Improving farming systems efficiency in southern NSW
GRDC project Number 9175150/CFF00011

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Executive Summary

The southern NSW farming systems project (CFF00011) was established in July 2017 after 12-month consultation period and extensive literature review demonstrated a significant gap in profitability and efficiency ($/ha/mm) of current cropping systems (i.e. actual *vs* potential) despite good agronomy of individual crops. The average annual gross margin of the best 3-4-yr sequences was often ~$400/ha higher than the worst, and $150 to $250/ha higher than the most common "baseline" sequences. We established research sites and associated simulation studies to investigate strategies to increase the conversion of rainfall to profit ($/ha/mm) across the crop sequence while managing weeds, diseases, soil fertility and risk.

Four sites were established in 2017 to cover the soil and climate variability across southern NSW at Greenethorpe, Wagga Wagga and Condobolin (high, medium and low rainfall sites on red acidic loam soils), and a 4th site on a sodic clay vertosol at Urana. At each site, the "baseline" system (sequence of canola-wheat-wheat or canola-wheat-barley; timely sown in late April-early May; and with a conservative Decile 2 N strategy) was compared with a range of other systems that varied in (i) crop diversity (inclusion of legumes), (ii) sowing time (early and timely) and (iii) N strategy (conservative Decile 2 and optimistic Decile 7). Management protocols for all other input and management decisions (e.g. tillage and stubble management; variety choice; herbicide, fungicide and pesticide applications) were agreed by the project team using a consensus approach of best practice that was continually reviewed.

At all experimental sites, we identified systems with 3-yr average annual profit (EBIT) (2018-2020) that were **$200 to $300/ha more profitable** than the baseline system, and at 2 sites there were systems $700/ha higher than baseline. These more profitable systems included mixed systems involving early-sown, grazed crops (wheat, canola) with legumes (vetch) or higher N strategies. In crop only (un-grazed) systems, the timely sown, diverse sequences with high value legumes and more conservative N strategies were most profitable. In addition to the experimental data, longer-term simulation suggested that these **diverse systems also carried lower risk** as expressed by both variability in annual profit, and profit in the lowest 20% of years. There was also evidence of **decreasing disease risk and stable or declining weed populations** and a much **lower average herbicide cost in the diverse systems** compared to the baseline systems at all sites.

In summary, our first 3-year experimental phase has identified systems at all sites with significantly higher profit and lower risk than the current baseline systems. These also had either stable or declining weed and disease burdens. Our current simulation studies suggests these economic benefits are maintained in the longer-term.

These improved strategies and systems (worth $100 - $300/ha) are immediately relevant to the ~3.5 Mill ha of winter cropping in southern NSW which produces around 7.5 Mt of grain valued at ~$2.5 Bill pa. Assuming adoption of strategies worth only half the demonstrated increase (i.e. $100/ha) could be achieved on only 10% of the area, would still represent a potential value from the investment of **$35 Mill pa**.

Confirmation, continuation and further communication of these results to achieve this potential impact for southern NSW growers is the goal of Phase 2, currently in negotiation.

Extended Summary

Rational and background

The southern NSW farming systems project (CFF00011) was established in July 2017 after 12-month consultation period (June 2016 to July 2017) with 305 growers and advisors, and an extensive review of the literature (see M106 Report). The goal was to establish research sites focussed on strategies to increase the conversion of rainfall to profit ($/ha/mm) across the crop sequence while managing weeds, diseases, soil fertility and risk.

The project built on previous work demonstrating that the "gap" in efficiency ($/ha/mm) of crop current systems (i.e. actual *vs* potential) was significant despite good agronomy of individual crops. For example, GRDC-funded projects completed prior to 2017 had shown that the average annual gross margin of the best 3-4-yr sequences was often ~$400/ha higher than the worst, and $150 to $250/ha higher than the most common sequences. (Swan et al, 2015a&b; Goward et al., 2016; Kirkegaard et al., 2017; Ag'N'Vet unpub. Report).

Diversity: Previous research revealed that diversity of crops and practices underpinned higher profitability while managing weeds, diseases and risk. The intensive continuous canola-wheat sequences common in southern NSW were profitable in the short-term but were unsustainable due to weed and disease pressure and were declining in N-fertility. Diverse legume options (high-value pulse, low value-pulse, hay, graze and brown manure options) all had potential, but had not been considered in a systems context.

Early sowing: Early-sowing of slower-maturing wheat and canola, both for grazing and grain could improve water-use efficiency, but the potential legacy of dry and N-depleted soils following those crops was of concern. Understanding where earlier sowing added value and where adjusting crop sequences to accommodate these crops were the next steps to maximise the benefits of these options, especially in medium and low rainfall systems.

Nitrogen: Finally, agronomists had become increasingly aware that water and N always co-limit yield and that maintaining adequate N supply, from fertiliser or legume sources was vital to optimise WUE, arrest soil organic matter decline and close the yield gap. N decisions are important profit drivers, but an over-emphasis on single year responses (i.e. NUE of individual crops) rather than system thinking was leading to reduced yield and SOM decline. Monitoring the impact of N strategies in diverse crop sequences was a key focus for the project.

At the time the experiments were designed, there was no published experimental data that explored the potential to increase system-level efficiency and profit ($/ha/mm) with interactions of different crop sequence, sowing date and N-management strategies.

Our review of the previous literature, wide industry consultation and pre-experimental modelling predicted significant potential to **increase annual profit of existing C-W-W systems (by up to $250/ha), and to increase system WUE from $1.5/ha/mm to $2.5/ha/mm** with improved decisions on sequence, sowing dates and N management.

This was the significant opportunity our project targeted on behalf of southern NSW growers.

Research approach and methodology

The wide consultation period with 305 growers and advisors across southern NSW during June 2016 to July 2017, and an extensive review of the literature, provided direction in the selection of sites and experimental approaches for the project.

Four sites were established in 2017 to cover the soil and climate variability across southern NSW at Greenethorpe, Wagga Wagga and Condobolin (high, medium and low rainfall sites on red acidic loam soils), and a 4th site on a sodic clay vertosol at Urana. At each site, one or two local consultants were co-opted into the project team to provide ongoing agronomic and extension advice.

