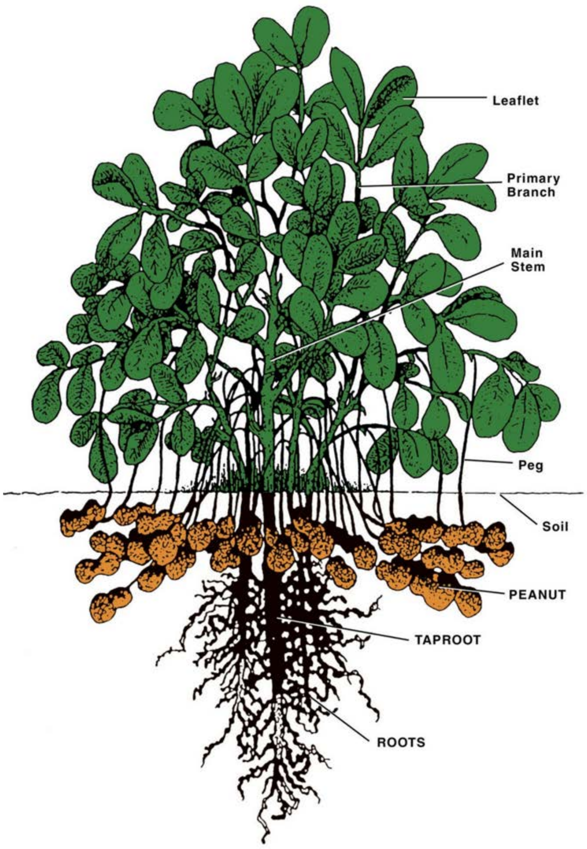

Figure 5. Drawing of a peanut plant structure

Grower experience of Kairi⁽ᵇ⁾ on release was marred with poor grades and yields not meeting grower expectation. The Coastal Burnett Regional committee of the GRDC Growers Solution Project for Coastal/Hinterland Queensland and NSW North Coast project identified and prioritised field trials to evaluate strategies to maximise the productivity of Kairi⁽ᵇ⁾.

To provide information for growers a number of field trials were established over 17/18 and 18/19 growing seasons.

Materials and methods

This paper focuses on three field trials conducted over two years.

The <u>first</u> field trial was established in the 2017/18 peanut season a factorial trial of two populations (120,000 and 240,000 plants/ha), by two row configurations (single or twin rows), by three nutrition regimes (standard practice, extra Ca & B, and extra nutrition based on commercial agronomic lab 'Hortus' recommendations). Treatments were replicated four times in a randomised complete block (RCB) design. The trial was planted on 10/10/17. The Hortus treatment was a flexible nutrition program based on petiole sap tests. Please note that the 'single' row configuration refers to two rows 85cm apart on a 1.8m bed; whereas the 'twin' row configuration refers to four rows planted on the 1.8m bed, with the outside-most rows being 85cm apart with a 36cm gap between the innermost rows as in Figure 6. All plots received the standard fertiliser application (listed below) and the soil was conventionally tilled and beds were formed. The plots were three beds wide by 25m length. The soil type was a yellow dermosol (sandy-loam top soil, over a light clay sandy loam) in the Farnsfield district south of Bundaberg.

Figure 6. Twin row configuration in the background and single row configuration in the foreground

The standard fertiliser recommendations were to apply sufficient lime to push the pH up to 6.5 (~4 t lime/ha); 20 kgN/ha; 18 kgP/ha; 97 kgK/ha; 5 kgS/ha. There were also in-crop additions of manganese and boron. The extra Ca & B treatment had an extra tonne of gypsum applied pre-flowering and boron as Solubur® @ 2 kg/ha. The crop was irrigated with a high pressure travelling irrigator and weeds and foliar diseases (mainly late leaf spot) were controlled with herbicides and fungicides respectively.

The crop was dug on 20/3/18 (161 DAP), a yield quadrat of 14.4m^2 was marked out of each plot. The crop was field dried for about seven days. The yield samples were then threshed using a 'KEW' self-propelled small-plot thresher with the pods collected in labelled hessian bags that were placed into a tobacco barn with only the fan running. The yields and grades were determined by the method outlined below.

The data was analysed by ANOVA for an RCB design with a factorial treatment structure using the Genstat® computer package version 16.1. Pairwise testing of means was conducted using a protected LSD test at P=0.05.

The second field trial was implemented in the following 2018/19 season. The trial design was changed to a randomised complete block consisting of eight replicate blocks each with eight plots randomly allocated to two row configurations (single or twin) by four target populations (60,000, 120,000, 180,000, or 240,000 plants per hectare) See Table 1. The trial was planted on the 4th October 2018.

Table 1. The treatment list for the Kairi population by row configuration field trial (second field trial)

Treatment #	Target population (Plants/ha)	Row configuration
1	60,000	Single
2	60,000	Twin
3	120,000	Single
4	120,000	Twin
5	180,000	Single
6	180,000	Twin
7	240,000	Single
8	240,000	Twin

The trial was established on a sandy-loam soil (yellow dermosol) at Farnsfield. The previous cane crop was harvested and trash baled prior to the cane stool being removed with conventional tillage. At least one month prior to planting, 4t lime/ha was applied to correct soil pH and ensure an adequate soil calcium status. A fertiliser blend containing 20kgP, 30kgN and 100kgK/ha was broadcast and incorporated with a rotary hoe prior to 1.8m beds being formed.

The peanuts were planted using a 'Monosem™' vacuum plate planter. The seeding rate was electronically altered at each plot. The rate of seed supplied was calibrated to allow for 90% germination and 90% establishment. The planting furrow was opened with a double disc opener and then rhizobia inoculant (Group P) as a peat slurry was water injected onto the seed in the planting furrow.

Each plot was 30m long and three cane rows wide. The site was kept weed-free with combinations of pre and post emergent herbicides (Dual Gold®, Flame®, Blazer®, Verdict® and 2,4 – DB) applied at registered rates. Fungal pathogens such as white mould and late leaf spot were controlled with prophylactic applications of registered fungicides. The crop was grown using supplementary irrigation supplied via a low-pressure over-head centre pivot that delivered approx. 30mm every 7 to 10 days.

The crop was dug on 12/3/19 (160 days after planting (DAP)), the crop was then field dried for about seven days. A yield quadrat of 14.4m^2 was marked out of each plot and threshed using a 'KEW' self-propelled small-plot thresher. Pods were collected in labelled hessian bags that were placed into a tobacco barn with only the fan running. The yields and grades were evaluated with the method outlined below.

Actual plant populations were estimated from plant counts. Populations were variable and did not reflect the target populations. As a result, measured plant populations were considered as a continuous variable in the analysis rather than using the categorical target populations.

A linear fixed model was fitted to the data with fixed effects of row configuration (Rows-factor) and the continuous variable of actual plant population and interactions between these terms. Where there was evidence of curvature across population, a quadratic fit was applied to the population variable. Replicate block was fitted as a random effect. A parsimonious model was achieved by sequentially removing non-significant terms from that model but always retaining the main effects terms, including the linear population term.

Data were analysed using GenStat 19th edition (VSN International, 2015) Significance tests were performed using a LSD at 5% level.

The third field trial came about because agribusinesses were approaching peanut growers offering a range of calcium products as an alternative to gypsum. A trial was implemented at the request of the growers to determine the efficacy of these alternative products. The experiment design was a randomised complete block consisting of 10 replicate blocks each with four treatments randomly allocated; see Table 2. The trial was co-located beside the Kairi⌽ population by row configuration experiment and was established on 2/11/18.

Table 2. The treatment list for the 'Kairi⌽' population by row configuration field trials

Treatment #	Calcium fertilisation strategy
1	Nil
2	Natural gypsum (1t/ha)
3	Micro-fine prilled gypsum (200kg/ha)
4	Liquid gypsum (20L/ha)

The peanuts were planted using a 'Monoson™' vacuum plate planter. The planter was calibrated to establish 180,000 plants/ha. The planting furrow was opened with a double disc opener and then rhizobia inoculant (Group P) as a peat slurry was water injected onto the seed in the planting furrow.

Each plot was 30m long and three cane rows wide. The various calcium treatments were applied on 12/12/19 (40 DAP). Product for each plot (natural and fine-prilled gypsum) were weighed out for each individual row and were applied by hand. The liquid gypsum was applied by a three-point linkage mounted spray rig using 'twin cap' 02 'Drift Guard' nozzles calibrated to supply 280L water volume/ha.

The site was kept weed-free with combinations of pre and post emergent herbicides (Dual Gold®, Flame®, Blazer®, Verdict® and 2,4 – DB) applied at registered rates. Fungal pathogens such as white mould and late leaf spot were controlled with prophylactic applications of registered fungicides. The crop was grown using supplementary irrigation supplied via a low-pressure over-head centre pivot that delivered approx. 30mm every 7 to 10 days.

The crop was dug on 4/4/19 (154 DAP). A yield quadrat of 14.4m^2 was marked out of each plot. Yields and grades were determined by the method outlined below

The kernels from the grading sample were then processed in a food blender and passed through a 2mm sieve. Samples were sent to Queensland Department of Environment and Science – Chemistry Centre in Brisbane to determine treatment effect on kernel calcium concentration using Plant Elements nitric microwave digest ICP technique.

Treatment effect of measured parameters were determined via ANOVA using Genstat 19th edition (VSN International, 2015) Significance tests were performed using a 'Fischer Protected LSD' at 5% level.

After harvesting and drying, peanut samples from all three field trials were processed in an identical manner - namely: The samples were put over a 'KEW peanut cleaner' at DAF Kingaroy Research Facility to remove soil and extraneous matter. The sample was then weighed. A 1,000g sub-sample was then hulled and hand shelled to remove peanut shell. The kernels were then placed over the 'KEW peanut grader' to determine treatment impact on grade/quality using the following sieves:

- Oil = kernels that passed through a 21/64th round sieve
- Split = kernels that passed through a 16/64th slotted sieve
- MFG = kernels that passed through a 22/64th round sieve
- 2's = kernels that passed through a 24/64th round sieve

- 1’s = kernels that passed through a 25/64th round sieve
- J’s = kernels that passed over the 25/64th round sieve.

The percent of each grade was determined by dividing the weight of each grade (in grams) by the original 1,000g sample. Shell percentage was determined by the difference of the sum of all the grades from the original 1,000g sample. Gross crop value was calculated from the 2017 peanut supply contract for runner peanuts at: $1,650/t for J’s; $1,500/t for 1’s; $1,300/t for 2’s; $1,200/t for splits; $450/t for MFG; $150/t for oil’s. Gross margins were calculated using the Farm Economic Analysis Tool (FEAT) and PCA indicative gross margin; with individual plot yield, grade and seed and fertiliser inputs accounted for.

Results and discussion

Results from the first field trial, demonstrated that Kairi did not have a different nutritional requirement to that of Holt as there was no difference in yield or grade (or any other measured parameter) between the standard, extra calcium and boron or the ‘Hortus’ treatment. Similarly, row configuration offered no yield improvements.

However, increasing the target population from 120,000 plants/ha to 240,000 plants/ha significantly (P=0.002) improved nut-in-shell yield by 6%. More importantly, increasing the population significantly increased the percentage of high value ‘Jumbo’ kernels and decreased the percentage of worthless shells. The combination of improved yield and grade offered by the higher population significantly increased gross crop value by $754/ha; representing a 13% improvement. Peanut seed is expensive, so increasing population means increased input costs. To account for these variables a crop gross margin was calculated and statistically analysed. Increased planting population significantly (P=0.010) improved gross margin by $515/ha. This increase is gross margin means that the 240,000 plant/ha treatment had a 24% higher gross margin than the 120,000 plants/ha treatment. There were no treatment interactions, see Table 3.

Table 3. The effect of population, row configuration and nutrition on peanut productivity, grade-out, gross crop value, payment price and gross margin. Means within a column not followed by a common letter are statistically different (P=0.05).

	NIS (t/ha)	J's (%)	1's (%)	2's (%)	Split (%)	MFG (%)	Oil (%)	Shell (%)	GCV ($/ha)	$/t	Gross Margin ($/ha)
Population (P)											
120K	6.72 [b]	41 [b]	3 [a]	6	9 [b]	4 [a]	6 [a]	32 [a]	5,840 [b]	866.3 [b]	2,128 [b]
240K	7.19 [a]	45 [a]	2 [b]	5	10 [a]	3 [b]	5 [b]	30 [b]	6,594 [a]	917.1 [a]	2,643 [a]
P value	0.002	0.010	0.048	0.057	0.024	0.011	0.024	0.004	<0.001	0.003	0.010
LSD	0.28	2.8	0.4	-	1.2	0.7	0.1	1.2	384	31.8	383.7
Row Config (R)											
Single	7.03	43	3	5	9	3	5	31	6,306	894.0	2,428
Twin	6.88	43	3	5	10	3	5	31	6,128	889.4	2,344
P value	0.262	0.852	0.440	0.731	0.752	0.797	0.319	0.708	0.351	0.771	0.657
Nutrition (N)											
Std	6.98	43	3	5	10	3	5	31	6,201	887.3	2,521
Extra Ca&B	6.92	44	3	5	10	3	5	30	6,258	902.3	2,308
Hortus	6.96	43	3	5	9	3	5	31	6,192	885.5	2,328
P value	0.947	0.704	0.849	0.924	0.943	0.392	0.841	0.668	0.953	0.633	0.602
Interaction P values											
P * R	0.712	0.350	0.254	0.722	0.519	0.756	0.481	0.097	0.348	0.242	0.565
P * N	0.956	0.302	0.180	0.393	0.724	0.156	0.394	0.855	0.735	0.432	0.942
R * N	0.857	0.584	0.488	0.572	0.567	0.409	0.766	0.795	0.841	0.905	0.964
P * R * N	0.302	0.907	0.434	0.968	0.577	0.416	0.952	0.693	0.702	0.903	0.880

Poor seed quality and potential planter calibration issues resulted in the target populations not being achieved in the second field trial.

However, there was a significant effect of population on nut-in-shell yield, with an established population of 180,000 plants/ha having the highest yield of 6.16t/ha. This yield was nearly 50% better than the lowest population and 7% higher than the yield at 150,000 plants/ha. This is an important finding as current recommendations for the industry standard variety Holt⦶ is to establish 150,000 plants/ha, see Figure 7.

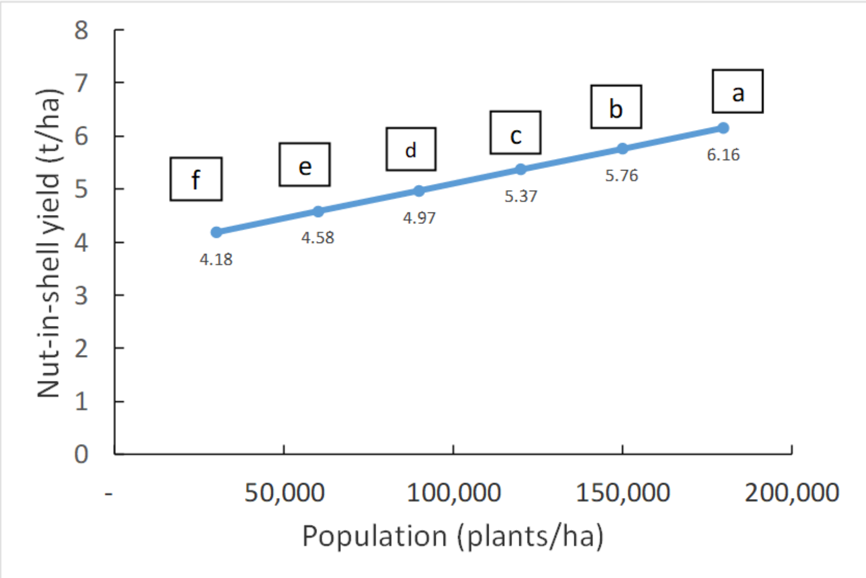

Figure 7. Population effect on nut-in-shell yield of peanut variety 'Kairi⦶' for the second field trial 2018/19. Data points with the same letter are not statistically different (P=0.05)

Importantly, population had a significant effect on grades. The payment price to a grower depends on the crop grade (or quality), with jumbo kernels (Figure 8) being the most valuable, oil grade kernels the least valuable and shells worthless (Figure 9).

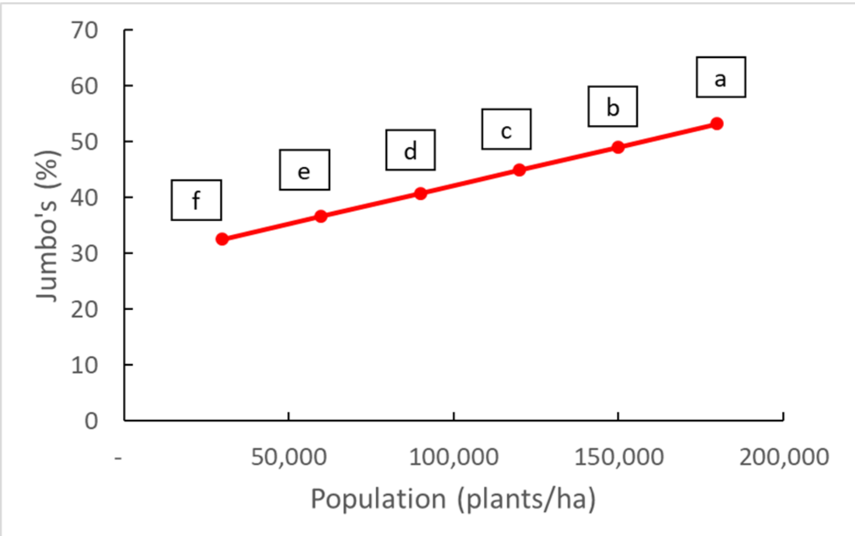

Figure 8. Population effect on Jumbo grade peanuts for variety 'Kairi⦶' in the second field trial. Data points with the same letter are not statistically different (P=0.05)

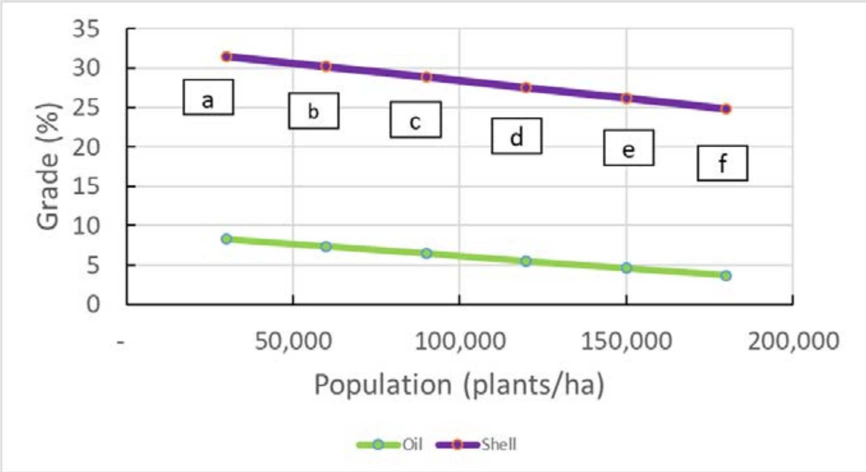

Figure 9. Population effect on oil grade kernels and shell percentage for peanut variety 'Kairi⁽ᵈ⁾' in the second field trial. Data points with the same letter are not statistically different (P=0.05)

Grades are a measure of crop quality and growers are paid accordingly on a $/t basis. The improvement in jumbo's and reduction in oil's and shell's results in a payment price of $1,014/t for the highest population which is $41/t and $82/t more than the 150,000 plants/ha and 120,000 plants/ha respectively. The 180,000 plants/ha treatment had the highest gross crop value of $6,167/ha. This value is $555/ha and $1,109/ha more than the 150,000 plants/ha and 120,000 plants/ha treatments respectively (Table 4).