At each site, the local consultations established the common or "baseline" crop sequence and management strategies, as well as the potential improvements and modifications to the system that were of most interest to include at each site. Pre-experimental modelling was also used to explore the likely outcome of the proposed systems to prioritise those for inclusion. At each site, the baseline system (i.e. as nominated by growers) consisted of a **canola-wheat-wheat or canola-wheat-barley sequence, with timely sowing (late-April-early May) and with a decile 2 (conservative) N strategy.** A range of other 2 and 3-yr crop sequences that included a range of legumes (high value, low value, diverse end use) were established. In some sequences the interaction of early (from March) and timely (late April) sowing times, and two nitrogen strategies (conservative decile 2 and optimistic decile 7) were investigated. This generated 25 different "systems" at the Wagga Wagga core site, and a subset of 16, 12 and 11 systems at Greenethorpe, Urana and Condobolin respectively selected by growers and consultants to be the most relevant to those environments. At all sites, the systems were replicated (x3) and phased to capture seasonal interactions. In addition, a "flexible" treatment managed by the consultants at each site was included to compare a more "tactical" approach with the strategic, phased systems described above.

Management protocols for all other input and management decisions (e.g. tillage and stubble management; variety choice; herbicide, fungicide and pesticide applications) were agreed by the project team using a consensus approach of best practice that was continually reviewed.

In addition to baseline sampling and soil characterisation, a common set of measurements enabled a full understanding of system performance and facilitated crop simulation, and analysis of economic return and risk over the longer term. Measurements included;

- Soil water and mineral N prior to sowing and after harvest to 1.8m (1.4m at Wagga Wagga)
- Crop production (biomass, yield components) and product quality and nutrient removal
- Soil disease and weed assessments (soil inoculum and seedbank levels), crop observations
- Forage production and quality and estimated animal production on grazed crops
- Legume N fixation estimates using N15
- Costs of variable inputs (fertiliser, seed, pesticides), operations and crop income
- On site weather stations for meteorological observations

More detailed soil baseline characterisations facilitated the use of APSIM simulations and soil water sensors were established at some sites as a learning tool for local growers.

Key findings and insights

The 2018 and 2019 seasons were consecutive Decile 1-2 seasons across all sites, while the 2020 season was Decile 8-10 (described by many as the "best season in memory"). Despite this extreme variability across the years, important outcomes in relation to project objectives were:

● ***Profitability of systems*** Depending on the site and system (sequence x sowing time x N strategy) and despite two consecutive Decile 1-2 years, the average annual 3-yr EBITS ranged from **$200/ha to $1200/ha.** Some systems were resilient (stable in ranking across years).

● ***Confirmation of the opportunity for improved efficiency at the systems scale***. The 3-year average annual EBITs calculated for the systems from 2018-20 revealed that <u>at all sites</u> there were systems achieving **<u>$200-$300/ha above the baseline system</u>**. At two sites, there were systems that were **$700/ha above the baseline** (see Figures 1 a-d).

● ***Diversity*** Grain legume crops, and diverse sequences including legumes outperformed the baseline canola-wheat sequences <u>at all sites</u> during the dry seasons and at 2/4 sites in the wet 2020 season. This resulted from both the profitability of the legumes, and in some cases the significant legacy of increased soil water (20-60 mm) and/or soil N (50-100 kg/ha) on subsequent crops. In some cases, the legacies of extra water left at harvest had diminished at the sowing of subsequent crops due to reduced soil cover after the legumes, but this was dependent upon the pattern of summer fallow rainfall. Of the non-grazed systems, the most consistently profitable diverse system was timely-sown, high-value legume (chickpea or lentil)-canola-wheat with Decile 2 N. Diverse systems that include a legume are shown as orange in Figure 1 a-d at each site, compared to the Baseline (C-W-W or C-W-B) in black.

● ***Early sowing (and grazing)***. Early-sown grazed crops (wheat and canola) have been highly profitable in all seasons. They were 2-3 times more profitable than non-grazed equivalents in the dry years even without grain harvests, and highly profitable in wetter years. Legacies of dry soils reduced grazing biomass and grain yield in the 2nd dry year. Grazed wheat and canola crops were especially responsive to higher N (both fertiliser and legumes) due to increased forage and grain yield. In all cases, the early-sown un-grazed systems were less profitable than the baseline, partly due to the limited varietal choice for this practice. Early-sown grazed systems at Wagga Wagga and Greenethorpe are shown in green in Figure 1 a, b.

● ***N strategies***. The more robust N strategy (Decile 7) provided increased biomass for grazing crops or hay cuts but had either no effect or negative effects on grain yield and profit in the dry 2018-19 years. However, the unused N in dry seasons carried over to improve biomass and yield in subsequent years, especially in the wet 2020 year, where residual N from legumes and fertiliser significantly increased the yield. As a result, Decile 7 strategy was more profitable over 3 years than Decile 2 strategy in Baseline and Intensive Baseline (cereal-canola) systems, while the Decile 2 strategy was more profitable over 3 years in Diverse sequences with legumes. The N strategies are identified as 2 or 7 for specific systems in Figure 1 a-d.

The Figures below show the average annual EBIT from highest to lowest over the 3-year period 2018-20 for each system at each site using the both actual "spot" costs/prices (left) and long-term average costs/prices (right) with systems organised in the same order. This shows that with a few exceptions, there are only minor changes to the ranking of the systems that were cost/price dependant.

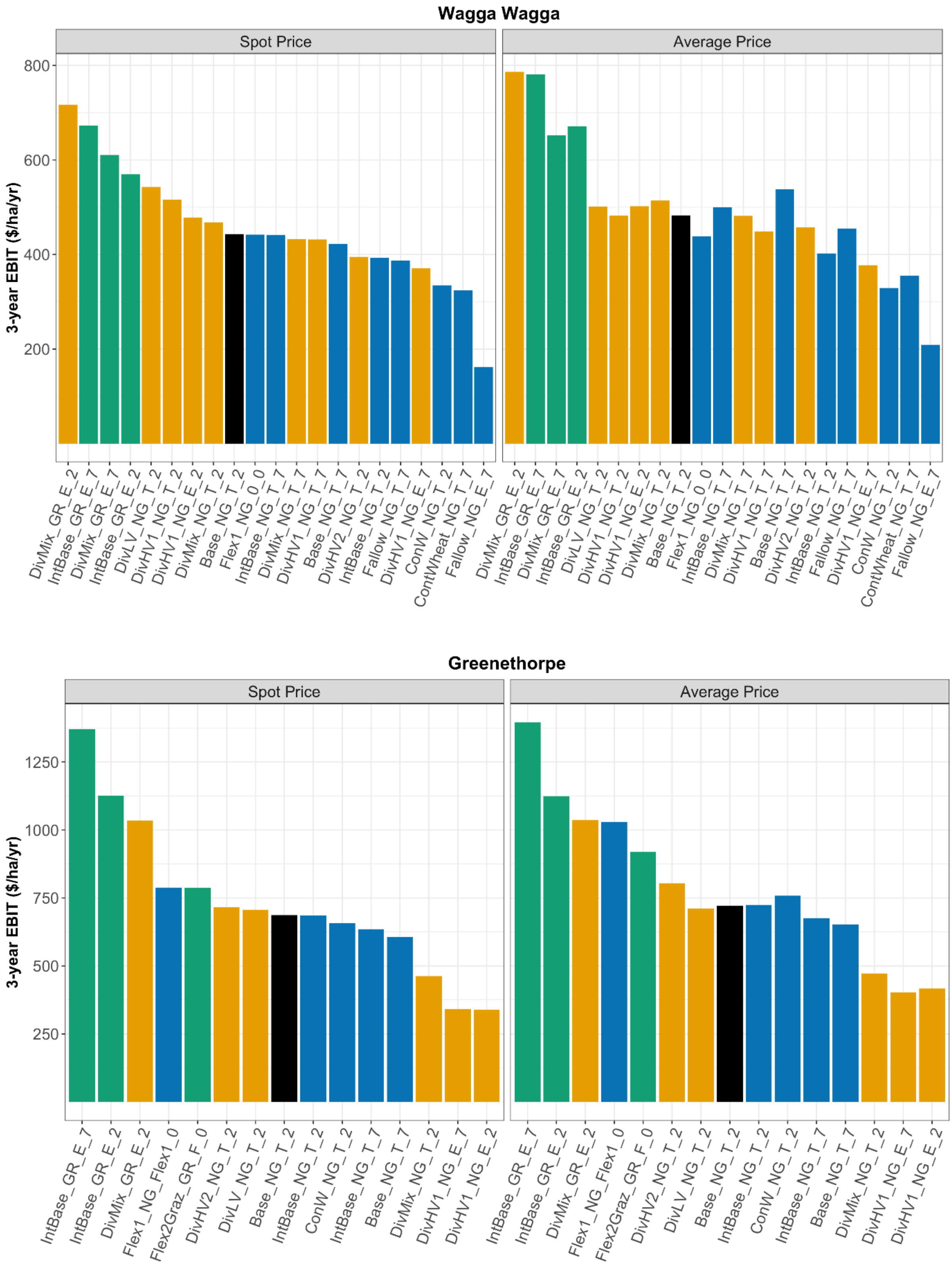


Figure 1a, b. Average annual 3-year EBITs for different systems using actual cost/price for 2018-2020 (left) and long-term average cost/price (right) at Wagga Wagga and Greenethorpe. Baseline system (C-W-W, Timely sowing, Decile 2N) = black; Grazed systems=green; Diverse systems with legume = orange) (NG=no grazing; Gr=grazing; E=early sowing; T=timely sowing; 2=Decile 2 N strategy; 7= Decile 7 N strategy).