Table 4. Population effect on payment price and gross crop value.
Values in columns with the same letter are NOT statistically different (P=0.05).

Population	Payment price ($/t)	Gross crop value ($/ha)
30,000	809 [f]	3,395 [f]
60,000	850 [e]	3,949 [e]
90,000	891 [d]	4,503 [d]
120,000	932 [c]	5,058 [c]
150,000	973 [b]	5,612 [b]
180,000	1,014 [a]	6,167 [a]
P Value	<0.001	<0.001
LSD (P=0.05)	463	45

Please Note: Gross crop value (GCV) is an economic measure that is a multiplication of the yield by payment price. Please do not confuse GCV with a crop gross margin, as a GCV does not take into consideration the extra cost of seed for the different treatments.

The twin-row configuration did not offer any improvement in yield or grade. Commercially the twin-row configuration would require capital investment into different planters or planting the paddock twice; these data would suggest that such investment is not warranted.

The third field trail demonstrated that there were no calcium fertilisation treatment effects on peanut yield (P=0.127). The commercial practice of applying gypsum in-crop resulted in a yield of

5.11t/ha which was not different to the control (5.07t/ha) where no gypsum was applied, see Figure 10.

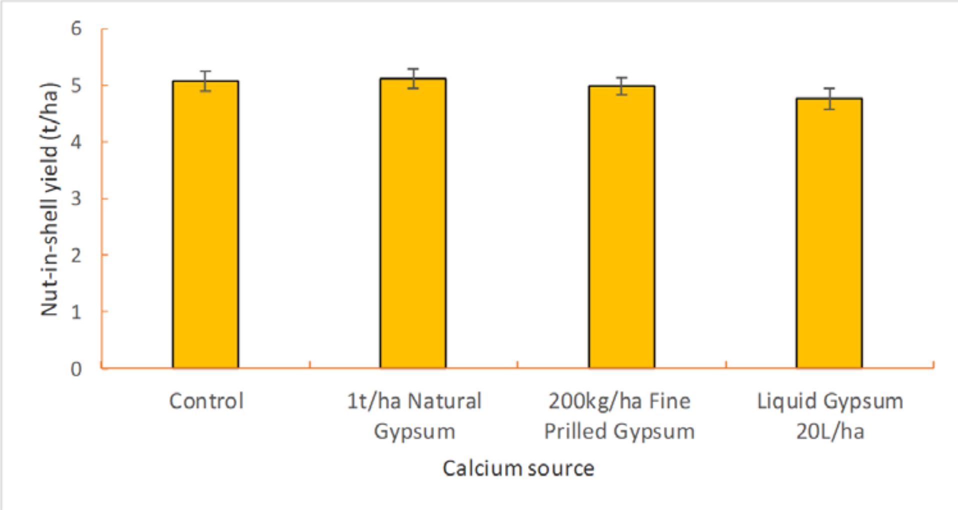

Figure 10. The effect of in-crop calcium fertilisation strategy on peanut variety 'Kairi⒫' yield. *Error bars are +/- standard error of treatment mean.*

From a kernel quality perspective, there was no effect of in-crop calcium fertilisation strategy on the percentage of the high value jumbo kernels (P=0.245); the low value oil grade kernels (P=0.114) or the worthless shell percentage (P=0.471) (data not shown).

Due to the lack of treatment effect on yield and/or grade there were no statistically significant calcium fertilisation effects on gross crop value (GCV) or payment price, refer to Table 5.

Table 5. The effect of in-crop calcium fertilisation strategy on gross crop value and payment price.

Treatment #	**Gross crop value ($/ha)**	**Payment price ($/t)**
Nil	4,569	899
Natural gypsum (1t/ha)	4,651	904
Micro-fine prilled gypsum (200kg/ha)	4,357	870
Liquid gypsum (20L/ha)	4,095	851
P Value	0.100	0.326
LSD (P=0.05)	-	-

Whilst in-crop calcium fertilisation strategies failed to have an impact on yield, grade and ultimately GCV, there was an effect on kernel calcium status. The application of natural gypsum at 1t/ha significantly increased the kernel calcium concentration by 31% over the control treatment. However, there was no evidence that the application of the micro-fine prilled product or the liquid product had an effect on kernel calcium concentrations applied at the rates used in this experiment.

The range of calcium treatments had some interesting interactions on some other kernel cation concentrations. For example, the kernels in the liquid gypsum treatment had very similar calcium, magnesium and sodium concentrations to the control. However, the application of gypsum at 1t/ha significantly improved kernel calcium status yet significantly reduced kernel magnesium and sodium concentrations relative to the control. Whilst the micro-fine prilled gypsum treatment did not have an effect on the kernel calcium concentrations, it did have significantly lower magnesium and sodium kernel concentrations relative to the control (Table 6). These findings could be of interest if there is a market for peanuts with increased calcium levels.

Table 6. The effect of in-crop calcium fertilisation strategy on peanut calcium, magnesium and sodium concentrations.
Values in columns followed by the same letter are NOT statistically different (P=0.05)

Treatment #	**Calcium %**	**Magnesium %**	**Sodium %**
Nil	0.0456 [b]	0.1739 [a]	0.0326 [a]
Natural gypsum (1t/ha)	0.0599 [a]	0.1589 [b]	0.0220 [c]
Micro-fine prilled gypsum (200kg/ha)	0.0467 [b]	0.1605 [b]	0.0289 [b]
Liquid gypsum (20L/ha)	0.0445 [b]	0.1706 [a]	0.0334 [a]
P value	<0.001	<0.001	<0.001
LSD (P=0.05)	0.0032	0.0069	0.0019

Conclusion

Data from these field trials highlights that the yield, grade and therefore profitability of recently released peanut variety Kairi⊕ is improved by establishing 180,000 plant/ha. Whilst there is increased cost to the grower from increasing seeding rates, the improvement in yield, grade and in-turn gross margin, more that justifies the extra seed cost incurred.

Despite the fact that Kairi⊕ has a larger kernel size than Holt⊕, we could not find any evidence that Kairi⊕ has a requirement for a different nutrient management strategy than what is typically 'industry practice' for high-input peanut production in coastal environments. However, it is also evident that peanut growers' profitability would benefit from a calcium fertilisation decision support tool. The calcium trial (third field trial) backed up previous research that demonstrated that if a paddock has lime applied to ameliorate pH then the in-crop application of gypsum offers no improvement in yield or grade.

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Herbicide resistance survey results of the Northern cropping region

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Key words

glyphosate resistance, sowthistle, fleabane, feathertop Rhodes grass, awnless barnyard grass

GRDC code

UCS00024, US00084

Take home message

- Glyphosate resistant weeds are present in the northern region. Glyphosate failed to control all of the fleabane populations tested. Glyphosate resistance was also prevalent in feathertop Rhodes grass, windmill grass and awnless barnyard grass, with resistance detected in 68%, 58% and 36% of populations, respectively. Only 14% of sowthistle populations were resistant to glyphosate
- Evolved herbicide resistance to haloxyfop was also detected in feathertop Rhodes grass, albeit at a low frequency
- Other herbicides such as 2,4-D amine, propaquizafop and clethodim provided good control of the broadleaf and grass weeds tested
- Farmers and agronomists should incorporate non-chemical weed management tactics to ensure sustainability of current herbicides
- These survey results provide a first glimpse into the state of herbicide resistance in key crop weeds for Queensland and the Northern region.

Introduction

The area of the Northern grain cropping region from Central Queensland to Dubbo in New South Wales (north to south) has a diverse cropping system, often with both winter and summer cropping, or summer fallow for moisture storage. Effective weed control in crop and fallow is heavily reliant on herbicides such as glyphosate. For the past 30 years, heavy reliance on glyphosate has seen more and more weed species become resistant to this herbicide. This includes annual ryegrass, awnless barnyard grass, liverseed grass, windmill grass, fleabane and sowthistle (Cook 2014, Widderick et al. , 2014, Cook et al. 2004).

Despite the increasing number of herbicide resistance cases, the full extent of herbicide resistance in this part of the Northern region is unknown. The first whole of region survey of key winter and summer weed species started in winter 2016 and was completed in summer 2017/2018. Weed seeds collected from the survey were screened for resistance against various herbicides. This report primarily covers the herbicide resistance screening carried out by the Department of Agriculture and Fisheries, Queensland.

Material and methods

The Department of Agriculture and Fisheries, Queensland (DAF) was responsible for herbicide resistance screening of sowthistle, fleabane, barnyard grass, feathertop Rhodes grass, windmill grass and liverseed grass. Populations of the species listed above that were collected in New South Wales by Dr John Broster of Charles Sturt University were also screened by DAF.

Seed germination

Weed seeds were grown in their growing seasons following the survey. Sowthistle were grown from late March to late November while fleabane and the summer grasses were grown from late November to mid-May.

Sowthistle and summer grass seeds were germinated on 0.6% agar for 4 to 7 days in the glasshouse and transplanted into trays (50 seedlings/population/tray) of potting mix. The trays were then placed onto drip trays filled with enough water to keep the soil moist without causing any water logging for the first few days. After 7 days, the plants were watered from above. A similar approach was used for fleabane, with the exception that fleabane seeds were sown directly into trays of potting mix. After 7 days, fleabane seedlings were thinned to the required density (10 seedlings per column, up to 5 columns).

Herbicide resistance screening

Plants were grown until they reached the three to five leaf growth stage. They were then treated at the recommended label rate for each herbicide (Table 1) with the appropriate adjuvant (if required). For weeds that are not on label for a particular herbicide, the recommended rate for the closest relative weed was used. Assessment of survivors was carried out at 21 days after treatment (DAT). Plants were considered surviving if there were actively growing tillers (grass weeds) or regrowth from the growing point (broadleaf weeds).

Table 1. Herbicides and rates used for screening various weed species for resistance.

Weed species	Herbicide (note rates are of active ingredient)
Sowthistle	Glyphosate (729 g ae/ha) 2,4-D amine (1050 g ai/ha) Velocity (bromoxynil 210 g ai/ha + pyrasulfotole 37.5 g ai/ha) Chlorsulfuron (15 g ai/ha)†
Fleabane	Glyphosate (729 g ae/ha) † 2,4-D amine (1050 g ai/ha)
Feathertop Rhodes grass	Glyphosate (729 g ae/ha)†* Haloxyfop (78 g ai/ha) Clethodim (90 g ai/ha) Paraquat (400 g ai/ha)
Awnless barnyard grass Liverseed grass	Glyphosate (729 g ae/ha) Propaquizafop (60 g ai/ha) Clethodim (90 g ai/ha) Imazapic (96 g ai/ha)**
Windmill grass	Glyphosate (729 g ae/ha) Clethodim (90 g ai/ha)***

†Not registered for control of this weed species

*Glyphosate used as stand-alone and not in tank-mix with 2,4-D amine as per label requirement.

** Used alone as post-emergence . Note that imazapic is only registered for stand-alone use against these weeds as a pre-emergent application.

***As per APVMA permit PER89322 (but without the double knock)

Results

Sowthistle

In total 221 sowthistle populations from Queensland and New South Wales were collected. Only 197 populations were viable for screening with glyphosate and 2,4-D amine. Glyphosate resistance was detected in 14% of the populations tested (Table 2), while 100% of the populations were susceptible to 2,4-D amine. Screening of 136 populations with Velocity® and chlorsulfuron showed that Velocity was able to control all populations while poor control (95% populations survived) was achieved with chlorsulfuron (Table 2).

Table 2. Percentage of populations surviving treatment with different herbicides assessed 21 DAT.

Weed Species	Number of populations tested	Glyphosate (%)	2,4-D amine (%)	Chlorsulfuron (%)	Velocity (%)
Sowthistle	197	14	0		
	136			95	0
Fleabane	61	100	0	n/a	n/a

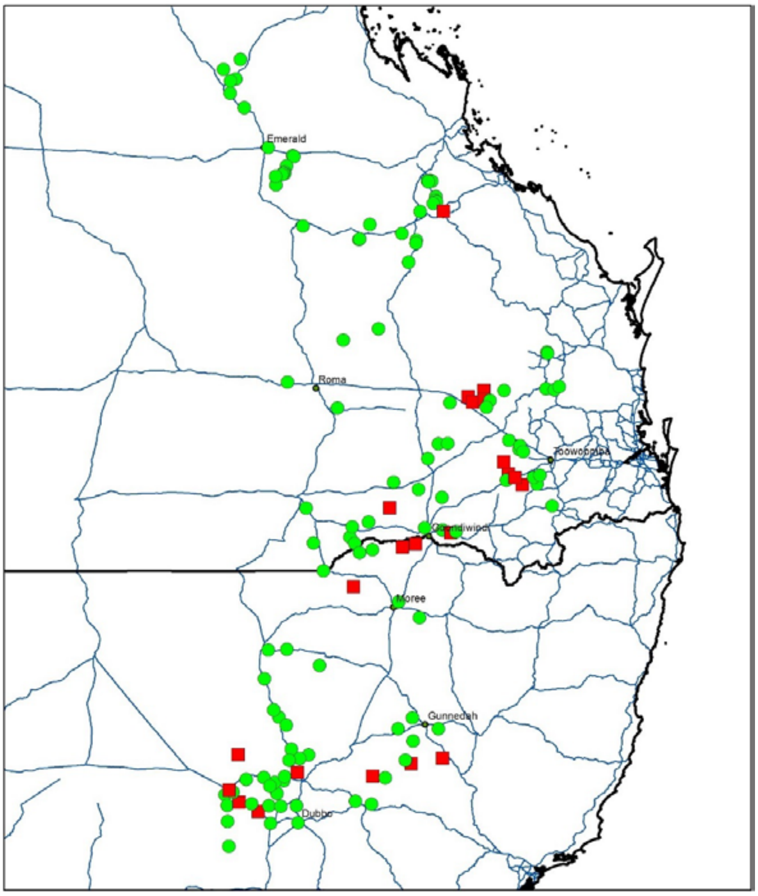

Figure 1. Map of glyphosate resistant and susceptible sowthistle populations across the northern grain cropping region. Red squares represent resistant populations while green circles represent susceptible populations.

Fleabane

There were 100 fleabane populations collected across the Northern region but only 61 viable populations (Figure 2) were screened with glyphosate and 2, 4-D amine. Glyphosate, which is not registered to control fleabane, failed to control all of the fleabane populations tested. However, no population survived treatment of 2, 4-D amine (Table 2).

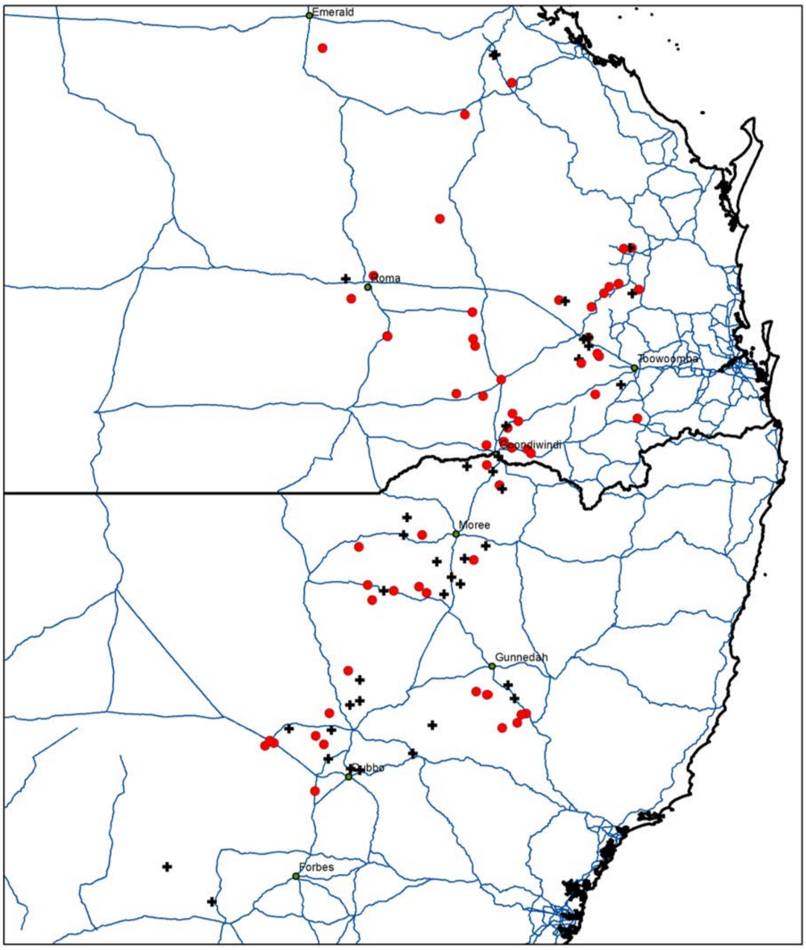

Figure 2. Map of fleabane populations across the northern grain cropping region surviving glyphosate application. Red circles are populations surviving the target glyphosate application rate, while black crosses represent non-viable populations.

Feathertop Rhodes grass

Screening of 62 viable populations revealed 68% survived the glyphosate target rate (noting that glyphosate is not registered for FTR control) (Figure 3, Table 3). One population survived treatment with haloxyfop, while all populations were controlled with clethodim and paraquat.

Table 3. Percentage of feathertop Rhodes grass populations surviving treatment with different herbicides, assessed 21 DAT.

Weed species	Number of populations tested	Glyphosate (%)	Haloxyfop (%)	Clethodim (%)	Paraquat (%)
Feathertop Rhodes grass	62	68	2	0	0

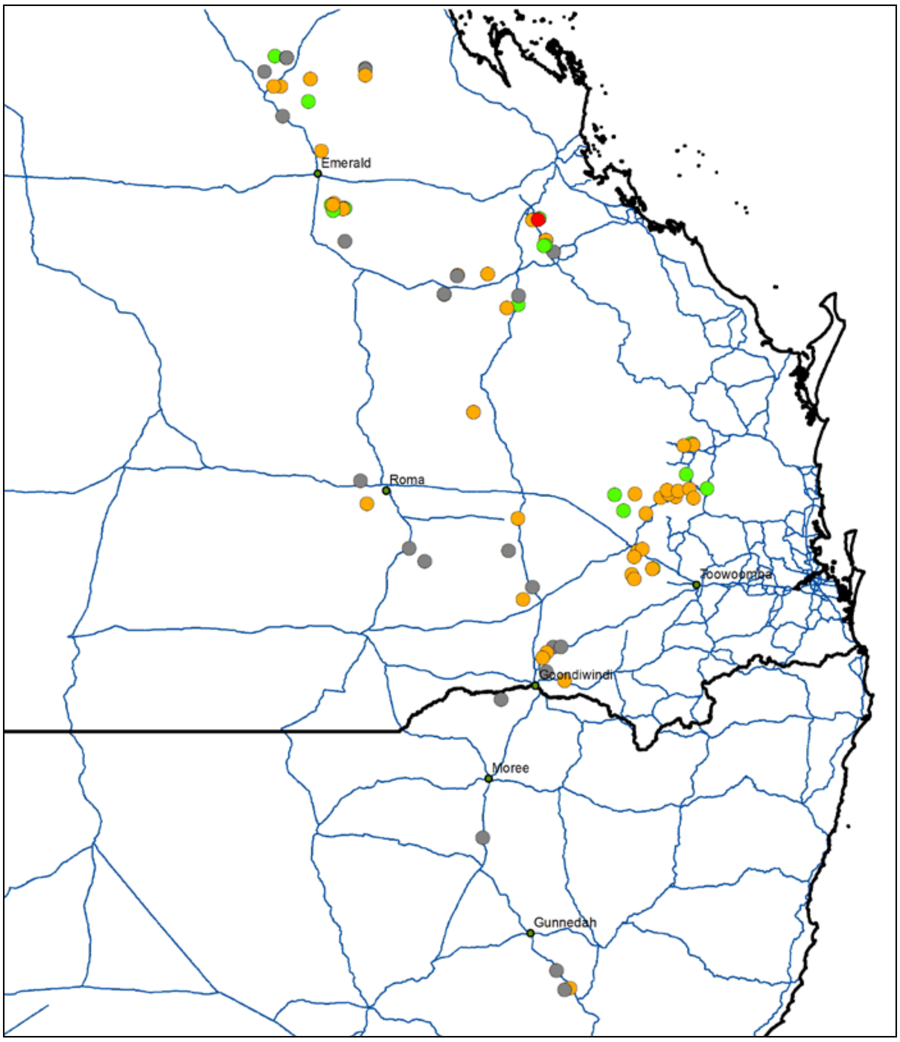

Figure 3. Map of glyphosate resistant and susceptible feathertop Rhodes grass populations across the northern grain cropping region. A red circle represents a glyphosate and haloxyfop resistant population, yellow circles represent glyphosate resistant populations that are susceptible to haloxyfop, green circles represent populations susceptible to all herbicides tested, and grey circles represent populations that were not viable.

Awnless barnyard grass

Screening of 42 viable populations revealed 36% were resistant to glyphosate (Figure 4, Table 4), while all of the populations were susceptible to propaquizafop, clethodim and imazapic (noting imazapic was applied as a foliar application and not a soil residual treatment).

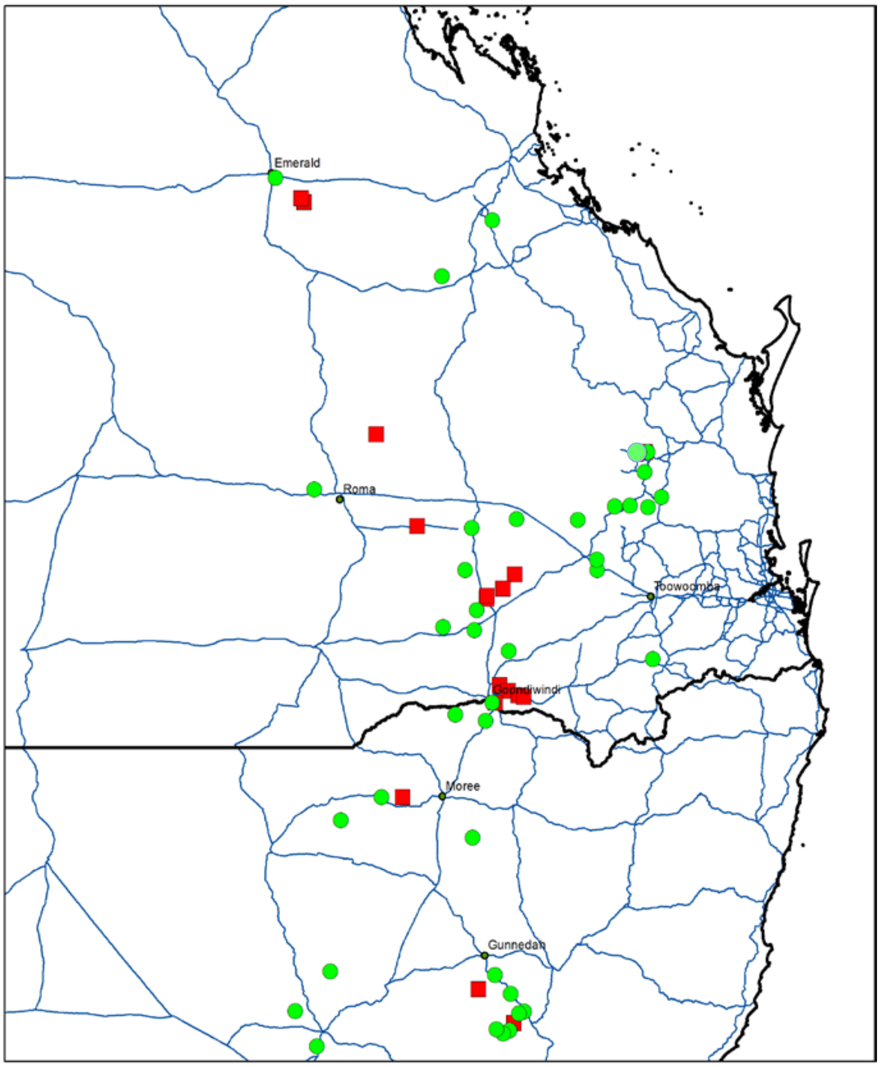

Figure 4. Map of glyphosate resistant and susceptible awnless barnyard grass populations across the northern grain cropping region. Red squares represent resistant populations while green circles represent susceptible populations.

Table 4. Percentage of awnless barnyard grass, windmill grass and liverseed grass populations surviving treatment with different herbicides, assessed 21 DAT.

Weed species	Number of populations tested	Glyphosate (%)	Propaquizafop (%)	Clethodim (%)	Imazapic (%)*
Awnless barnyard grass	42	36	0	0	0
Liverseed grass	3	0	0	0	0
Windmill grass	12	58	n/a	0	n/a

* Imazapic was applied as a foliar application, and not a soil residual treatment

Windmill grass

Screening of 12 viable populations revealed that more than half of them (58%) survived the target glyphosate rate (Table 4). All of the populations were controlled by clethodim.

Liverseed grass

There were only 14 liverseed grass populations collected across the Northern region. Almost none of them were viable. Herbicide resistance screening of the viable populations (3) showed no evolved resistance to any of the herbicides tested (Table 4).

Discussion

For years, there have been anecdotal reports of certain weed species becoming more difficult to control. This project provides, for the first time, proof of widespread occurrence of herbicide resistance in key weed species in the Northern region.

Glyphosate resistance is the most pressing issue, as all of the weed species tested have populations that were able to survive robust glyphosate application rates, except for liverseed grass (noting only three liverseed grass populations were tested). Especially worrying is fleabane, where total glyphosate failure was recorded. Frequency of glyphosate survival for the other weed species ranges from low (14%, sowthistle) to moderate/severe (68%, feathertop Rhodes grass).

Glyphosate is not registered for control of feathertop Rhodes grass, as it has been known to provide unreliable control. The inclusion of glyphosate screening to feathertop Rhodes grass was to confirm the extent of survival.

Despite the number of weed species and populations that have evolved glyphosate resistance, it should be noted that other herbicides tested were still effective. 2,4-D amine controlled all of the fleabane and sowthistle populations tested, including the ones that survived glyphosate.

Group A herbicides such as haloxyfop, propaquizafop and clethodim gave good control of the summer grass weeds, with only one feathertop Rhodes grass sample surviving haloxyfop treatment.

Imazapic, a group B herbicide that was used post-emergence in our screening, provided good control of awnless barnyard grass and liverseed grass populations. It should be noted imazapic is only registered for pre-emergent control of both awnless barnyard grass and liverseed grass. For post-emergent application the label requires it to be tank-mixed with paraquat. As such, these results should be interpreted with caution.

Viability of the weed seeds was one of the issues in our herbicide resistance screening. All of the weed species tested had populations with non-viable seeds, ranging from 10% (sowthistle, glyphosate and 2, 4-D amine) and up to nearly 80% of populations (liverseed grass). Some of these non-viable seeds were immature, and we believe some of the weed seeds were exposed to herbicide treatment shortly before collection, which could contribute to non-viability of seeds.

The presence of evolved herbicide resistant weeds in the Northern region is expected, given the reports of resistant weeds in the past. However, the extent of the some of the resistance, e.g. fleabane to glyphosate, is truly worrying. This survey offers, for the first time, an overview of the widespread nature of herbicide resistant weeds in the Northern region in key weed species. Continued heavy reliance on herbicides for weed control is likely to exacerbate the resistance challenge for growers and agronomists. Other weed management tactics that incorporate non-chemical weed control such as crop competition, targeted tillage, and harvest weed seed control (Widderick, Ruttledge, McKiernan, *personal communication*) should be seriously considered to ensure the herbicides that we have now continue to be effective in the future.

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Growing competitive sorghum and mungbean crops to suppress summer weeds

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Key words

crop competition, sorghum, mungbean, feathertop Rhodes grass, awnless barnyard grass

GRDC code

US00084

Take home message

- Feathertop Rhodes grass (FTR) and awnless barnyard grass (ABG) are both difficult to control summer grass weeds with both species prone to herbicide resistance evolution
- Growing a competitive sorghum or mungbean crop can reduce growth and seed production of FTR and ABG
- ABG is more susceptible to the impacts of crop competition than FTR
- Sorghum competitiveness can be increased by growing the crop at a narrow row spacing (50 cm) and increased density (10 to 15 plants/m^2)
- Mungbean competitiveness is most effectively increased through the use of narrow row spacing (25 and 50 cm)
- Consider growing a competitive summer crop to take pressure off relying solely on in-crop herbicides for summer grass control.

Introduction

Herbicides are a main stay of weed control in conservation cropping systems. However, reliance on herbicides for weed control has caused widespread herbicide resistance.

Key summer weeds in the northern region are feathertop Rhodes grass (*Chloris virgata*) (FTR) and awnless barnyard grass (*Echinochloa colona*) (ABG). Both weeds have populations confirmed as resistant to glyphosate and there has recently been confirmed cases of group A (haloxyfop) resistance in FTR.

To minimise further resistance and to retain herbicide efficacy, non-chemical weed control tactics, such as growing a competitive crop, are needed. A competitive crop can suppress in-crop weeds and reduce total reliance on herbicides for weed control. There are a number of agronomic approaches that lead to increased crop competition including, narrow row spacing, increased plant density, as well as species and cultivar choice. Each of these approaches can provide an advantage to the crop over weeds in competition for water, nutrients, light and space.

In the northern cropping region, sorghum is a key summer crop. However, there are challenges in controlling summer grass weeds in this crop due to the lack of herbicide options and the wide row spacing commonly used.

Mungbean is another commonly grown summer crop, which as a broad leaf crop, provides an opportunity to apply grass selective herbicides pre- or post-plant or post-emergence for summer grass weed control. However, mungbeans are poorly competitive and like sorghum, are commonly grown in wide rows, greatly reducing competition against in-crop weeds when compared to narrower row spacings.

This paper highlights key findings from four years of research on the impact of competitive sorghum and mungbean crops on the growth and reproductive development of FTR and ABG.

Materials and methods

Field experiments, duplicated in SE Qld (Hermitage) and NW NSW (Narrabri), investigated the effects of narrow row spacing, increasing crop plant density and cultivar choice of sorghum and mungbean on competition with weeds. In each experiment, herbicides were not applied, and artificial weed populations were established either through sowing weed seeds and thinning to target population (Hermitage), or by transplanting weeds into the crop (Narrabri). Target crop and weed populations were established in fixed quadrats where crop and weed growth were measured. Three mungbean varieties Crystal⦶, Jade⦶ and Satin⦶, selected for cultivars comparison, are protected under the Plant Breeders Rights Act 1994.

Results

Sorghum

Row spacing

Over the 2018/19 summer growing season, at both Hermitage and Narrabri, sorghum cultivars Taurus, 85G33 and Rippa were grown at row spacings of 50 and 100 cm and a crop density of 10 plants/m^2. At both sites, there was a competitive advantage for sorghum grown at 50 cm row spacing. Only data from the Hermitage site are shown here, but the effect was mirrored at the Narrabri site.

Reducing row spacing from 100 to 50 cm reduced (P=0.002) the biomass of ABG plants by 55% (Figure 1A). Similarly, ABG seed production was reduced (P<0.001) at the 50 cm row spacing (Figure 1B).

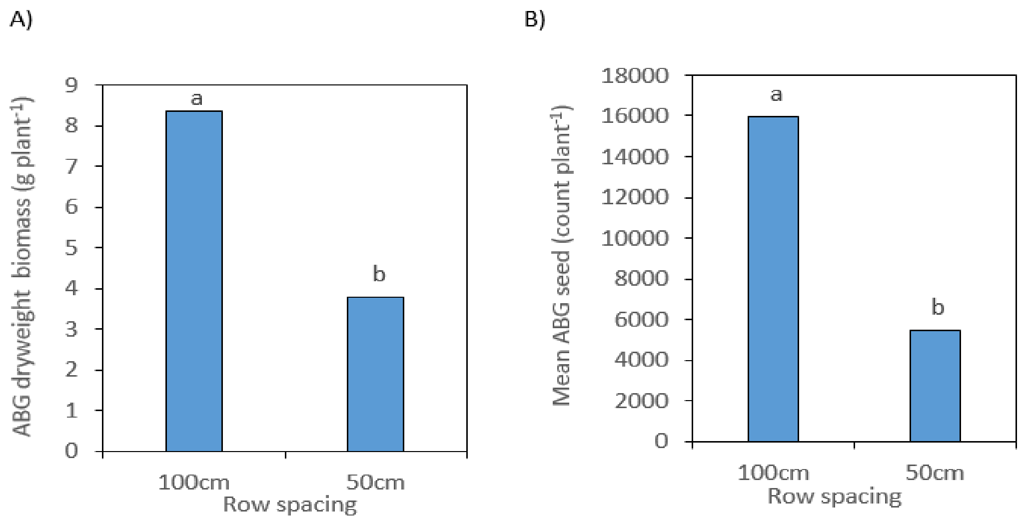

Figure 1. Awnless barnyard grass (ABG) A) biomass and B) seed production as affected by sorghum row spacing at Hermitage, Qld 2018/19. Within each graph, different letters indicate significant (*P*<0.05) difference after pairwise comparison.

Narrow row spacing in sorghum reduced FTR biomass (P<0.001) and seed production (P<0.001) (Figure 2). At the 50 cm row spacing, biomass and seed production were 48 and 56% lower, respectively.

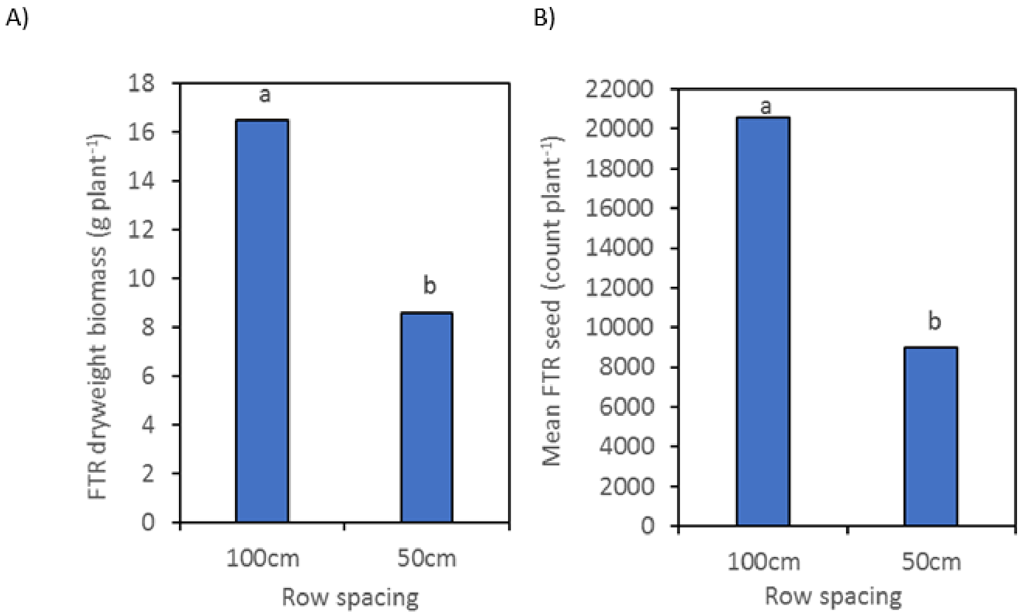

Figure 2. Feathertop Rhodes grass (FTR) A) biomass and B) seed production as affected by sorghum row spacing at Hermitage, Qld 2018/19. Within each graph, different letters indicate significant (*P*<0.05) difference.

Crop density

Increased sorghum plant density reduced the growth and seed production of both FTR and ABG. In a 2017/18 field trial at Hermitage, an increasing sorghum density significantly reduced both ABG (P=0.001) and FTR (P=0.004) seed production (Figure 3).

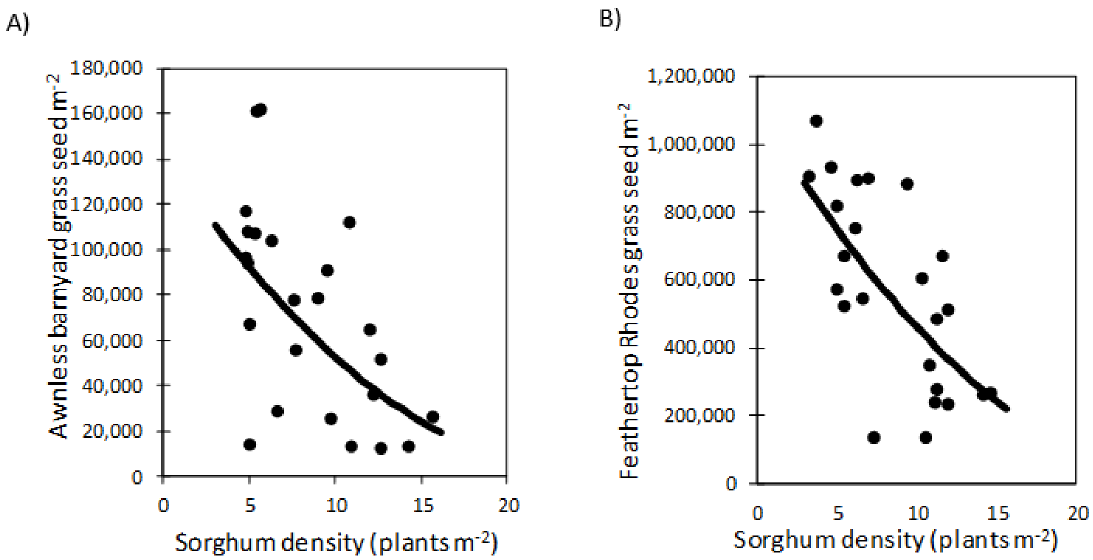

Figure 3. Relationship between sorghum plant density and seed production of A) awnless barnyard grass and B) feathertop Rhodes grass, Hermitage, Qld 2017/18.