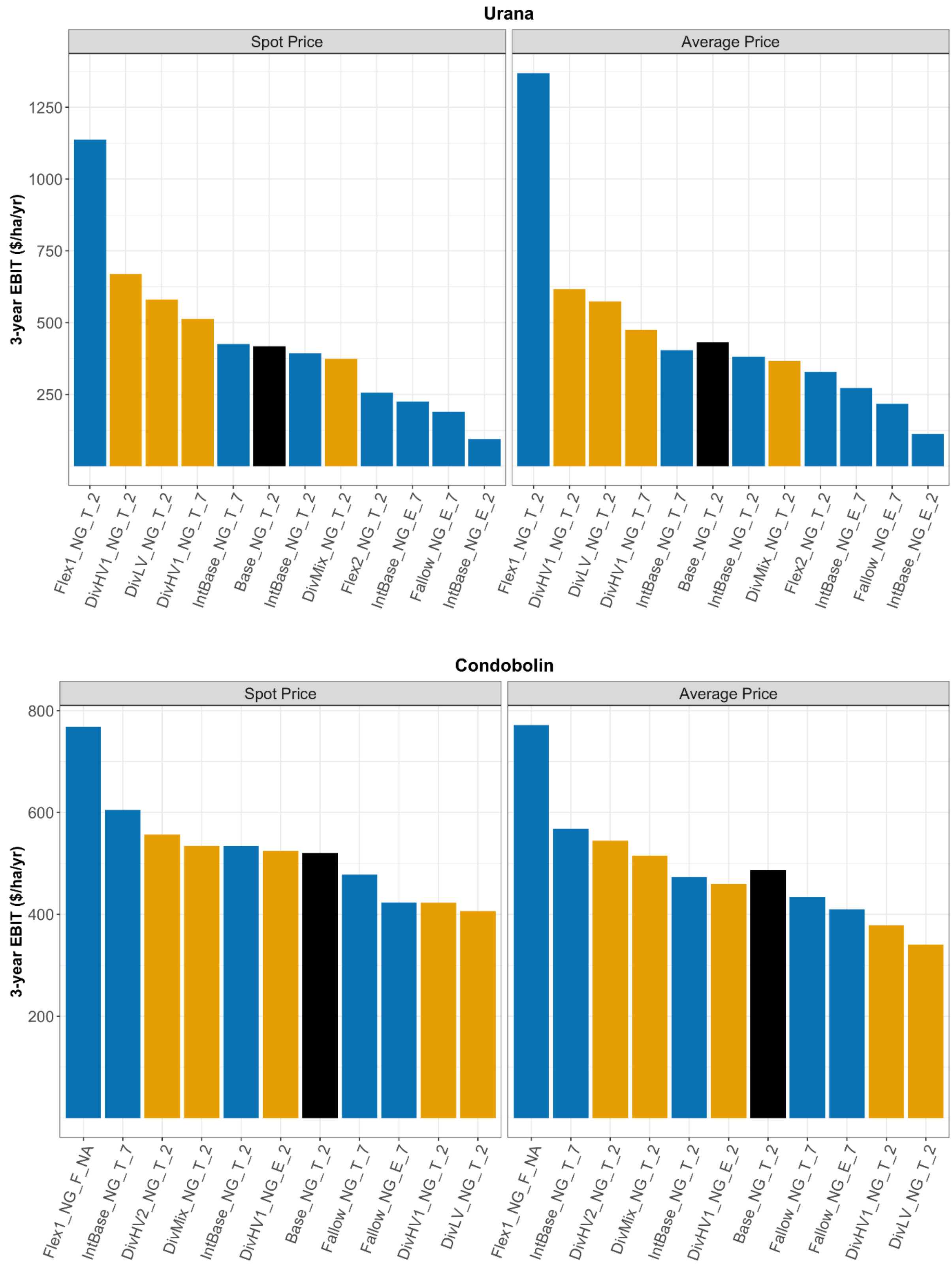


Figure 1c, d. Average annual 3-year EBITs for different systems using actual cost/price for 2018-2020 (left) and long-term average cost/price (right) at Urana and Condobolin. Baseline system (C-W-W, Timely sowing, Decile 2N) = black; Diverse systems with legume = orange). E=early sowing; T=timely sowing; 2=Decile 2 N strategy; 7= Decile 7 N strategy).

● ***Longer-term simulation outcomes on profit and risk.*** Long-term simulation studies (which capture the water and N impact only) show a range in annual median EBIT of different systems consistent with the experimental outcomes ($400/ha to $1400/ha). Figure 2 shows a summary at the four sites of three different un-grazed sequences (Intense baseline C-W; High Value Diverse Ch-C-W; Baseline C-W-W) timely sown, and with different N strategies of Decile 2, 5, 7 and 9. The long-term simulation results show consistency with the experimental results for example (i) the sequence including a legume is more profitable than the baseline, and the response to increasing from Decile 2 to 7 N strategy is profitable in the Baseline and Intense Baseline sequences without legumes, but is less profitable in sequences with a legume, except at Wagga Wagga. However important interactions were predicted between sites and systems. For example, earlier sowing and more robust N strategies were more profitable at Greenethorpe (high rainfall) but resulted in profit penalties at Condobolin. Interestingly at all sites, the diverse crop sequence option with lower N rates are generating some of the highest gross margins with less variability. These diverse options also combine higher average profit with higher profit in the lowest 20% of years demonstrating reduced risk and increased resilience (Figure 3) and are also more efficient in water use in both average and poorer seasons (Figure 4). More detail on the approaches to simulation are given in Milestone 127.