Increasing sorghum plant density and narrower row spacing similarly reduced growth of ABG in the Narrabri trial (Figure 4). Weed biomass at a narrow row spacing of 50 cm was lower at each corresponding crop density than at a wide row spacing of 100 cm. Within each row spacing, the ABG biomass was lower at a high sorghum density (15 plants m^{-2}) compared with a low sorghum density (5 plants m^{-2}).

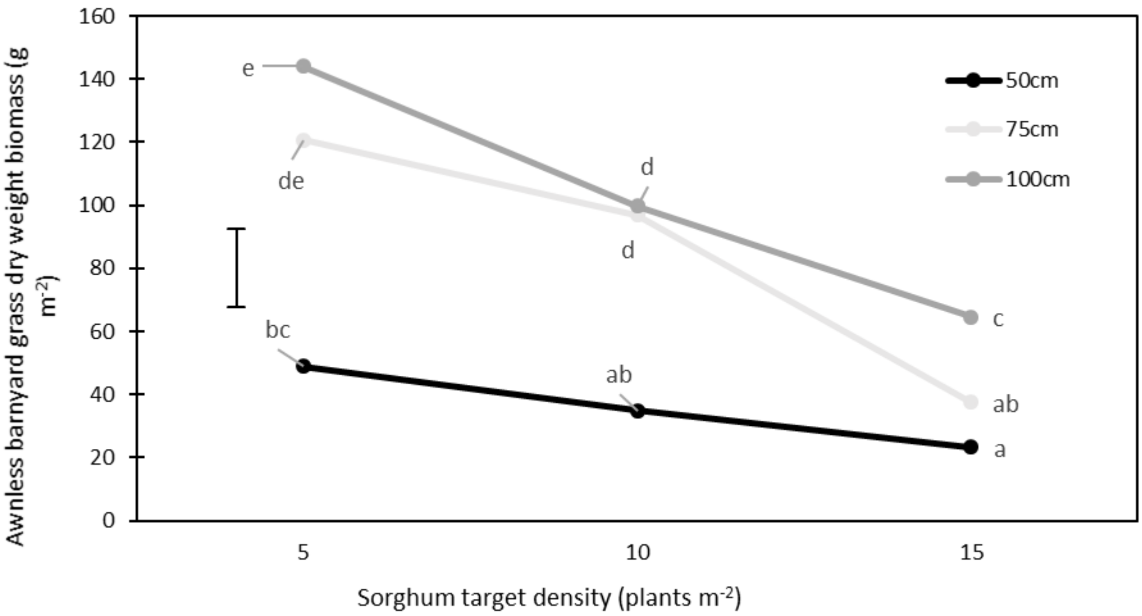

Figure 4. Effect of sorghum row spacing and crop density on awnless barnyard grass biomass. Narrabri, NSW 2017/18. Data points with a different letter are significantly different (P=0.05). LSD = 24.7.

Cultivar

At the Hermitage site, sorghum cultivar had no impact on the suppression of either FTR or ABG. In contrast, at the Narrabri site, the biomass production of ABG was significantly reduced by the Rippa cultivar (P=0.04) compared to Taurus (Figure 5). However, in this same trial, the seed production of ABG was not affected by sorghum cultivar (P=0.599).

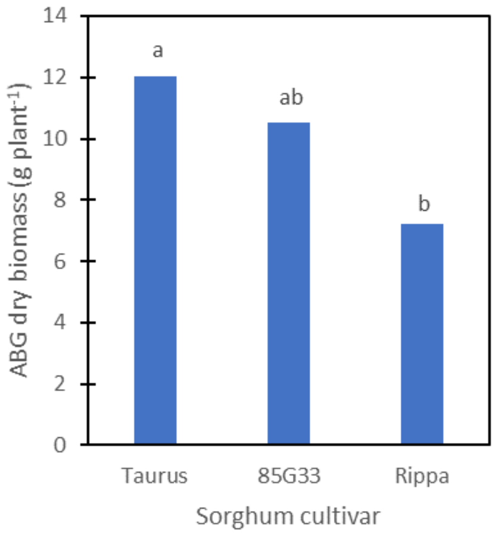

Figure 5. Awnless barnyard grass (ABG) biomass as affected by sorghum cultivar at Narrabri, NSW 2018/19. Different letters indicate significant (*P*<0.05) difference after pairwise comparison.

Crop yield

In most of the field trials, sorghum grown at narrower row spacing or higher crop density had no impact on crop yield. This demonstrates that, the use of agronomic practices of narrower row spacings and increased crop plant densities that increased sorghum competition effects on weeds, did not reduce yields. In fact, in one of the Narrabri field trials, increased sorghum density and narrow row spacing resulted in yield increases (Figure 6). At both sites, there were no differences in yield between cultivars.

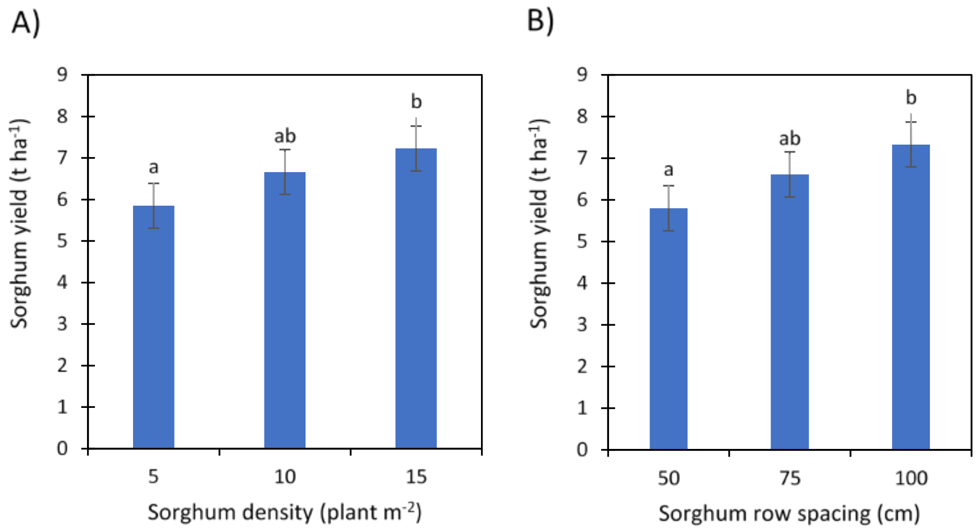

Figure 6. Effect of A) sorghum density and B) sorghum row spacing on sorghum grain yield, Narrabri, NSW 2017/18. Data points on each graph with a different letter are significantly different at P=0.05. LSD bar is shown on both graphs = 54.

Mungbean

Row spacing

Establishing mungbean crops in narrower row spacings consistently reduced the seed production and growth of both ABG and FTR in multiple field trials over four summer seasons. Hermitage site results are presented to indicate these consistent trends.

Mungbean grown at a narrower row spacing of 25 and 50 cm reduced the number of ABG seed produced compared to a wider row spacing of 75 cm (Figure 7A). Similarly, narrow row spacing reduced FTR seed production (Figure 7B).

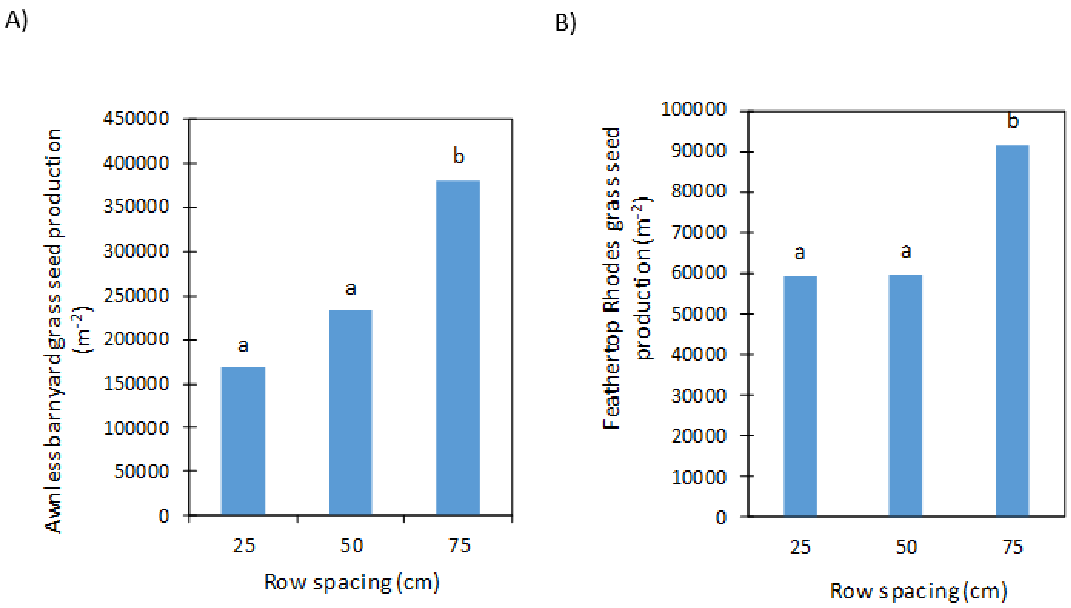

Figure 7. Effect of mungbean row spacing on A) feathertop Rhodes grass and B) awnless barnyard grass seed production, Hermitage, Qld 2016/17. Data with a different letter are significantly different (P=0.05). LSD=28,260 (A) and 125,934 (B).

Reducing row spacing from 75 to 50 and 25 cm decreased ABG biomass by 89% and 96%, respectively (Figure 8A). FTR biomass was also reduced (*P*=0.02) when row spacing was reduced from 75 to 25 cm (Figure 8B). There was no difference (P>0.05) in FTR biomass between 25 and 50 cm row spacing.

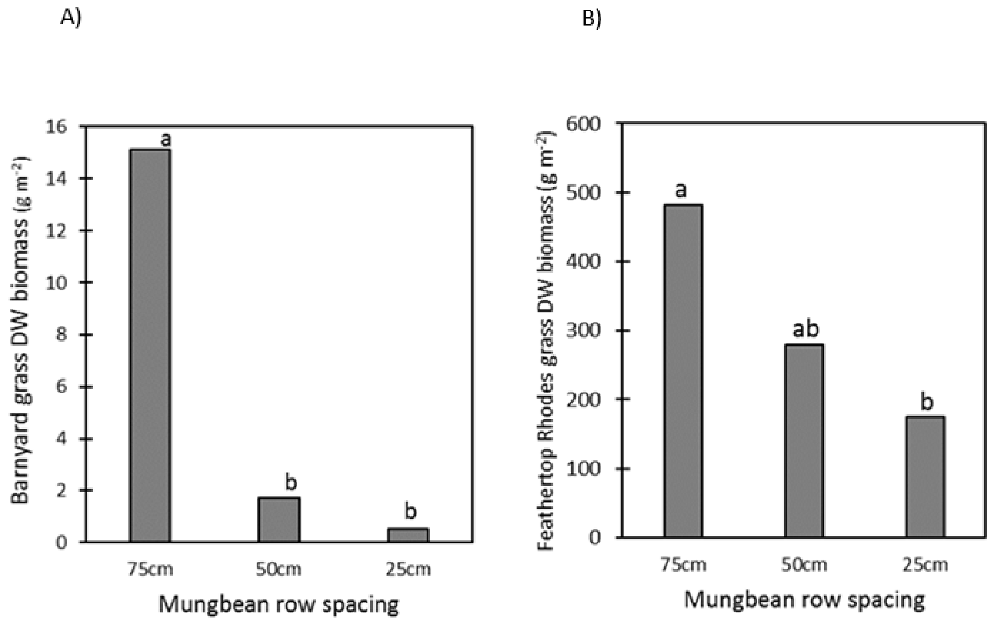

Figure 8. Effect of mungbean row spacing on the dry weight (DW) biomass of A) awnless barnyard grass and B) feathertop Rhodes grass at Hermitage, Qld 2017/18. Different letters indicate significant (*P*<0.05) difference after pairwise comparison.

Crop density

Across field sites, crop density consistently had no or little impact on the competitiveness of mungbean. Only at one Narrabri field trial was there an interaction (P=0.013) between row spacing and crop density for ABG biomass (Table 1). As row spacing widened, there was a general increase in ABG biomass at each mungbean plant density. Within each row spacing, crop density had no effect on ABG biomass, except for at 25 cm where a lower crop density of 20 plants m^{-2} had significantly greater biomass.

Table 1. Effect of mungbean row spacing and density on awnless barnyard grass dry weight biomass, Narrabri, NSW 2017/18. Back-transformed data presented with log-transformed numbers in parentheses. Numbers followed by a different letter are significantly different (P=0.05). LSD on transformed data = 0.4026.

Mungbean density (plants m^{-2})	Weed biomass (g m^{-2}) at each row spacing		
	25 cm	50 cm	75 cm
20	37.9 (3.7) b	47.8 (3.9) bc	62.4 (4.1) c
25	19.0 (3.0) a	46 (3.8) bc	64.2 (4.2) c
30	13.9 (2.7) a	33.7 (3.5) b	67.4 (4.3) c

Cultivar

The comparison of mungbean cultivars Crystal$^{(b)}$, Jade-AU$^{(b)}$ and Satin II$^{(b)}$ across a range of row spacings identified a cultivar effect at Hermitage but not at Narrabri. Unfortunately, there was poor establishment of FTR, so only results for ABG are presented here. ABG biomass was the least when grown under the cultivar Satin II$^{(b)}$ (Figure 9). While there was no difference between Crystal$^{(b)}$ and Jade-AU$^{(b)}$, the trend was for a lower ABG biomass in Jade-AU$^{(b)}$. A similar effect was shown for ABG seed production with a significantly (P<0.001) lower number of seeds plant^{-1} in Satin IIᶲ and Jade-AUᶲ, but with the least seed being produced in Satin IIᶲ (Figure 9).

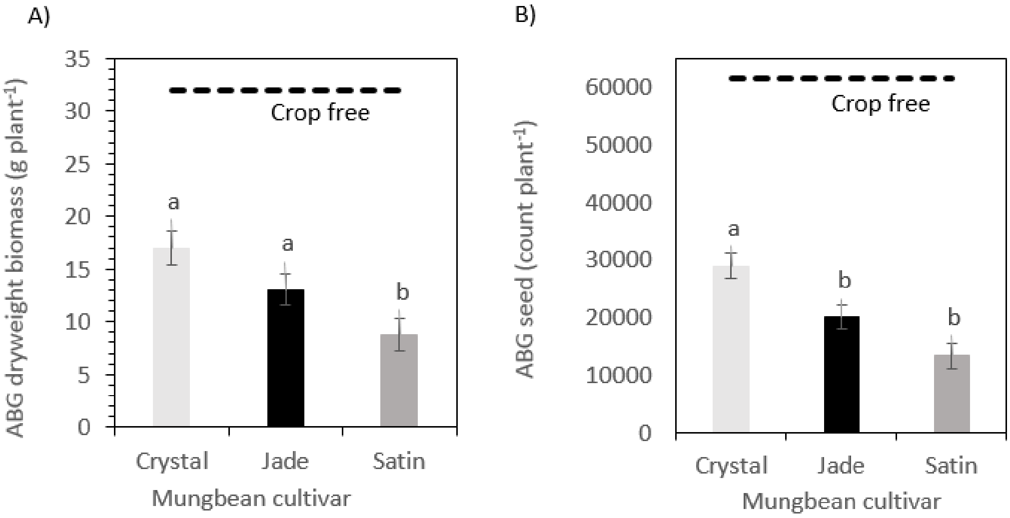

Figure 9. Awnless barnyard grass (ABG) A) biomass and B) seed count as affected by different mungbean cultivars at Hermitage, Qld 2018/19. Standard error bars are shown. Different letters indicate significant (*P*<0.05) difference after pairwise comparison. LSD = 4.1 (A) and 6934 (B). Crop free indicates mean ABG biomass and seed production in fallow plots.

Throughout the field trial, crop canopy cover (%) was assessed by analysing overhead crop photos. This enabled a comparison of potential shading effects of the mungbean cultivars (Figure 10). From 38 days after emergence (DAE) and until the final assessment at 72 DAE, Satin IIᶲ had the greatest canopy cover (P<0.001). While the canopy cover of Crystalᶲ and Jade-AUᶲ was not different at most sampling times, except for 51 DAE, where the canopy cover provided by Jade-AUᶲ was greater. These results help to explain why under Satin IIᶲ there was less ABG biomass and seed production.

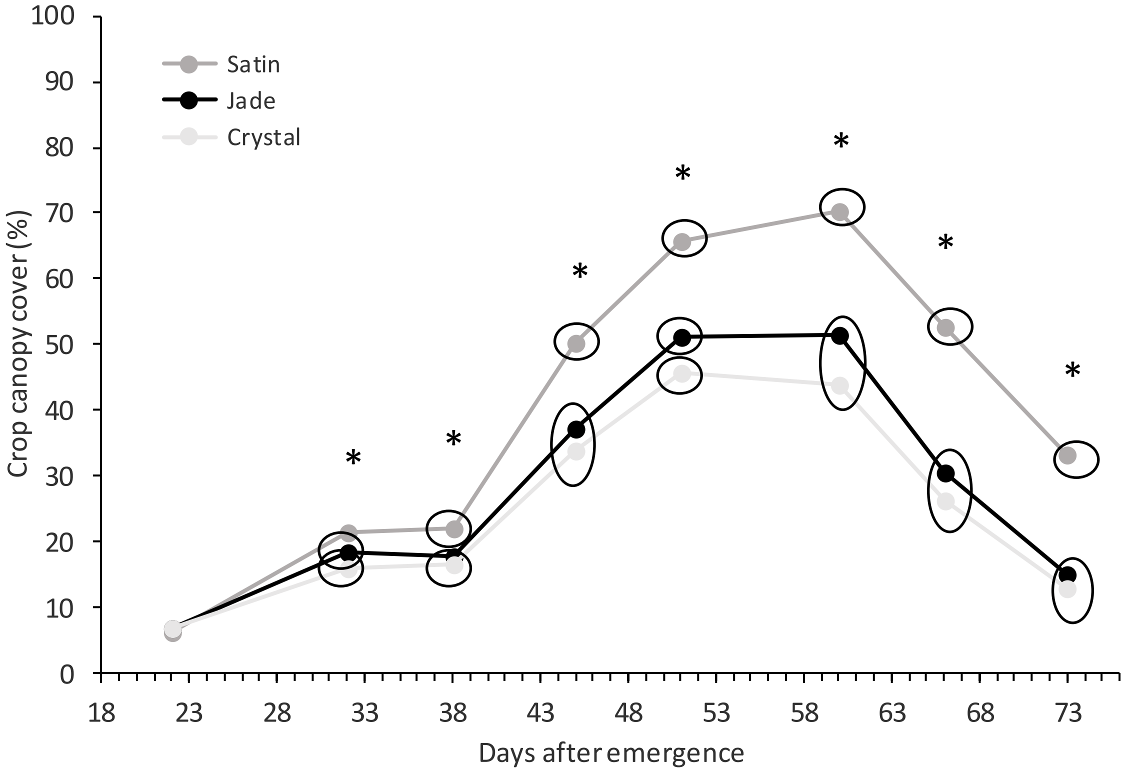

Figure 10. Canopy cover (%) over time of mungbean cultivars at Hermitage, Qld 2018/19. At each time of assessment, * denotes a significant difference. Points within an assessment time that are circled together are not significantly different. Overall LSD = 6.008.