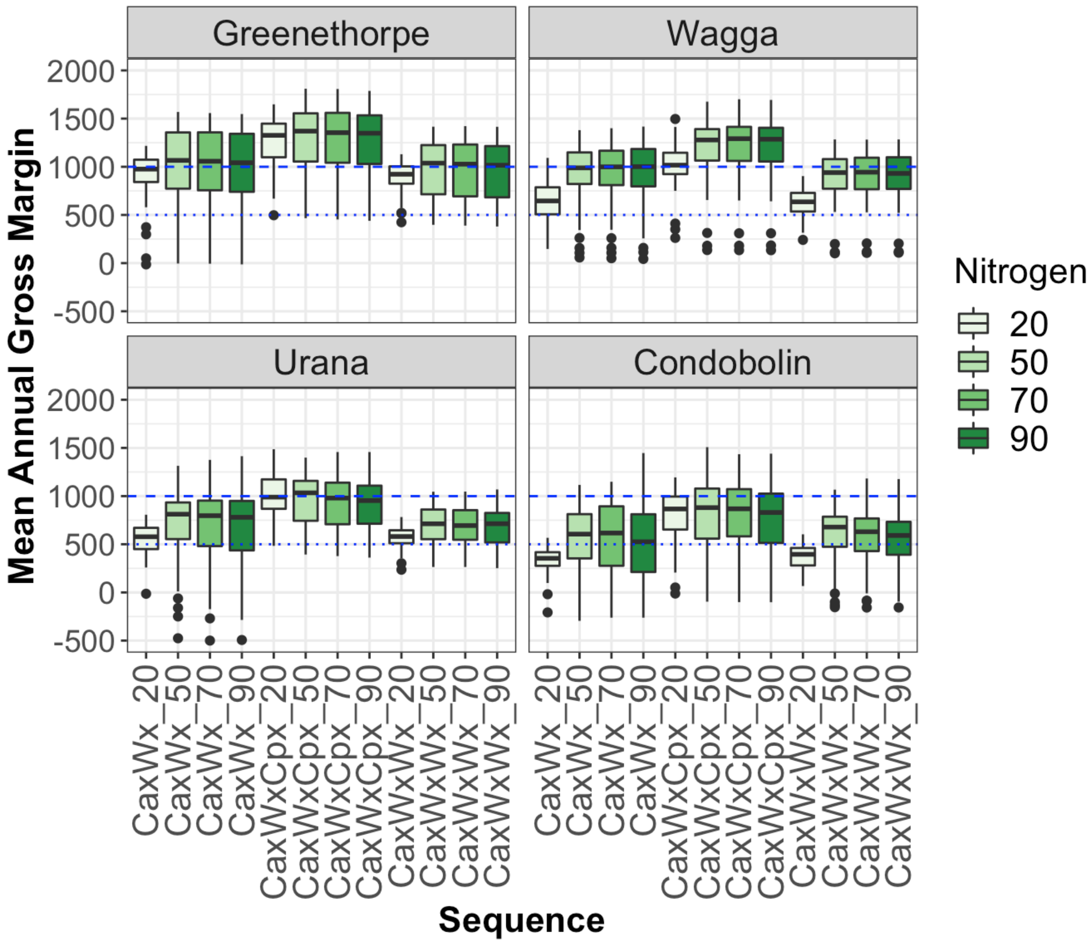


Figure 2. Average gross margins ($/ha/yr) calculated on a sequence basis across all sites for three selected sequences (Intense baseline Ca-W; High value Diverse Ca-W-Cp; Baseline C-W-W) with four different N fertilizer topdressing strategies (Decile 2, 5, 7, 9 are shown as 20, 50, 70, 90). (Ca=canola; W=wheat; Cp=chickpea).

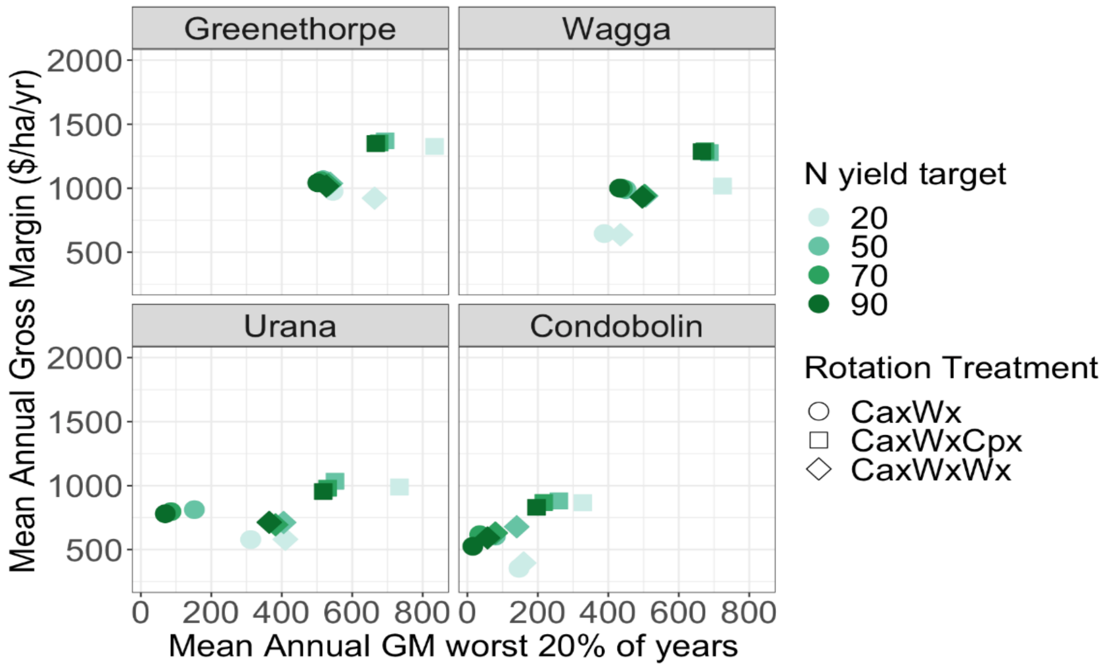


Figure 3. Average gross margins ($/ha/yr) plotted against average gross margin in the worst 20% of years as an indicator of risk. Sequences (Intense baseline Ca-W; High value Diverse Ca-W-Ch; Baseline Ca-W-W) with four different N fertilizer topdressing strategies. (Decile 2, 5, 7, 9 are shown as 20, 50, 70, 90). (Ca=canola; W=wheat; Cp=chickpea).

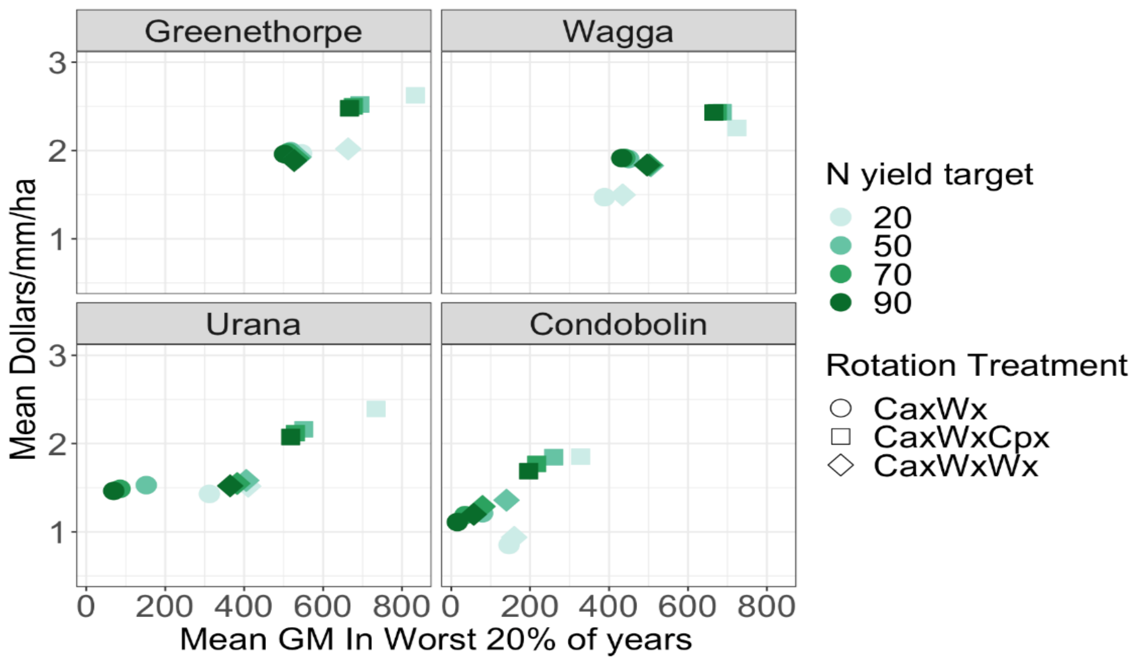


Figure 4. Average water use efficiency ($/ha/mm) plotted against average gross margin in the worst 20% of years as an indicator of risk. Sequences (Intense baseline Ca-W; High value Diverse Ca-W-Cp; Baseline Ca-W-W) with four different N fertilizer topdressing strategies (Decile 2, 5, 7, 9 are shown as 20, 50, 70, 90). (Ca=canola; W=wheat; Cp=chickpea).

● ***Impact of systems on disease levels***

The disease inoculum levels were measured in 2018 (before) and after (2021) the 3-year phase in selected systems varying in crop diversity (intensity of cereals) to monitor any unfavourable changes in the levels of disease generated by different systems. Initially the sites were relatively free of serious cereal root disease levels with only crown rot at Urana in the high-risk category and Take-all at Greenethorpe (Iandra) in the medium risk category (Table 1). Some of the minor and more promiscuous diseases (e.g. Pythium) were also present at medium levels at some sites. Over the course of the experiment there were relatively few concerning increases in disease levels overall (see Table 1, 2021), however there were significant changes at some sites in disease inoculum levels according to the sequences. These are presented in more detail in Appendix 1, but some of the consistent and noteworthy shifts in disease inoculum levels at the sites included:

(i) Increases in crown rot inoculum at all sites in cereal dominated sequences and reductions in more diverse sequences with crown rot disease expressed significantly in the dry 2018/19 seasons.

(ii) Increases in *Pratylenchus neglectus* inoculum at most sites across the years with the highest populations in continuous wheat and canola-wheat sequences (both hosts) and lower populations in diverse sequences including non-host legumes

(iii) Presence of *Pratylenchus thornei* at Wagga Wagga and Urana (low levels) where it increased in diverse and baseline sequences (canola is the only non-host).

(iv) At Greenethorpe (Iandra) *Rhizoctonia* and Yellow Leaf Spot also increased in cereal dominated sequences but not to damaging levels

In terms of disease expression at the sites, the major disease observed in the two dry seasons of 2018 and 2019 was crown rot. Assessments of maximum disease incidence in the crowns of wheat at maturity was 92%, 77% and 33% at Urana, Greenethorpe and Wagga respectively and in barley 52% and 37% at Urana and Wagga (no barley at Greenethorpe). These levels of disease expression were consistent with the inoculum levels shown in Table 1.

In the wetter year of 2020, leaf diseases tended to be a more critical issues with a significant amount of fungicide used for control of diseases in all crops. Prior to the fungicide application in July, the severity of yellow leaf spot in wheat was ranked across different systems at Greenethorpe (1=low disease, 5=high disease). The continuous wheat (W-W-W) was rated highest at 4.5, Baseline (C-W-W) at 3.2, and Diverse systems (legume-C-W) at 1 to 2.

Wheat yields in 2020 also reflected an effect of crop intensity at the sites. For example at Wagga the yield of continuous wheat (1 in 1 intensity) was only 5.2 t/ha, the yield of sequences that were 1 in 2 or 2 in 3 (Intense Baseline and Baseline) were 6.4 to 6.9 t/ha, while the yields of the Diverse sequences that had wheat 1 in 3 were 7.0 to 7.5. In addition, the more diverse sequences tended to be more responsive to higher N indicated a higher yield potential presumably resulting from a healthier root system. More detail and discussion is provided in the GRDC Update papers in Appendix 2.

In summary, with the exception of crown rot, we have not seen the systems at any site develop any high risk disease levels over the course of the experiments.

Table 1. Changes in overall maximum disease inoculum risk levels between 2018 and 2021 at the four experimental sites

	Maximum disease risk at each site							
	Condobolin		Greenethorpe		Urana		Wagga Wagga	
	2018	2021	2018	2021	2018	2021	2018	2021
Crown rot *Fusarium pseudograminearum*	Low	Medium	Low	Low	High	High	Low	Low
Ascochyta blight and leaf spot on field peas *Didymella pinodes* + *Phoma pinodella*	BDL	Medium	Medium	Low	BDL	BDL	BDL	Low
Stem nematode *Ditylenchus dipsaci*	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Take-all (oat strain) *Gaeumannomyces graminis* var. avenae	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Take-all (wheat + oat strains) *Gaeumannomyces graminis* var. avenae + tritici	BDL	BDL	Medium	BDL	BDL	BDL	BDL	BDL
Cereal cyst nematode *Heterodera avenae*	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Ascochyta blight field peas *Phoma koolunga*	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Root Lesion Nematode (neglectus) *Pratylenchus neglectus*	Low	Low	Low	Medium	Low	Low	Low	Medium
Root Lesion Nematode (thornei) *Pratylenchus thornei*	BDL	BDL	BDL	BDL	Low	Low	Low	Low
Rhizoctonia *R. solani* AG8	BDL	BDL	Low	Low	BDL	BDL	BDL	BDL

	Maximum population density at each site							
	Condobolin		Greenethorpe		Urana		Wagga Wagga	
	2018	2021	2018	2021	2018	2021	2018	2021
White grain disorder *Eutiarosporella darliae* + *E. pseudodarliae*	BDL	BDL	BDL	BDL	Low	BDL	BDL	BDL
Wheat pathogen *Bipolaris sorokiniana*	Low	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Soil-bourn fungus *Macrophomina phaseolina*	Low	Low	Medium	Medium	Medium	Medium	Medium	Medium
Ascochyta blight chickpea *Phoma rabei*	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Root Lesion Nematode (penetrans) *Pratylenchus penetrans*	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Root Lesion Nematode (quasitereoides) *Pratylenchus quasitereoides*	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Yellow leaf spot *Pyrenophora tritici-repentis*	BDL	Low	Low	Low	Low	Low	BDL	Low
Pythium root rot *Pythium* clade F	Medium	Medium	Medium	Medium	Low	BDL	Low	Medium

● ***Impact of systems on weeds and weed control costs***

The sites selected for the project had no initial intractable weed issues. Recommended weed control practices were employed in each system in order to maintain control using best bet control strategies, so the impact of weeds can be reflected in the average annual cost for weed control, and by monitoring changes in weed number and spectrums with assessments of weed seed banks.