Crop yield

There was not a consistent trend for mungbean yield in response to either row spacing or cultivar. However, across trials, mungbean yield was not affected by crop density. Differences in crop yield results are likely to be a seasonal response.

At one Hermitage trial, a higher yield was measured in plots of 25 cm rows (1.8 t ha^{-1}) compared to 50 cm rows (1.5 t ha^{-1}) or 75 cm rows (1.4 t ha^{-1}) (Figure 11). At the same Hermitage site, Satin II⊕, which was the most competitive cultivar, was also the highest (P<0.001) yielding cultivar (Figure 12). Crystal⊕, which was the least competitive, also had the lowest yield.

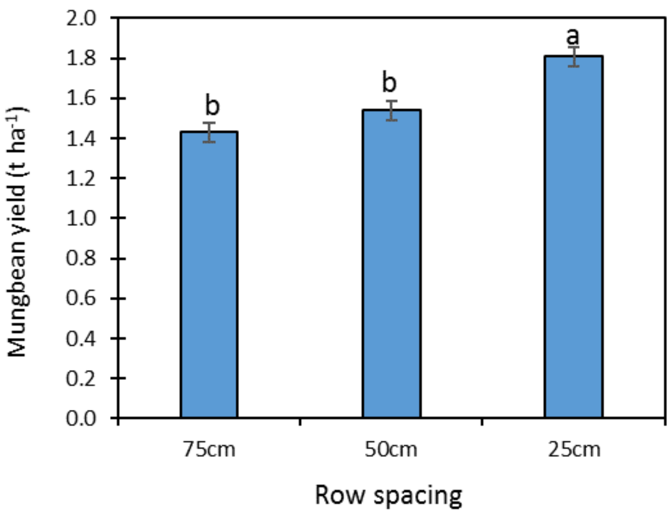

Figure 11. Effect of mungbean row spacing on crop yield at Hermitage, Qld 2017/18. Different letters indicate significant (P<0.05) difference after pairwise comparison for that graph. LSD = 0.1492. Standard error bars are shown.

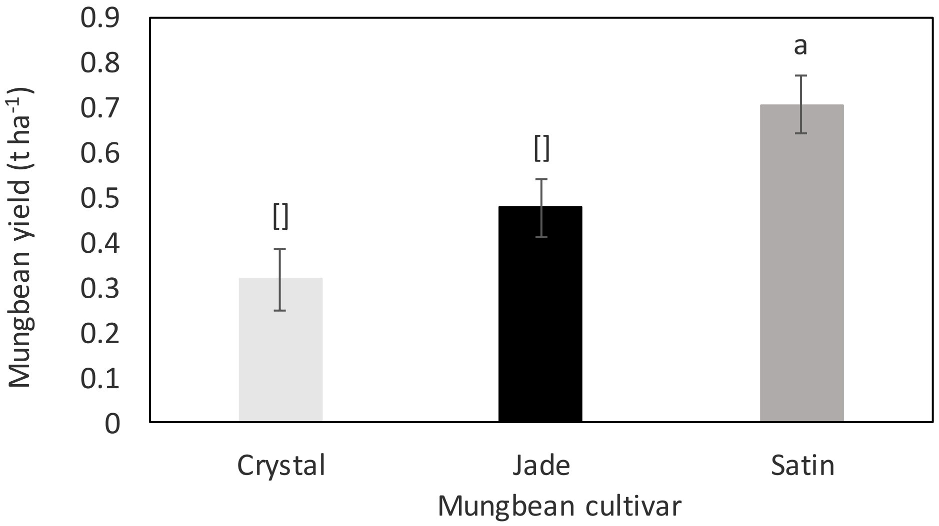

Figure 12. Yield of different mungbean cultivars at Hermitage, Qld 2018/19. Standard error bars are shown. Different letters indicate significant (*P*<0.05) difference after pairwise comparison. LSD = 0.124.

Conclusion

Our research shows there are weed control benefits in growing competitive sorghum and mungbean crops. Although some of the findings have differed between trials and seasons, results show narrow row spacing can improve competitiveness for both crops and is the approach that will likely have the largest and most consistent impact on weed growth and seed production. Increasing sorghum plant density also consistently increased the competitive effects of this crop against these weeds, whereas mungbean density had less impact. Cultivar choice may have an impact in both crops but is likely to be dependent upon seasonal conditions. Favourably, our results show that growing a competitive crop not only reduces weed competition and seed set but can improve or maintain crop yield.

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Pros and cons of an integrated weed management farming system - findings from the central Qld farming systems trial

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Key words

IWM, Integrated Weed Management, farming systems, nutrition, WUE, GM/mm

GRDC code

DAQ00192

Take home message

- Integrated weed management has performed better than the *Baseline* system across most of the indices measured as part of the farming systems trial
- Additional biomass production has not correlated with additional yield, relative to other systems using the same crop rotation
- The improved performance has come at a nutritional cost which will need to be managed if implemented on a broader scale.

Introduction

Growers face challenges from declining soil fertility, increasing herbicide resistance, and increasing soil-borne pathogens in their farming systems. Changes will be needed to meet these challenges and to maintain the productivity and profitability of our farming systems.

The Queensland Department of Agriculture and Fisheries (QDAF), CSIRO and the New South Wales Department of Primary Industries (NSW DPI) are collaborating to conduct an extensive field-based farming systems research program. This program focuses on developing farming systems to better use the available rainfall to increase productivity and profitability.

The northern farming systems project is investigating how modifications to farming systems affect the performance of the cropping system as a whole over multiple crops in the sequence. This involves assessing aspects of these systems including water use efficiency, nutrient balance and nutrient use efficiency, changes in pathogen and weed populations and changes in soil health.

System rules and protocols were developed around agronomic practices (i.e. rows spacing, plant population), crop types and rotations, crop frequency, planting time/windows, tillage practices, fertiliser rates and planting moisture triggers to preserve the integrity of each of the six systems in place at Emerald. Crops for all systems, excluding the integrated weed management (IWM) system, were managed under a no-till, controlled traffic planting with full stubble retention. Narrow row crops (≤ 50cm) are typically sown with a double-disc opener and wide-row crops were sown with a tyned precision planter.

1. **Baseline**
   A conservative zero tillage system targeting one crop/year. Crops are limited to wheat, chickpea and sorghum, with nitrogen rates for cereals targeting median seasonal yield potential for the measured Plant Available Water (PAW) at planting. Aligned with the Baseline system at the Pampas core site.
2. **Higher crop intensity**

Focused on increasing the cropping intensity to 1.5 crops/year when water allows. Crops include wheat, chickpea, sorghum, mungbean and forage crops/legumes, with nitrogen rates on cereals targeting median seasonal yield potential. Aligned with the Higher crop intensity system at the Pampas core site.

3. **Higher legume**
   The frequency of pulses in the Baseline system is increased (i.e. one pulse crop every two years) to assess the impact of more legumes on profitability, soil fertility, disease and weeds. Nitrogen rates on cereals targeting median seasonal yield potential. Aligned with the Higher legume system at the Pampas core site.
4. **Higher nutrient supply**
   Nitrogen and phosphorus rates of the Baseline system are increased targeting 90% of yield potential based on soil moisture in an environment of variable climate. The crops and other practices are the same as the Baseline system. Aligned with the Higher nutrient system at the Pampas core site.
5. **Higher soil fertility**
   Based on the Higher nutrient supply system an additional 60t/ha of manure (wet weight) was applied to change the starting soil fertility level. This system is designed to see if higher initial soil fertility can be maintained with greater nutrient inputs. Aligned with the Higher fertility system at the Pampas core site.
6. **Integrated weed management (IWM)**
   This minimum tillage system is focused on one crop/year but can employ a wide range of practices to reduce the reliance on traditional knockdown herbicides in Central Queensland (CQ) farming systems. The IWM system used a narrow row spacing of 25cm and a wider row spacing of 50cm for crops such as sorghum. Target plant populations are also lifted by 50% to also increase competition (60,000 plants/ha instead of 40,000/ha). Crops include wheat, chickpea, sorghum and mungbean, with nitrogen rates on cereals targeting median seasonal yield potential.

Water balance and dynamics

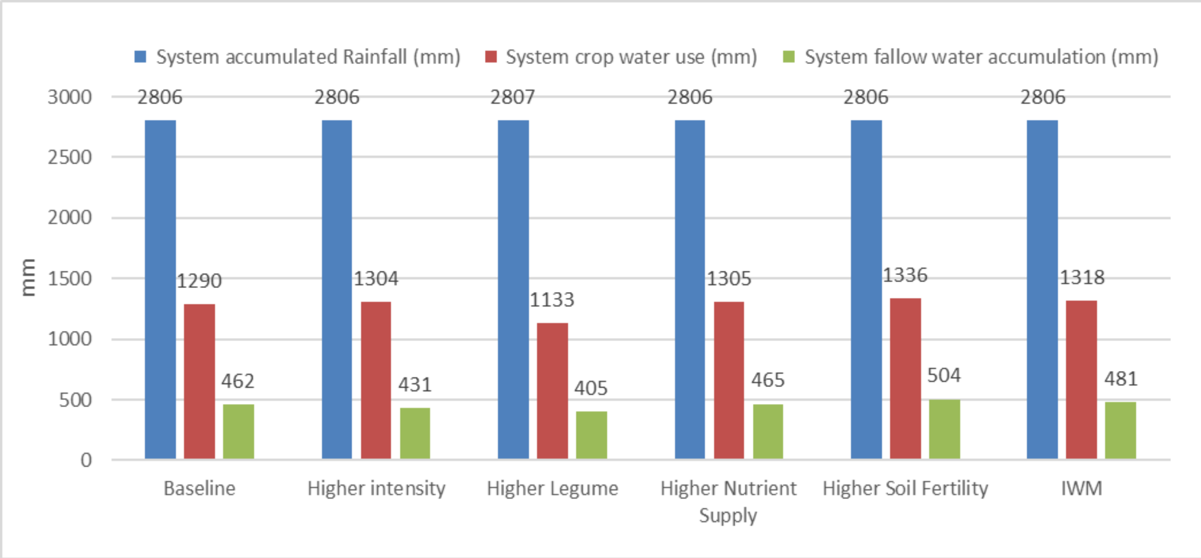

Figure 1. Comparison of systems water use and fallow water accumulation over the duration of the trial. Blue bars indicate total rainfall since planting in 2015, red bars indicate calculated total water used by each of the systems and the green bars indicate total fallow water accumulated over the duration of the trial.

Of the total rainfall received to date on the Emerald site, only a quarter of it has fallen in crop. The efficiency of how different systems converted the fallow rainfall into plant available water varied by an accumulated value of 88mm PAW over the past five years between the *Higher fertility* system (504mm PAW) and the *Higher legume* system (405mm PAW) (Figure 1).

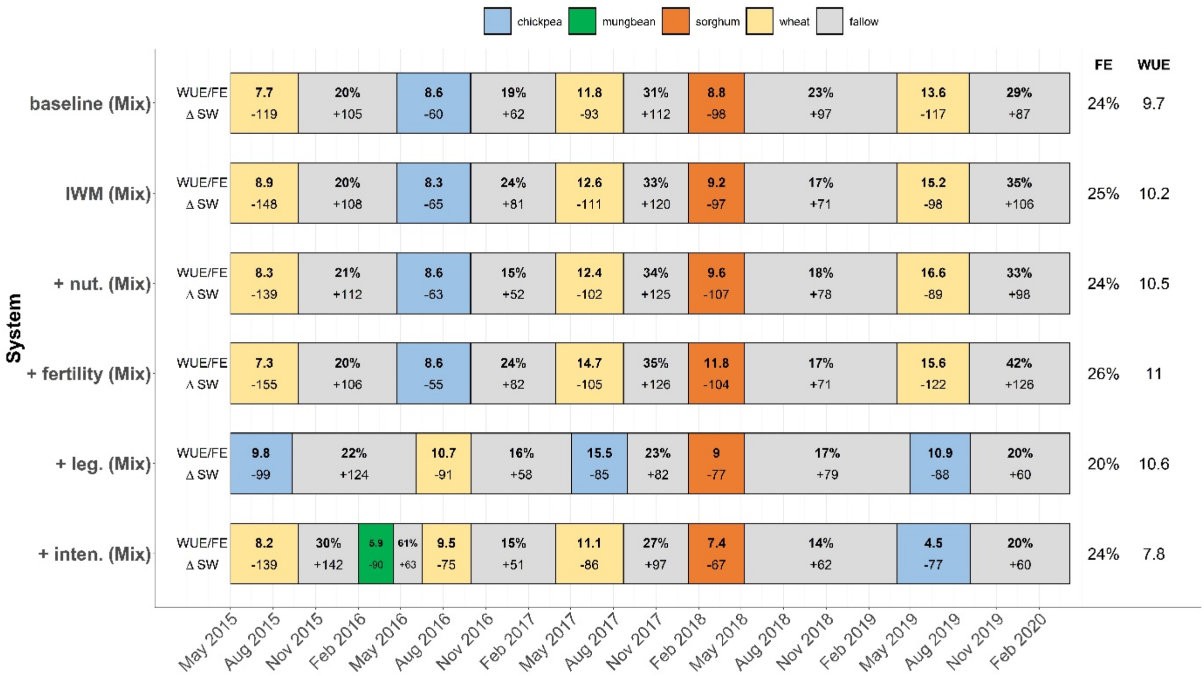

Figure 2. All six-systems crop rotation, grain WUE, Fallow Efficiency (FE %) and soil PAW fluctuations (+/- mm) measured at planting or harvest over the life of the trial to date. To the right of the graph are system FE and WUE figures to date.

Rainfall Use Efficiency (RUE), $/mm rain received, is the ultimate indicator of how efficiently a system is converting rainfall to income. However, this is calculated based on two other key measures of water capture and use efficiency, these being; fallow efficiency (FE %): how much fallow rainfall a system is able to capture over a growing period; and water use efficiency (WUE) (kg/ha/mm): a calculation that determines how much grain (kg) is produced per hectare relative to available water during the growing season.

FE % is calculated by dividing fallow rainfall by the change in PAW between harvest of the last crop and planting of the next crop. A value of 20 – 25% for a zero-till system on cracking vertosol soils is a rule of thumb figure for capture of fallow rainfall. As of planting in 2019, all systems were sitting close to or in this range (Figure 2). *Higher legume* has the lowest FE % of all the systems at 20%, while the *Higher fertility* system has the highest on 26%. The *IWM* systems has averaged 25% over the same period, which was 1% better than the two other systems using the same cropping rotation.

Crop WUE (kg/mm) provides an insight into how efficiently each individual crop is converting available water into grain and/or biomass. The WUE (kg/ha) calculation is:

$$\text{WUE (kg/ha)} = \frac{\textit{All grain (or plant material) prodcued}}{\textit{Total water used}}$$

The calculation for the water used figure is (PAW @ planting – PAW @ harvest) + any rainfall (or irrigation) which was applied between planting and harvest.

To winter planting 2020, Crop (grain) WUE saw the *Higher fertility* system ahead of all other systems, with an efficiency value of 11.3 kg/mm, a 1.3 kg/mm improvement over the *Baseline* system. The *IWM* system sits middle of the pack at 10.5 kg/mm, still a 0.5 kg improvement over the *Baseline* system for only the addition of extra seed and narrower row spacing.

Table 1. System water dynamics indices from 2015 to winter plant 2020.

System	*Rainfall (mm)*	*System crop water used (mm)*	*System rainfall usage efficiency*	*WUE grain (kg/mm/ha)*	*WUE biomass (kg/mm/ha)*	*Grain produced per Ha (kg/ha)*	*Biomass produced per Ha (kg/ha)*	*Difference grain/ha produced (kg/ha)*	*Difference biomass/ha produced (kg/ha)*
Baseline	2806	1290	46 %	10.0	31	12911	39573	0	0
Integrated weed management	2806	1318	47 %	10.5	35	13780	45715	869	6142
Higher nutrient Supply	2806	1305	46.5 %	10.7	31	13947	40567	1036	994
Higher fertility	2806	1336	47.6 %	11.3	33	15125	44087	2213	4514

The table above shows the crop water use efficiency data for the four systems which have maintained the same cropping rotation since the start of the trial. This has meant the same planting date and the same harvest date. As such, the fallow and in-crop rainfall are the same for all four systems.

Despite the background treatment differences in all four systems listed in Table 1, the spread of system rainfall usage efficiency across the period have been relatively minimal with a spread of only 1.6%. However, total grain and plant material (biomass) produced show clear differences in system performances over the past five years.

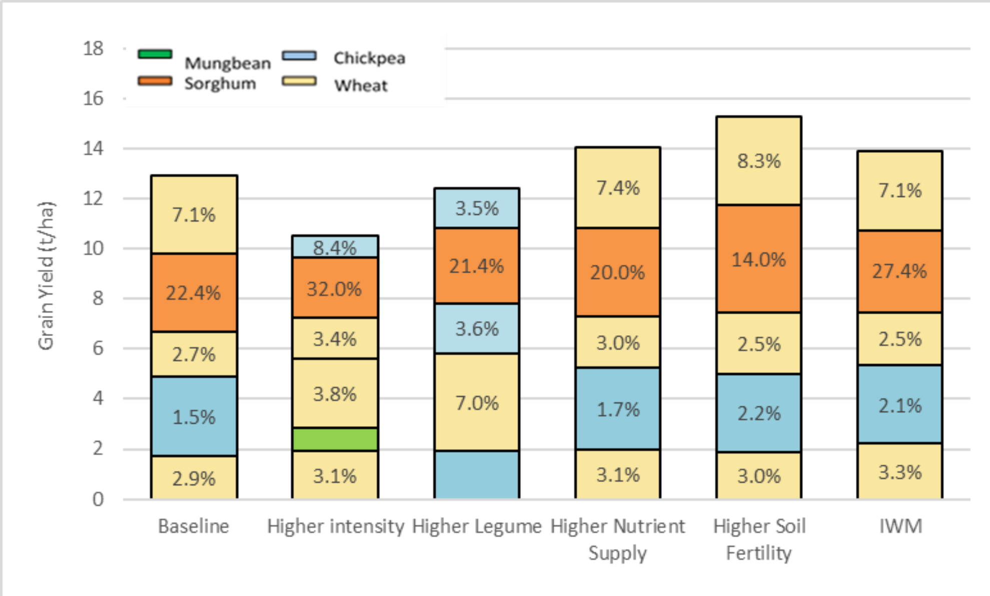

Figure 3. Cumulative crop yields over the past 5 years and associated grain screenings for each of those crops

Typically, there is a strong correlation between biomass production and final grain yield. However, this has not been the case for these Emerald systems. The *IWM* system has produced the most biomass per hectare over the life of the trial to date. However, both *Higher fertility* and *Higher nutrient supply* have produced more grain (Table 1). The *Higher fertility* system also captured more water in the fallow (503mm) than the IWM system (481mm). The *Higher nutrient supply* system only 16mm lower at 465mm over five.

Despite the higher cumulative biomass produced by the *IWM* system, grain screenings have stayed on par with the other three systems using the same cropping rotation; the only exception being the 2018 sorghum crop that crop saw screenings rise to 27% compared to the 22.4%, 20 % and 14% of the other three systems (Figure 3). However, yield was still similar to *Baseline* and *Higher nutrient supply*.