The overall number of weeds declined over the 3-year period at Greenethorpe and Urana by around 50% and remained relatively unchanged at Wagga Wagga and Condobolin. In 2020-21 very few differences in weed numbers had developed between the systems at the sites. At Wagga Wagga (mostly toadrush, annual ryegrass) and Urana (mostly toadrush, Indian hedge mustard, wild oats) there was no difference between systems. At Greenethorpe (fumitory, mustard, fleabane, prickly lettuce and Shepherd's purse) weed numbers were lower in continuous wheat presumably because good control of broadleaf weeds occurred every year in the cereal. Grazing also appeared to reduce weed numbers. There was no annual ryegrass issue in the trial, but glyphosate resistant ryegrass was encroaching from paddocks surrounding the trial. At Condobolin there were lower weed numbers in the Intense Baseline systems (canola-wheat) presumably because of the option to use herbicide tolerant canola varieties every second year.

As a result of the best-bet management of weeds within each system and the resultant stable or declining weed populations at the sites, it is perhaps more useful to compare the cost of herbicides across the systems in achieving good weed control. Figure 5 shows the average annual cost of weed control across the systems at each site, and the range is summarised below in Table 2.

Table 2 Summary of annual herbicide costs ($/ha) at each site

Site	Range in annual herbicide costs ($/ha)
Wagga Wagga	$180 to $110
Greenethorpe	$130 to $45
Urana	$140 to $80
Condobolin	$110 to $80

Some of the important observations regarding weed control costs from Figure 5 include:

(i) The Baseline treatment (C-W-W or C-W-B, timely sown with Decile 2N) are among the most expensive for herbicide costs at all sites.

(ii) Grazed treatments tend to have lower weed control costs partly due to withholding periods and that grazing provides some control of early weeds

(iii) Systems including fallow treatments have low average weed costs

(iv) Most Diverse options that include legumes have lower herbicide costs than the Baseline treatments.

In summary, Baseline systems are not generating weed problems but have higher herbicide costs than Diverse systems at all sites. This will be part of the reason for the higher EBITs in Diverse systems compared to The Baseline systems.

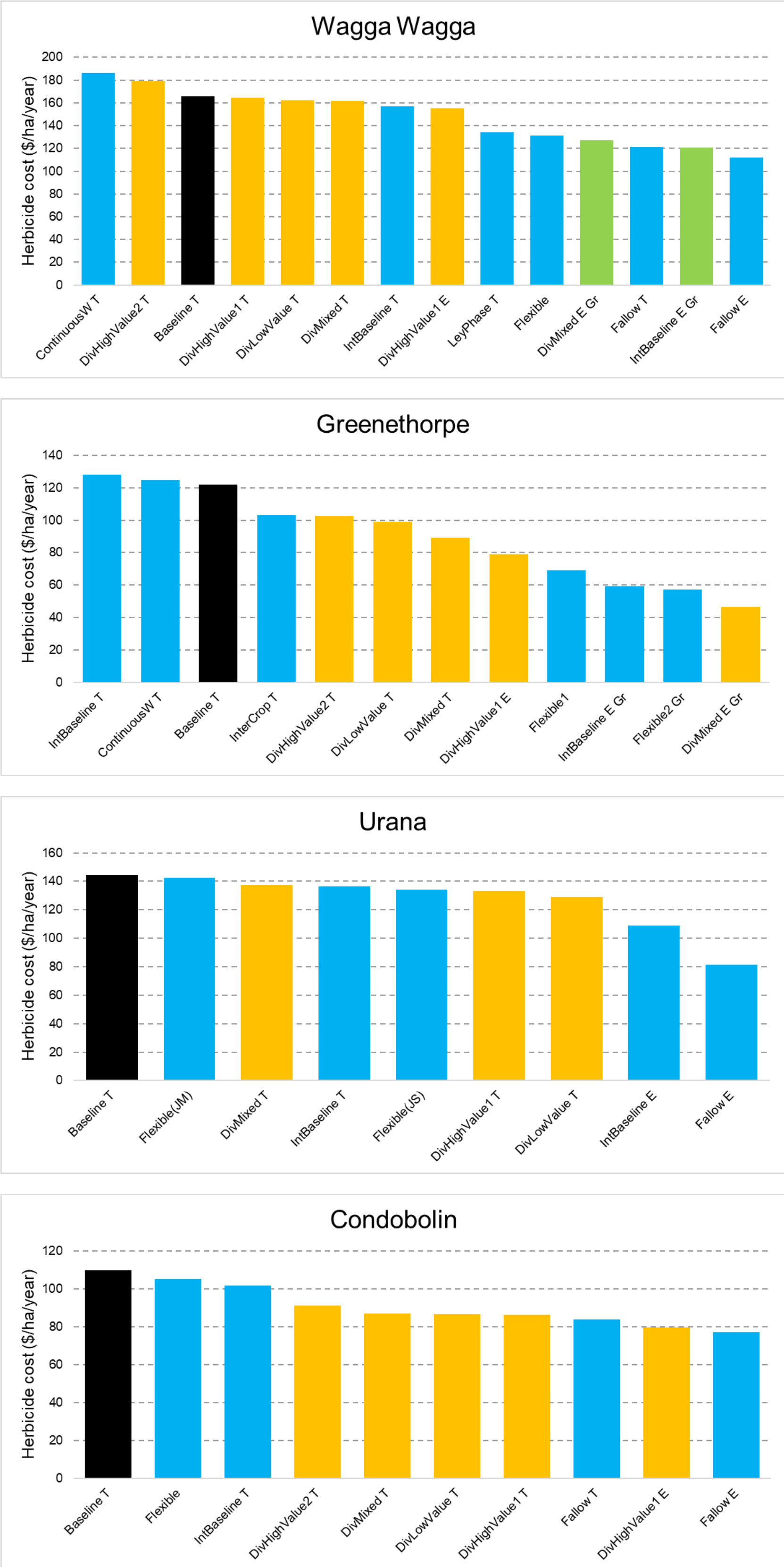


Figure 5. Average annual cost of herbicides in selected systems at each site. Baseline system (C-W-W, Timely sowing, Decile 2N) = black; Grazed systems=green; Diverse systems with legume = orange) Gr=grazing; E=early sowing; T=timely sowing).