A 2,000 ha cropping operation in CQ with an average rainfall of 560mm running a *Baseline* system over a five-year period would have produced 25,800 tonnes of grain. In comparison, using the *IWM* system would have produced 27,500 tonnes of grain (7% improvement over baseline), the *Higher nutrient supply* system would have produced 27,900 tonnes (8% improvement over baseline) and the *Higher fertility* system would have produced 30,250 tonnes (17% improvement over baseline), all for the same amount of water available.

System profitability performance

The *Higher fertility* system (at $1.14/mm/ha) has been 6.5% more profitable than the second-best system, *Higher legume* (at $1.07/mm/ha) over the past five years (Table 2). The *IWM* system (at $1.05/mm/ha) is sitting in the middle of the pack, similar to *Higher nutrient supply* and *Higher legume* from an economic standpoint.

Its performance has exceeded the *Baseline* system (at $0.93/mm/ha) without the cash boost from higher value legume crops, or the extra boost from nitrogen (N) and phosphorus (P) application for potentially higher yield. However, it is reasonable to question how long this treatment will be able to stick with these two other systems as fertility begins to run down.

Table 2. Summary table of operating revenue and expenditure of the six systems over the life of the trial to December 2019. Table also shows the accumulated gross margin (GM), system return on variable costs (ROVC) and what our GM/mm of rainfall over the duration of trial.

System	*System income ($/ha)*	*System fallow costs ($/ha)*	*System variable costs ($/ha)*	*System gross margin ($/ha)*	*System return on variable costs ($/ha)*	*System WUE GM ($/mm)*
Baseline	$4,061	$484	$1,012	$2,392	$4.01	$0.93
Higher intensity	$2,842	$474	$1,238	$1,343	$2.30	$0.52
Higher legume	$4,485	$484	$1,031	$2,733	$4.35	$1.07
Higher nutrient supply	$4,371	$484	$1,055	$2,659	$4.14	$1.03
Higher soil fertility	$4,635	$484	$1,048	$2,954	$4.42	$1.14
IWM	**$4,309**	**$484**	**$932**	**$2,722**	**$4.62**	**$1.05**

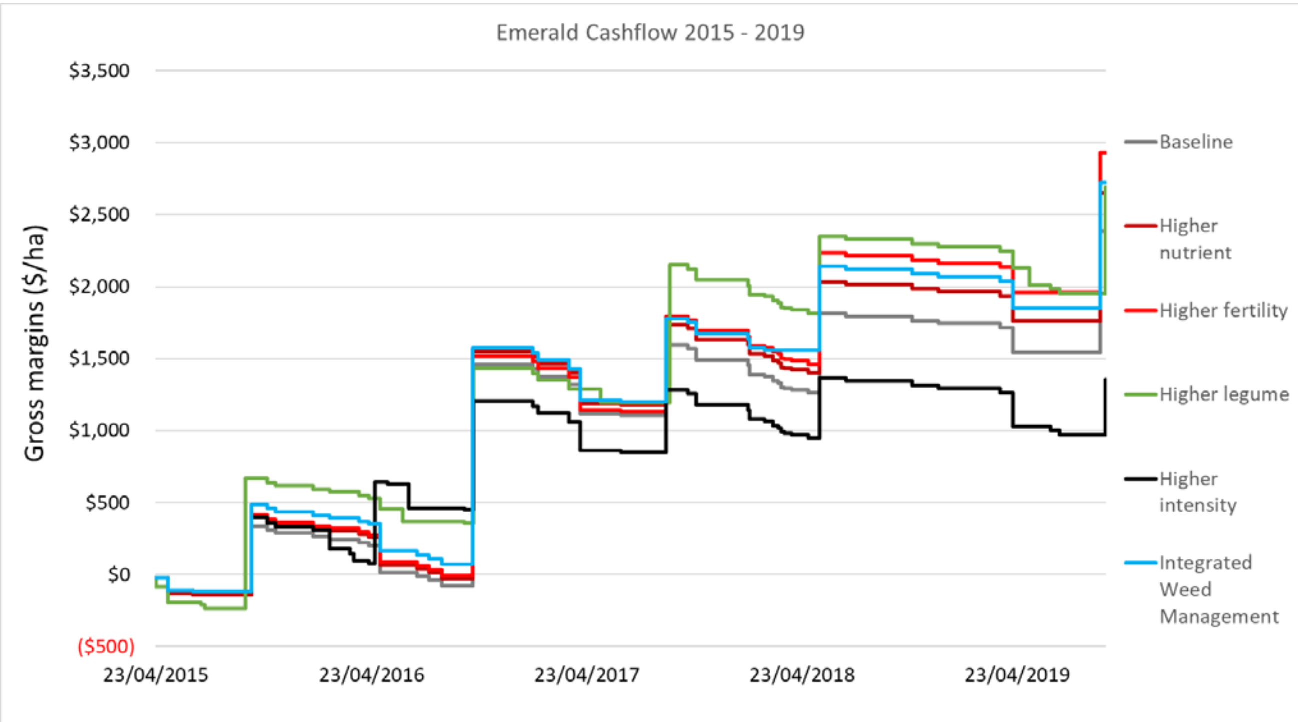

Figure 4. Systems' cash flow - 2015 to harvest 2019 for all six systems. All systems have been profitable to date; however, since the winter crop of 2016, the Higher intensity system has struggled to improve.

The gross margins ($/mm/ha) values in Table 2 can also be extrapolated to the theoretical 2,000 ha cropping enterprise in CQ with an average rainfall of 560mm over a five-year period. The expected gross margin for a *Baseline*-based farming system would be $5.2 million. The *Higher nutrient supply* system would have generated an additional $560,000 for the same amount of water. The *IWM* system would have generated $672,000 more than *Baseline* and impressively, the *Higher fertility* system would have generated an addition $1.2 million over *Baseline* for the same average rainfall in CQ over the five-year period.

Nutrient balance and dynamics

Nitrogen

Nitrogen (N) removal outstripped bagged supply for all systems as at harvest 2019 (Table 3). Of the four systems using the same rotation, *Higher fertility* shows the greatest deficit (-234kg N/ha) followed by *IWM* at (-220kg N/ha). The gap between *IWM* and *Higher nutrient supply* is significant at 45kg/ha. Total grain production from both systems over the past five years (Table 1) varied by less than 200kg, in favour of *Higher nutrient* supply. However, biomass production in the *IWM* system was significantly higher with an additional 5 t/ha produced over the period.

Table 3. System nitrogen cycle observations throughout life of the trial. Note the spike in N levels for *Higher fertility* because of the manure applied as part of the system setup.

System	*System N mineralisation in fallow*	*System Δ soil N (kg N/ha)*	*System N applied (kg/ha)*	*System N exported (kg/N)*	*System N balance (kg N/ha)*
Baseline	466	-2.0	82.8	289	-206
Higher nutrient supply ***(+nut.)***	437	24.5	133.42	308	-175
Higher soil fertility ***(+Fertility)***	690	156.1	101.2	335	-234
IWM ***(+IWM)***	463	-24.6	82.8	303	-220

Table 4. Calculation definitions for Table 3.

System N mineralisation in fallow	Calculation - Sum of **all fallow N mineralisation (kg/ha)**	What is the total amount of N mineralised in fallows over the duration of the trial?
System Δ soil N (kg N/ha)	Calculation - **N @ Baseline (t=0) (to 90cm)** - most recent **N @ Harvest/planting (to 90cm)**	What has been the change in total N from planting 2015 to today?
System N applied (kg/ha)	Calculation - Sum of all **(total) N applied (kg/ha)**	How much N has been applied in the form of bagged/liquid fertiliser?
System N exported (kg/N)	Calculation - Sum of all **grain N removed (kg)** across all years	What is the total amount of N removed in the form of grain over the life of the trial?
System N balance (kg N/ha)	Calculation - **total N applied (kg/ha)** - **nutrient exported (kg/N)**	Is the N nutrient running at a surplus or deficit based on grain removal?

A crop-by-crop N removal comparison indicates that removal by grain for both *IWM* and *Higher nutrient supply* has been very similar (Figure 6). However, the replacement N applied was significantly higher in the *Higher nutrient supply* (133kg N/ha N) than the *IWM* system (83kg N/ha) (Table 3). This difference is because of the different nutrition programs applied to the two systems as described earlier. The nitrogen rates targeting 50% yield potential for *IWM*, rather than the 90% yield potential for the *Higher nutrient supply*, led to a steady run-down of N reserves over the life of the project (Figure 5). Fallow mineralisation has assisted in keeping N application to a minimum. However, available mineral N (nitrate) is now 50kg of N/ha lower for *IWM* than the *Higher nutrient supply* (Table 3). The higher biomass production in the *IWM* system may be better suited to a higher nutrient supply in the future.

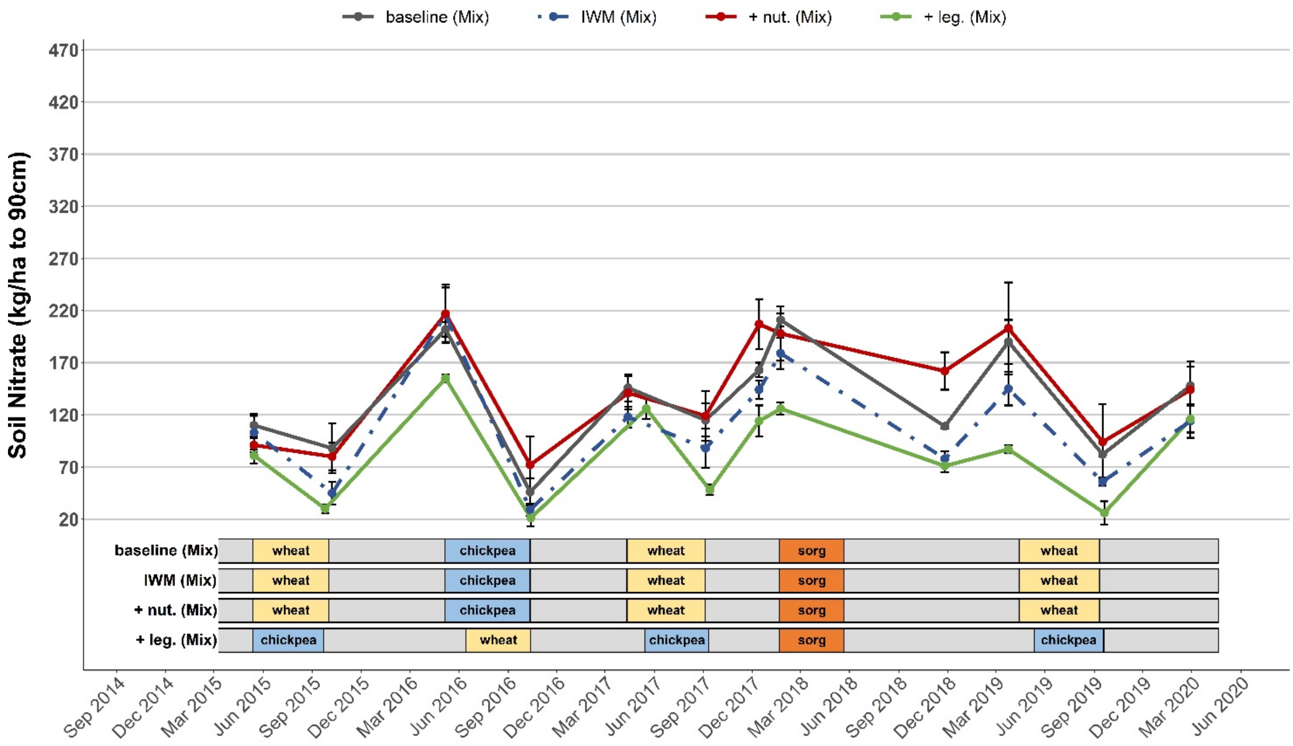

Figure 5. Soil nitrate levels for *Baseline, IWM, Higher nutrition* and *Higher legumes*. Note the difference in N levels between *Baseline, IWM* and *Higher nutrient Supply* over the life of the trial.

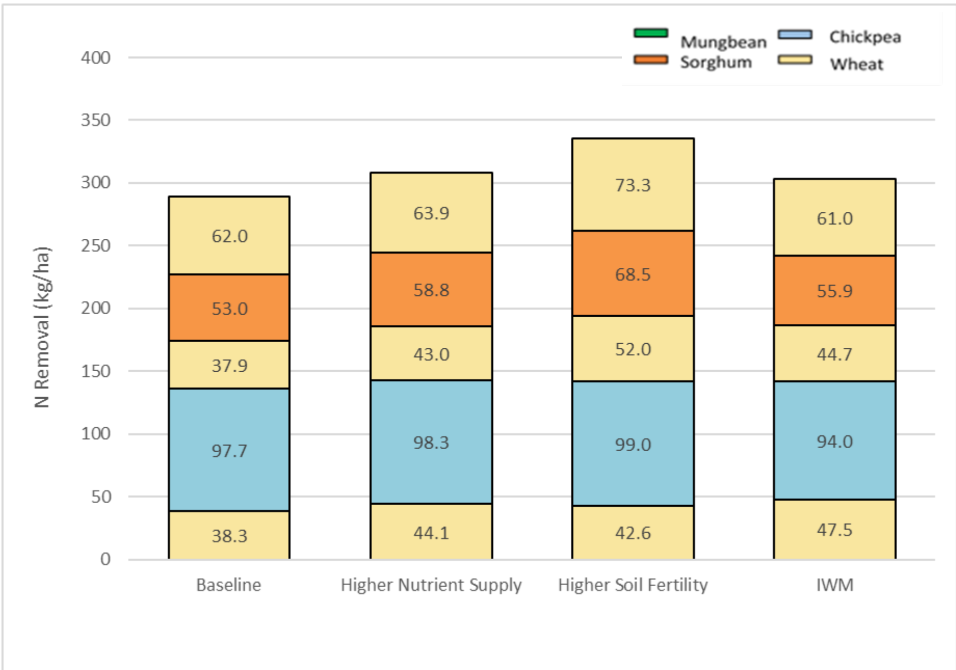

Figure 6. Crop nitrogen (N) removed based on grain analysis and crop yield - 2015 – Harvest 2019

Phosphorus and potassium

	Baseline	Higher nutrient supply	Higher soil fertility	IWM
System P applied (kg/ha)	*26.1*	*39*	*40.2*	*26.1*
System P exported (kg P/ha)	*42.5*	*46*	*53*	*44.1*
System P balance (kg P/ha)	-16.4	-7	-12.8	-18
Grain produced/kg of P removed	304	303	285	312

Table 5. System application and removal of (P) kg/ha from 2015 to harvest 2019 for the systems operating the same rotation.

Phosphorus removal in grain exceeded replacement by granular fertiliser for all systems. The average deficit across all systems was 12.8kg/ha of P with a spread across the systems of 14.5kg/ha of P. The *Higher nutrient supply* system has gone closest to keeping P usage in equilibrium over the period thanks to the higher rates applied. Interestingly, even the higher rates applied as part of the *Higher fertility system* have not kept pace with yields produced and subsequent removal. *IWM's* usage of P was slightly higher than *Baseline*, in-line with the higher yield produced. To rectify the deficit of 18kg/ha of P in the *IWM* system, an additional 82kg/ha of MAP (@ $800/t delivered Emerald) would need to be applied.

Potassium (K) usage for *IWM* again mirrored the *Higher nutrient supply* system with a total of 83kg K/ha removed. As expected, this value was slightly lower than *Higher nutrient supply* at 85kg/ha and slightly more than *Baseline* with 79kg/ha of K removed.

Organic carbon

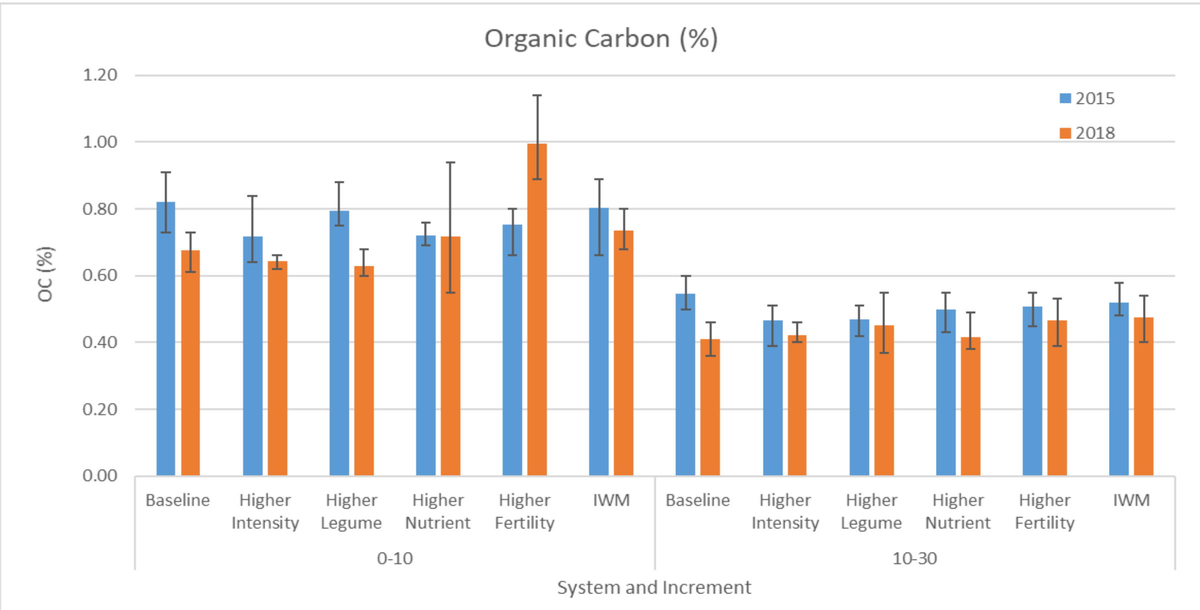

Figure 7. Observed organic carbon (%) levels at the 0-10cm increment and 10 to 30cm increments for 2015 and late 2018. Error bars indicate variation between replicates.

Only the *Higher nutrient* and *Higher fertility* systems receiving the 90th percentile nutrient applications maintained their organic carbon (OC) levels since the trial started in 2015. *Higher fertility*'s significant increase in OC % in the 0-10cm band was due to application of the 51 t/ha of manure. All systems using the 50th percentile nutrition program (*Baseline, Higher intensity, Higher legume* and *IWM* systems) saw a reduction in organic carbon % (Figure 7). While variable, OC % fell less in *IWM* than *Baseline* in the top 10cm, with lower or similar reductions to all three other comparable rotations in the 10 – 30cm range.

Weeds

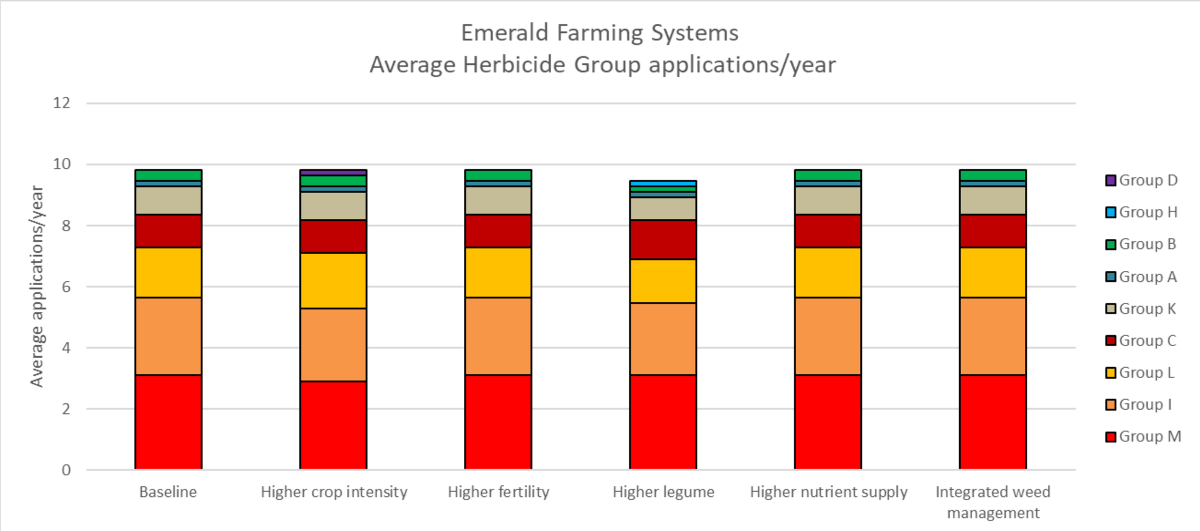

Figure 8. Average applications of herbicide chemical groups per year for each of the six systems.

Weeds are proactively managed for all systems in a timely manner at the Emerald trial site; it is not a weeds experiment, rather it is looking at the impact of IWM agronomy on the crop and system performance. Consequently, there was minimal difference in chemical applications or volumes between any of the systems. Residuals herbicides with broad crop compatibility have been used as much as possible to simplify management and not limit future cropping options.

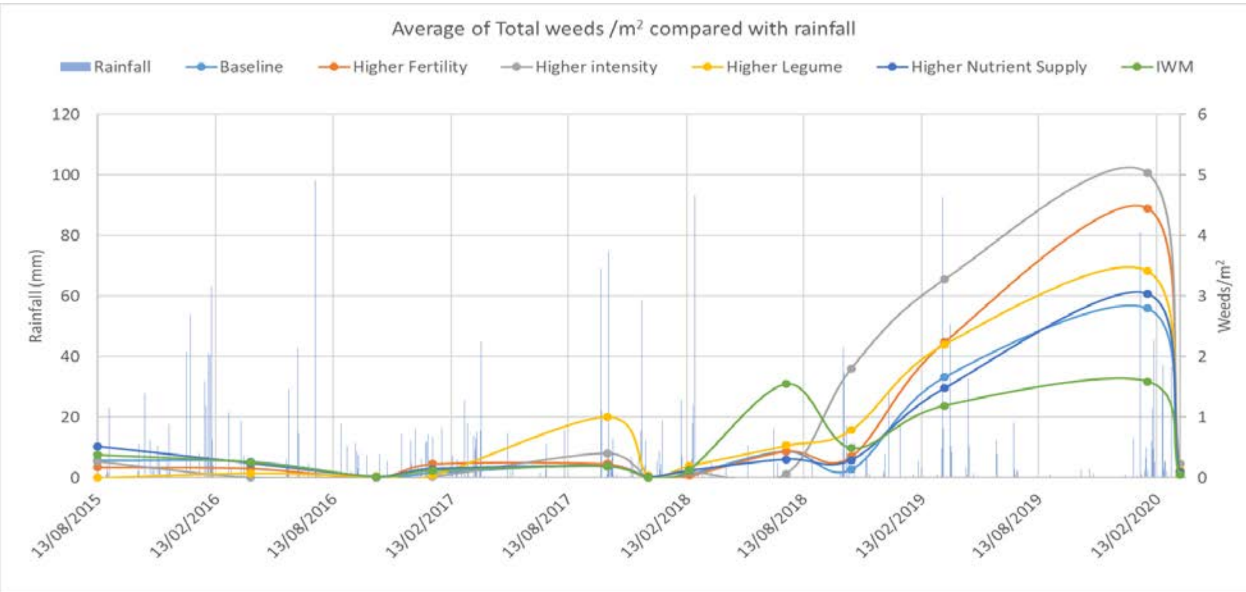

Figure 9. Daily rainfall events and total weeds/m^2 observed (broadleaf and grasses) prior to spray operations across the life of the trial to date.

However, prior to any knockdown spray event, weed counts are made, with a view to identifying any linkages between system and weed populations (Figure 9). Weed emergence did spike after the sorghum crop, possibly exacerbated by the extremely dry period in 2018-2019. While the numbers are not extreme, it is interesting to note that *Higher intensity* treatment was observed to have the highest weed count, while the *IWM* system had the lowest in early 2020. The other interesting point is that broadleaf weeds make up the majority of weeds observed on site. Feathertop Rhodes grass had only one outbreak on the site since the trial commenced, and that was directly related to the manure source, rather than any treatment effect.

Conclusion

The *IWM* system has provided insights into the cost of a system that was managed to produce additional biomass in crops to better compete with weeds. From a financial standpoint, the *IWM* system has outperformed the *Baseline* system comfortably, and just edged out the *Higher nutrient supply* system over the past five years. The fallow efficiency of *IWM* has been one of the better systems on site. However, many would have expected better in the variable seasons given the additional biomass and ground cover compared to other systems.

The financial win over the *Higher nutrient supply* system (despite producing slightly less grain) may be short lived, as the additional production over *Baseline* to match higher nutrient supply also saw an additional draw on soil fertility. For nitrogen, mineralisation has been able to fill the gap to date, but there is a clear trend of rundown (Figure 5), which at some point will start costing yield and grain quality, particularly in a better yielding crops unless the nutrient supply is increased.

Interestingly, biomass production for *IWM* has exceeded all other systems, but has not been converted into higher yields. Equally, grain quality attributes have not been significantly worse than any of the other systems, except for the sorghum crop in 2018. Why yields have not increased with biomass production needs further exploration. However, the heavy rotation to winter crop so far may have favoured crops that were better able to compensate when conditions worsened during grain fill.

Importantly, the premise of the system treatment was to assess the crop and systems performance of agronomy to manage weeds. While performance data to date are generally encouraging, there has been no significant difference in weed density. Weed densities were low and have not been exacerbated due to well-timed applications of both knockdown and residual herbicides across the life of the trial.

Finally, the *IWM* system has potential upsides to the *Baseline* system, but crop nutrition will need to be adjusted to achieve this full potential. Many trials across the northern grains region have shown that summer and winter crops can benefit from higher established populations in better seasons. However, we have not seen a downside from quality when crops have a tough finish either, at least for the winter crops in this trial.

Acknowledgements

An exceptional amount of data has been collected, recorded and analysed as part of this project not only for the Emerald site, but all seven sites across Queensland and Northern NSW. The co-ordination of these activities has occurred in collaboration between CSIRO as the lead for the Pampas core site, DAF QLD as the lead for the six regional sites across QLD and NSW and NSWDPI for maintaining a consistent protocol and design for the NSW based sites.

Locally I would like to acknowledge the local growers and consultants who have given up there time to assist in the development of the six systems in place at the Emerald site and again to review and provide feedback about the trials operation and management over the past 6 years.

I would also like to acknowledge the DAF regional research agronomy technical staff based in Emerald, led by Ellie McCosker and assisted by Jane Auer, who have diligently and efficiently done all and more that has been asked of them in amassing the significant dataset that has now been collated over the past six years.

Finally, I would like to acknowledge GRDC as co-funder, with DAF QLD of the Emerald site.

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Future farming: Machine vision for nitrogen assessment in grain crops

Alison McCarthy and Craig Baillie, University of Southern Queensland

Key words

real-time sensing, machine learning, simulation, APSIM, barley, pilot study

GRDC code

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Take home message

- A pilot simulation and field study demonstrated potential for machine vision to estimate in-season soil and leaf nitrogen status using cameras and image analysis for real-time sensing and control
- The modelled soil and leaf nitrogen were estimated with >80% accuracy using machine vision-detectable crop features estimated in combination with known underlying soil variability
- Further trials will evaluate and refine the machine vision system at the Future Farm core sites.

Aim

This aim of this research was to identify how machine vision could complement and be incorporated with soil sampling and other sensing technologies in a more automated nitrogen sensing system.

Introduction

Nitrogen management is vital to maximise agricultural crop yields. Nitrogen requirements can vary spatially over fields because of different soil properties and crop conditions. Nitrogen status is typically assessed using soil testing, grain protein levels and paddock history and applied prior to sowing. This pre-season nitrogen application sets approximately 80% of the average yield outcome. In-season top-up nitrogen is typically applied in high rainfall zones and irrigated crops which contribute to the remainder of the average yield outcome. In-season nitrogen status can be agronomically assessed from tiller counts, stand appearance and plant structure in some southern grains systems (Miller and Schober 2018; Voight 2019). Infield sampling may not be practical for timely in-season nitrogen management decisions and collection of tiller and density counts is typically labour-intensive.

Automated systems have been developed using reflectance sensing to increase the spatial and temporal resolution of assessments. Reflectance sensors (e.g. Crop Circle™) that measure vegetation indices from spectral reflectance and cameras that assess colour have been used for crop vigour assessments to estimate nitrogen content (Li et al. 2010; Porter 2010; Wang et al. 2014 and dos Santos et al. 2016). The measured reflectance of the crop can be compared with that of N-minus and N-rich strips to estimate nitrogen content with a linear regression and machine learning. For example, a type of machine learning, 'support vector machine', has been used to quantify nitrogen status from hyperspectral data (Chlingaryan et al. 2018). Support vector machines analyse data for classification and regression analysis and is particularly suited to high-dimensional data as it reduces overfitting. However, reflectance sensing (e.g. NDVI) has inconsistent correlations to nitrogen status across different stages and seasons (Poole and White 2008; Poole and Craig 2010).

Simulation modelling can also be used to automated nitrogen status estimation (Lawes et al. 2019) using the APSIM crop model). This involves linking available online weather, soil information and satellite imagery, with iterative simulations to estimate daily soil and leaf nitrogen requirements. This requires a high level of computing capacity and skill, which is not currently feasible in all regions and commercial cropping situations.

An alternative approach uses existing machine vision systems to compare agronomic crop features in N-minus and N-rich strip trials, providing a rapid, on-the-go machine vision nitrogen sensor. Machine vision systems have been developed for tiller counting by extracting individual leaves using colour thresholding and line detection (Boyle et al. 2015; Wu et al. 2019); and for plant density detection using colour thresholding and machine learning (Jin et al. 2017; Liu et al. 2017). Deep learning machine vision algorithms have also been used in agricultural image segmentation to detect crop flowering and fruiting structures in orchards (Chen et al. 2018; Kamilaris and Prenafeta-Boldú 2018; Koirala et al. 2020). Muñoz-Huerta et al. (2013) identified that more research is required for use of machine vision to determine crop nitrogen status, particularly to reduce the sunlight dependence on machine vision system performance. Fieldwork and simulation analysis have been conducted to identify how machine vision could complement and be incorporated with other sensing technologies in an automated nitrogen sensing system.

Method

Field site and data collection

Fieldwork was conducted to collect a dataset of replicated machine vision data from different cameras and plots, and APSIM simulations were conducted to estimate soil and leaf nitrogen status throughout the season for comparison. Barley was planted over a 0.4 ha area in USQ's agricultural plot on 9 August 2018 and harvested on 10 December 2018. Nitrogen was applied uniformly over the crop at planting and irrigation was applied on 9 August (30mm), 6 September (15mm) and 29 September (30mm). Soil moisture, plant height, canopy width and tiller counts were collected weekly between August and December 2018 for the barley trial in nine locations in a grid. Weekly soil nitrate-N, ammonium-N and leaf nitrogen were modelled using APSIM on the days of the plant measurements. APSIM was parameterised using the management information, soil characterisation samples (Hussein 2018), infield automatic weather station and soil nitrate-N and ammonium-N samples collected at harvest.

The machine vision systems compared were: (i) infield fixed cameras capturing oblique images every 3 hours; (ii) UAVs capturing oblique images in the visible waveband weekly; and (iii) multi-spectral Parrot Sequoia camera capturing top view images weekly. The multi-spectral imagery was used to collect spectral reflectance and estimate NDVI (normalized difference vegetation index) and NDRE (normalized difference red edge).

Comparing performance of nitrogen status algorithms

The literature review identified algorithms with potential to automatically determine nitrogen requirement from plant measurements in commercial fields which could be compared with different data inputs to identify which measurements to use: crop features (e.g. crop height, width, tiller counts), spectral reflectance (NDVI, NDRE, greenness) and soil water status (soil water content, drained upper limit). The nitrogen status algorithms evaluated are described below:

- Linear regression algorithm between all individual sensed measurements and N status
- Linear scaling algorithm which is a regression algorithm between sensed measurements in N-minus and N-rich plots in each management zone and sensed measurements in other zones with similar properties (e.g. soil water status, drained upper limit, sowing density) to

estimate nitrogen status with a linear scaling algorithm. The linear scaling algorithm is an extension of the linear regression approach which compared spectral reflectance/soil water status/crop features in all the plots and did not consider underlying variability which may have caused errors in the nitrogen estimation. In contrast, the linear scaling algorithm estimates nitrogen status in the crop considering the underlying variability in soil and crop properties. This is achieved by comparing the spectral reflectance/soil water status/crop features in the crop with crops in the N-minus and N-rich plots with the most similar measured soil water, estimated drained upper limit and measured sowing density.

- Machine learning algorithms linking single or multiple data streams using most influential data inputs for nitrogen. The influence of each data type was compared using a random forest classifier, while eight types of machine learning that were trained using the collected data were compared in Spyder®: logistic regression, support vector machines, random forest classifier, extra trees classifier, linear discriminant analysis, neural network, decision tree classifier and naïve Bayes. The datasets were broken into training and testing data sets with 50% of the data in each. The parameters in each machine learning algorithm were optimised before implementation. The machine learning algorithms were implemented with different input data combinations based on the feature importance results. Four sets of training data sets were evaluated: spectral reflectance with and without soil water status, crop features and all.

The linear regression algorithms and machine learning models were developed from datasets captured in Zadok's growth stages GS25-GS30 and compared with the raw measured data from the field study. The algorithms were evaluated with different manually measured crop features to identify which inputs to target in a machine vision system.

Evaluating robustness of machine vision algorithms to lighting

Machine vision systems (e.g. optical sensors, cameras) can be affected by the time of day, which can influence the nitrogen status assessment. From Figure 1, NDVI can vary by 6.3% between 8am and 11am and 1.3% between 11am and 7pm. The performance of simple colour threshold algorithms to measure canopy cover and greenness, were compared using images from infield cameras taken at different times during the day: early morning (5-8am), morning (8-11am), midday (11am-2pm), afternoon (2-5pm) and late afternoon (5-8pm). This would identify which times of day were optimal for data collection.

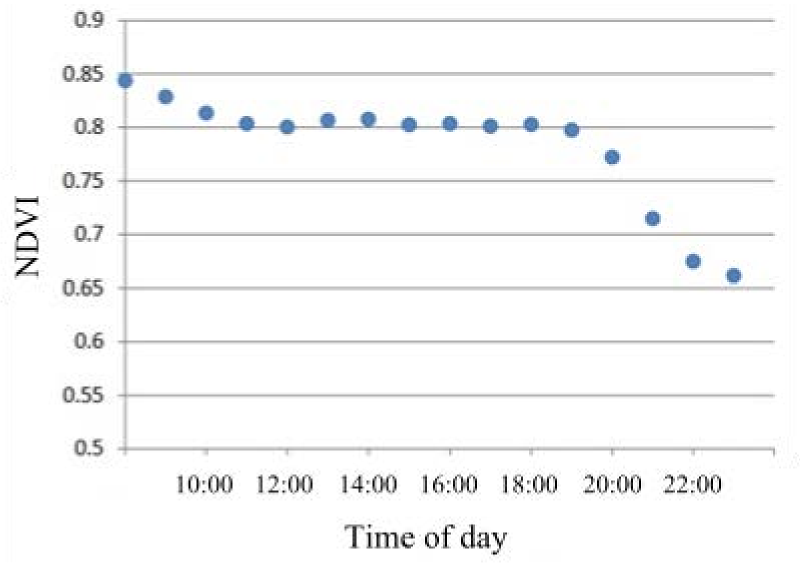

Figure 1. Relationship between GreenSeeker® NDVI sensor readings and time of day (adapted from Porter 2010).

Results

Linear regression algorithm for estimating nitrogen status

Table 1 compares the performance of linear regressions fitted between modelled soil and leaf nitrogen status and measurements of spectral reflectance (NDVI and NDRE), soil water status (volumetric soil water content and estimated drained upper limit) and crop features (height, width and tiller counts). These are shown as correlations of determination between 0 and 1 which are low and high correlations, respectively. These linear regressions were fitted on each day of machine vision and crop ground truthing data collection and the values shown in Table 1 were for the data types with the highest coefficients of determination. These were fitted for data between emergence (GS00) and harvest (GS99) and in-season nitrogen decisions are typically made by GS30.

From Table 1 , individual factors measured were only partially correlated with N status with correlations of determination of <0.4. This may indicate that multiple data types may be required to estimate nitrogen status, or there were errors in modelled soil and leaf nitrogen status from APSIM. This could also indicate that the field measurements were affected by factors other than nitrogen (e.g. soil characteristics and sowing density) which provided a level of error in measurement that needs to be reduced if a more accurate estimate of N status is to be made.

Simulated results showed the highest correlations between crop features and modelled leaf and soil nitrogen at GS30 which is the latest stage that in-season nitrogen decisions would be made. There was a low correlation between modelled nitrogen status and soil water status, spectral reflectance and crop features at most of the earlier and later growth stages.

Table 1. Data types at different days after sowing with the highest correlation for leaf and soil nitrogen. Variables with the highest correlations are closer to one and highlighted in grey.

Days after sowing	Zadok's growth stage	Modelled leaf N (g/m^2)		Modelled NH_4-N (ppm)		Modelled NO_3-N (ppm)	
		Data type	R^2	Data type	R^2	Data type	R^2
36	25	Soil water status	0.389	Crop features	0.289	Crop features	0.351
43	25	Crop features	0.285	Spectral reflectance	0.217	Crop features	0.251
50	30	Crop features	0.749	Soil water status	0.530	Crop features	0.781
60	42	Soil water status	0.391	Spectral reflectance	0.658	Spectral reflectance	0.564
67	59	Crop features	0.211	Spectral reflectance	0.692	Spectral reflectance	0.704
71	66	Crop features	0.296	Crop features	0.384	Spectral reflectance	0.375
78	72	Soil water status	0.462	Soil water status	0.285	Crop features	0.224
85	76	Spectral reflectance	0.340	Spectral reflectance	0.512	Spectral reflectance	0.409
93	81	Spectral reflectance	0.418	Spectral reflectance	0.666	Spectral reflectance	0.591
99	84	Spectral reflectance	0.345	Spectral reflectance	0.584	Spectral reflectance	0.411
105	90	Spectral reflectance	0.061	Spectral reflectance	0.369	Crop features	0.379
113	99	Soil water status	0.210	Soil water status	0.313	Crop features	0.379

Linear scaling algorithm for estimating nitrogen status

Table 2 compares how well the linear scaling algorithm estimated leaf and soil nitrogen status. Using crop features in the linear scaling algorithm produced the highest accuracy in estimating nitrogen status (82.3-87.4%). This high accuracy was consistent for all sources of underlying variability. There was a lower correlation between spectral reflectance and nitrogen status (66.2-70.4%). This indicates that crop features could be used without spectral reflectance for estimating nitrogen status, and that only one underlying variability field map (e.g. drained upper limit from the CSIRO Soil and Landscape Grid of Australia) could be used.

Table 2. Comparison of percentage accuracy for estimating soil and leaf nitrogen using a linear scaling algorithm considering different types of underlying variability.

Underlying variability data considered	Accuracy using spectral reflectance (%)	Accuracy using crop features (%)
Soil water	67.3±6.5	85.1±6.8
Drained upper limit	70.4±11.5	85.4±7.4
Sowing density	66.2±5.6	87.4±7.2
Soil water, drained upper limit and sowing density	66.8±6.6	82.3±10.8

Machine learning algorithm for estimating nitrogen status

Figure 2 compares the relative importance of using spectral reflectance, soil water status or crop features to reflect leaf nitrogen, soil ammonium-N and soil nitrate-N during GS25-GS30. The spectral reflectance had the largest influence on modelled leaf nitrogen status (42%), whilst crop features had the largest influence on modelled soil ammonium-N (54%). Soil water status and crop features contributed equally to modelled soil nitrate-N (38% each). This indicates that multiple data inputs (e.g. soil water and crop features or spectral reflectance and crop features) may be required to estimate both leaf and soil nitrogen status.

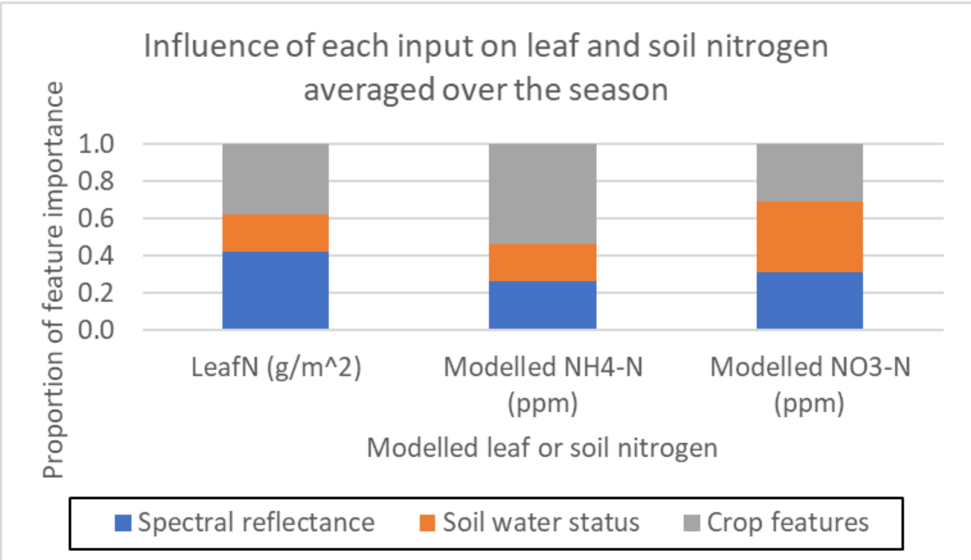

Figure 2. Comparison of feature importance for each input data type on modelled leaf and soil nitrogen for GS25-GS30.

Table 3 compares the percentage accuracy of each machine learning model with the six data input combinations for determining modelled leaf nitrogen, soil ammonium-N and soil nitrate-N. The accuracies using machine learning on the training dataset were generally low (<60%) but higher than the linear regression nitrogen algorithms (<40%) and lower than the linear scaling algorithms (>60%). This indicates that a larger training dataset is required for machine learning model training, potentially with additional ramped nitrogen treatments.

The highest accuracies were achieved using all data (59.2%) or spectral reflectance and soil water status (54.2%). Of the eight evaluated machine learning algorithms, support vector machines produced the highest overall accuracies (52.7%). The superior performance of the support vector machines over the other machine learning models may be caused by the reduced overfitting that is inherent in these types of machine learning models.

Table 3. Comparison of averaged percentage accuracy in modelled soil and leaf nitrogen using different machine learning models and data input combinations with those with the highest correlations highlighted in grey.

Data input combination	Logistic regression	Support vector machines	Random forest	Extra trees	Linear discrimination analysis	Nearest neighbour	Decision tree	Naïve Bayes
All	51.7±7.3	59.2±2.7	44.4±20.6	46.1±16.5	47.6±3.2	47.9±14.1	47.7±5.6	41.6±19.4
Spectral reflectance	52.2±9.3	51.1±11.2	44.0±9.1	44.4±12.8	51.3±6.1	46.8±11.4	49.0±0.9	39±14.1
Spectral reflectance and soil water status	50.2±4.9	54.2±5.5	45.0±17.3	53.1±5.5	45.2±1.9	49.6±11.6	51.7±5.4	40.8±13.9
Crop features	44.4±7.2	46.3±5.8	38.8±7.4	48.6±4.2	40.9±12.1	42.7±15.6	48.8±2.7	39.1±18.0

Considerations for machine vision development for automated nitrogen status sensing

Figure 3 shows the average difference in cover and greenness across the plots at different times of the day. The errors in cover and greenness because of lighting variation during the day were generally low and under 5%. The errors in cover and greenness were lowest at midday (2.6% and 3.3%, respectively), and highest in the early morning (4.8% and 8.0%, respectively). The results from the machine vision camera are consistent with the optical sensor (Porter 2010) with the largest errors in the early morning. The machine vision sensor has lower errors than the optical sensor during the later morning (4.3% for cover and 3.7% for greenness). Therefore, the impact of time of day on machine vision sensing is comparable with optical sensors.

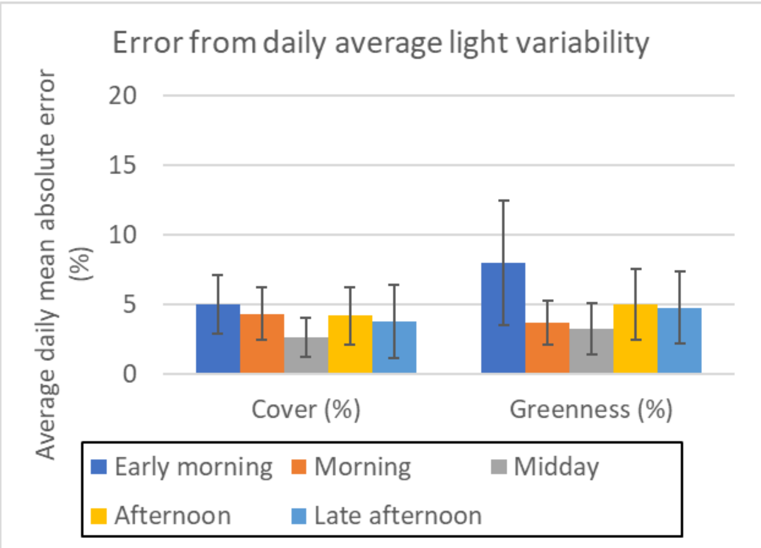

Figure 3. Daily mean absolute error in cover and greenness from infield cameras at different times of day with different lighting conditions.

Discussion

A pilot simulation and field study was conducted to establish the role of machine vision in a nitrogen sensing system. The performance of three nitrogen status algorithms were compared with modelled soil and leaf nitrogen and different combinations of measured data: spectral reflectance (current standard practice), soil water status and crop features that could be measured using machine vision.

A linear regression algorithm using single data inputs produced correlations that were generally low (<0.5) for all data types. This suggests that more than one data input is required to estimate nitrogen status. A linear scaling algorithm that also used underlying variability in sowing density and soil water status produced higher accuracy for estimating modelled soil and leaf nitrogen than linear regression. The highest accuracy was achieved using inputs of crop features (82.3-87.4%), and lower correlation was achieved using spectral reflectance (66.2-70.4%). This indicates that machine vision detectable crop features may improve indication of nitrogen status when compared with the current standard of spectral reflectance.

Machine learning algorithms had improved repeatability over linear regression but lower accuracy than the linear scaling algorithms with test accuracies of <60%. The highest accuracies were achieved using all data (59.2%) or spectral reflectance and soil water status (54.2%). The highest overall accuracies were achieved using the support vector machines (52.7%). A larger training dataset may be required with additional multiple rate nitrogen treatments to improve the machine learning algorithm performance.

Machine vision-estimated crop features may be impacted by time of day and lighting. However, this impact was comparable with optical sensors, with errors in cover and greenness over any day being <5%.

Conclusions

Machine vision has potential to improve nitrogen status estimation by sensing crop features in N-minus and N-rich plots. A linear scaling algorithm had an accuracy of 82.3-87.4% for modelled leaf nitrogen using plant features with underlying soil variability. This outperformed the same algorithm using spectral reflectance by 15%. Linear regression and machine learning models produced lower accuracies for modelled soil and leaf nitrogen status, potentially because additional data may be required for training. Further work will involve transferring the machine vision system and nitrogen status algorithms to Future Farm core sites nationally. This will enable refinement of the machine vision algorithms (e.g. deep learning) and evaluation of the nitrogen status algorithms with in-field measurements of soil and leaf nitrogen status.

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Smartphone apps under development to aid pest monitoring

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Key words

pest monitoring, image analysis, machine learning, smartphone app

Take home message

- A silverleaf whitefly and cotton aphid detection app is currently under development for the cotton industry to enhance pest management decision making
- Preliminary image analysis from smartphone images demonstrated ability to achieve up to 75% detection rate of silverleaf whitefly nymphs on the underside of cotton leaves
- Machine vision can be transferred to pest and crop sensing in grains with mobile or static camera installations (e.g. traps).

Introduction

Cotton pests such as silverleaf whitefly (SLW) and cotton aphids cause yield loss through plant feeding as well as the lint contamination from waste secretions. The management of these pests to prevent economic loss currently depends on manually counting these pests on leaves sampled from cotton fields to determine if changes in pest abundance warrants control action. This is a time-consuming process requiring 20-30 leaves to be sampled per 25 hectares of cotton and examined by eye for the presence and density of each pest. As a result, crop agronomists' sample and examine hundreds of leaves each week to complete a very menial task. The current decision chart in the Australian Cotton Pest Management Guide (CRDC 2019) that maps SLW numbers against day degrees is shown in Figure 1.

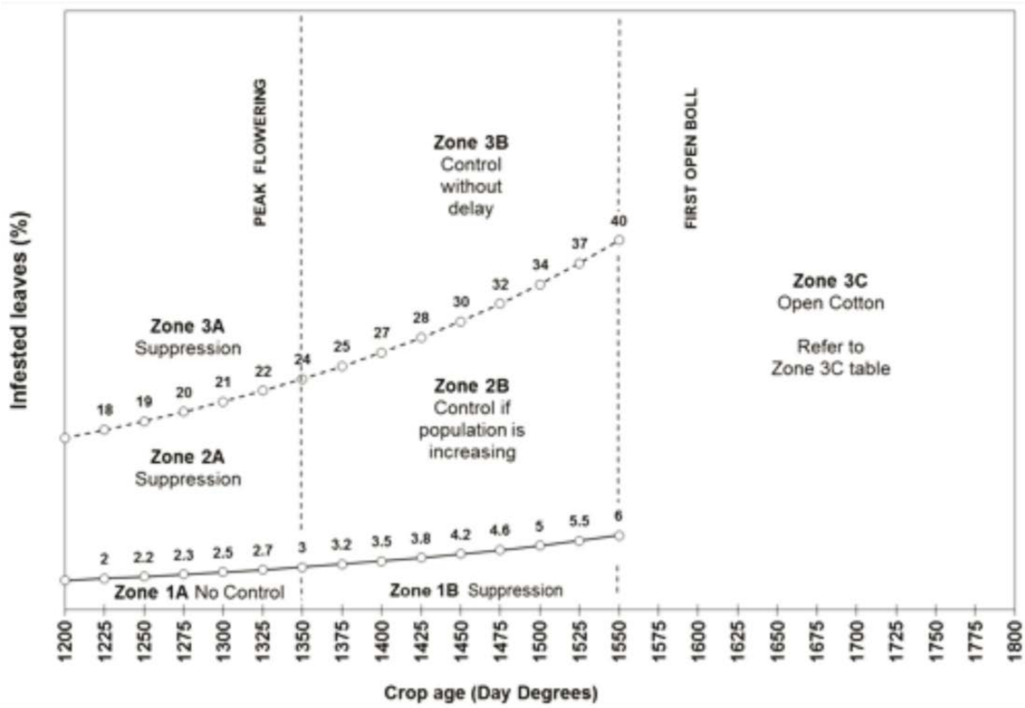

Figure 1. SLW management matrix. Source: CRDC (2019)

Image analysis techniques have potential to autonomously interpret images of cotton leaves, detecting and logging pest density to inform pest management decisions. Deep learning has been deployed in similar settings to detect whitefly adults (mCROPS 2019) on beat sheets (Xuesong et al. 2017), and insects in pest traps (Sun et al. 2017). These deep learning models are typically trained from images in controlled lighting and have F-scores (an indicator of accuracy) of 90-95%. Further development is required to adapt these techniques/models for infield application by agronomists collecting and analysing SLW samples. The accuracy of deep learning models trained from images in outdoor, commercial conditions are expected to be lower than 90-95% because of less consistency between images.

Embedded processing of a deep learning model on a smartphone app classifying and counting insects would allow agronomists to reduce the time spent in the field. Image collection would replace the need to examine and manually record insect presence on each leaf. This would underpin larger sampling and greater efficiency and accuracy for decision making.

Materials and method

Initial glasshouse trials and commercial field trials were conducted over the 2018/19 cotton season to enable the development of a sampling protocol. The two initial questions were (i) which smartphones could capture suitable images and (ii) what accuracy can be achieved with the smartphone models, with different camera resolutions. Three smartphone models were compared to identify a suitable minimum standard for camera quality.

An initial training dataset of 480 images and evaluation dataset of 80 images were collected from QDAF glasshouse cultures and Queensland commercial cotton farms near Goondiwindi, St George and the Darling Downs. In the evaluation dataset, approximately half of the images from each smartphone contained nymphs, and the other half were clean leaves. All images were ground truthed by manually recoding the numbers and locations of SLW nymphs. Potential nymph locations were also recorded where it was not clear on the image due to either small size or lack of focus. An example of nymph and potential nymph locations on a leaf in the evaluation dataset is shown in a smartphone image in Figure 2.

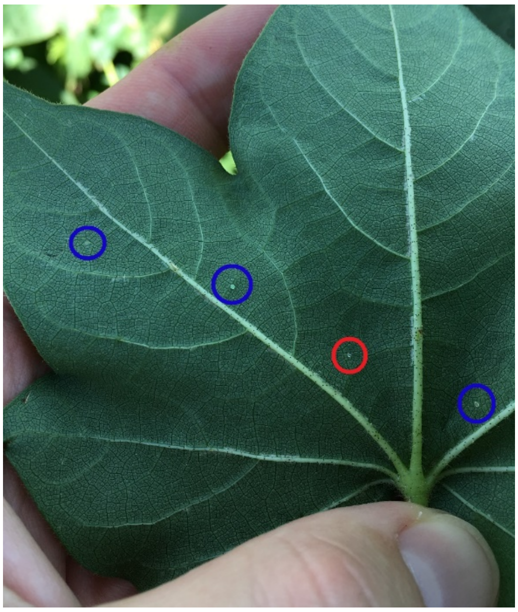

Figure 2. Three whitefly nymphs on an image from the evaluation dataset (blue circles), and one potential nymph (red circle), which is difficult to class by looking at the image

Deep learning models were trained using ground truthing data and images from different combinations of each smartphone to determine the influence of each device on model accuracy. The accuracy of the deep learning models were calculated using the precision, recall and F-score (equations 1-3). The F-score reflects both the precision and recall of the models and is used to evaluate models reported in the current literature. This enables comparison between the developed models and models in the literature. The F-score (Eq. 1-3) was calculated using true positives, false positives (Type I errors), and false negatives (Type II errors), and not true negatives as these could not be quantified in this application. Higher F-scores indicate higher accuracy in the deep learning model.

$$Precision = \frac{T_p}{T_p + F_p} \tag{1}$$

$$Recall = \frac{T_p}{T_p + F_n} \tag{2}$$

$$F_{score} = \frac{2*Precision*Recall}{Precision+Recall} \tag{3}$$

where:

T_p = True positives;

F_p = False positives; and

F_n = False negatives.

Results

The results for the best F-score from each training set are presented in Table 1. All deep learning models which used the iPhone model on its own or with other smartphone models produced the highest F-scores of all the combinations (71.7-75.8%). In contrast, the deep learning models that incorporated the Sony and/or Samsung models without the iPhone model produced F-scores of 44.0-55.6%. The performance disparity between smartphone models is likely due to dataset size and quality, something that will be addressed by using external collaborators to greatly increase image collection for the database. This variation in performance between models may also be caused by the different pre-processing that occurs on each smartphone brand and model that can further add variability to the appearance of the insects.

Overall, the trained models produced F-scores that were lower than 90-95% that have been reported in the literature. This is likely to have occurred because the images were captured outdoors, whilst those in the cited literature were captured in controlled indoor conditions. Controlled lighting provides a more consistent view of the subject, reducing the level of training data required and improving accuracy. In addition, this study has performed validation using multiple sensors, whereas training and validation were carried out using the one image sensor in earlier reported studies. The detection accuracy will be brought as close to 90% as possible through algorithm revising and defining an image capture protocol to limit poor lighting conditions in images from the field.

Table 1. Deep learning SLW detection test using optimal training and detection parameters.

Smartphone models used for training	Positive samples	Precision (%)	Recall (%)	F-score (%)
Samsung	330	46.0	42.1	44.0
Sony	718	31.7	33.7	32.7
Samsung and Sony	1048	51.8	60	55.6
iPhone	609	72.8	70.5	71.7
Samsung and iPhone	939	73.7	73.7	73.7
iPhone and Sony	1527	75.8	75.8	75.8
All	1857	76.7	69.5	72.9

App deployment

A closed alpha version of the app was deployed to a small test group of 8-10 agronomists for the 2019/20 cotton season. The alpha app included logging features so that agronomists could create farm units and subsequent pest management units and then log samples under each management unit. All images were collated into a new database for algorithm training which is ongoing in preparation for next season. Agronomists responded positively to the logging system and expect the app to be much faster than manually referencing the pest management guide.

For the 2020/21 cotton season, the app will enter a closed beta stage which includes an updated algorithm with cotton aphid detection and which attempts to sub-classify SLW nymphs into key groups (i.e. healthy, dead, emerged). This additional information will further aid agronomists and better inform pest control management decisions.

Conclusion

A silverleaf whitefly and cotton aphid detection app is currently undergoing development and testing for the Australian cotton industry, which will benefit IPM by reducing sampling times, enabling more precise detection and recording of pests, increasing sampling consistency between field personnel, and providing a digital storage platform on which future area-wide management strategies could be based. There is potential for this technology to be transferred across other crops (e.g. grains) for insect pest counting, and detection of symptoms or stress.

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