● ***Novel and emerging issues*** As is always the case in field experiments, we have made significant new observations on soil and crop responses which are important at the systems level which in some cases have required rethinking or further investigation but may open up new research opportunities. Briefly these have included:

* the comparative rooting depth of different crops – 4m in early-sown canola; 0.8 m in lentil

* difficulties in accurate soil characterisations (lower limits and drained upper limits)

* subsurface acidity, its impact on legume performance and the need for lime incorporation

* the importance of surface cover in dry autumns to facilitate successful earlier establishment

* benefit of intercrops - N fixation in canola/faba; disease control in chickpea/linseed.

* the dynamics of nitrogen availability in grazed crops – fate of N after grazing/topdressing

* the excellent performance of barley compared with wheat across the sites

* the comparative performance of grazing, hay and grain in dry seasons

* issues of scaling up to whole-farm thinking (e.g. dual-purpose crops, inclusion of legumes)

Industry engagement and impact

Grower and industry engagement has been significant since the establishment year (305 growers consulted directly in 2017), and has grown and strengthened during the project. We managed major field days at all sites in every year (300 attendees in both 2018/2019; 150 in 2020 despite COVID); 130 others requested private visits each year from at least 6 different agronomy/consultant groups; numerous pre- and post-season grower meeting invitations were accepted which have increased significantly as data accumulated – for example 4 meetings in March 2021 alone reached 250 growers and consultants face-to-face. The project team has thus interacted face-to-face on site, or in private meetings with around 2000 growers and consultants since the experiments were established in 2018.

As we compiled the first fully phased data set from the project, we accepted more invitations for GRDC Updates and RCSN presentations with 10 papers prepared and presented in 2020/2021. Evaluations suggest this research is amongst the most valued by attendees with very high registrations (150 to 500) and high ratings for web-based interactive presentations. We have also produced Groundcover and other industry articles, media interviews and articles. These GRDC Update papers represent the first stage in the development of scientific articles, which will require more thorough statistical and sensitivity analysis and simulation of the fully phased data and consideration at the whole-farm scale.

The value of the work was emphasised by numerous private consultants at 2020 field days and 2021 pre-season meetings and they provided significant direct feedback (letters) to GRDC managers about the value of the work and strong support for its continuation. The support emphasised its value in demonstrating the interactions and legacies of different management choices across time, including economic considerations, especially in agronomic contexts that represent state-of-the-art management in terms of the timeliness of operations. No other activity supported by GRDC provided the same systems context for their decision-making.

The novel approach taken in this farming systems work has attracted attention both nationally and internationally. Nationally we have made presentations to both southern GRDC RCSN committee (2020) and more recently to DPIRD managers tasked with developing systems research proposals in the western GRDC region. We have also hosted visits from scientists in DPI Victoria (Gary O'Leary) and the Northern GRDC panel. From an international perspective we have had visits to the sites from the Director of Rothamsted Research (Dr Achim Doberman) in the UK, senior researchers from INRAE (France), UC Davis (USA) and agronomists from Kansas State University (USA) during the Agronomy meetings in Wagga Wagga in 2019.

For more details of the communication activities see Milestone Reports 117, 124, 131.

Full copies of recent GRDC Update papers not included in previous Milestone Reports are provided in Appendix 2, and links to papers and recorded presentations are provided below.

Recordings:

A recording of the GRDC Grains Research Update online held last week is available here

A recording of the GRDC Grains Research Update online held last week is available here

GRDC Grains Research Update papers:

Managing water and N across years and crop sequences to drive profit

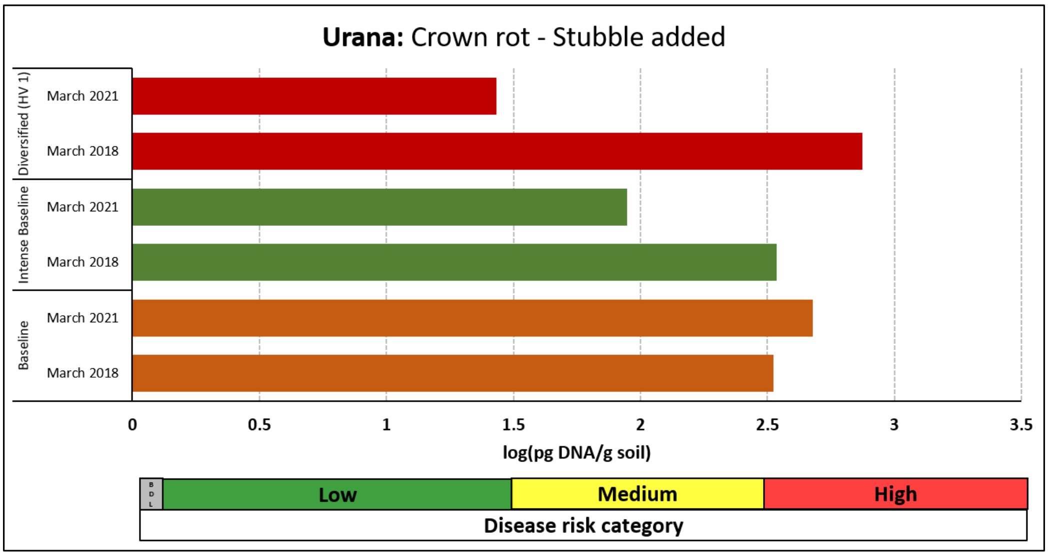
Managing crop differences in soil water extraction and legacy impacts within a farming system

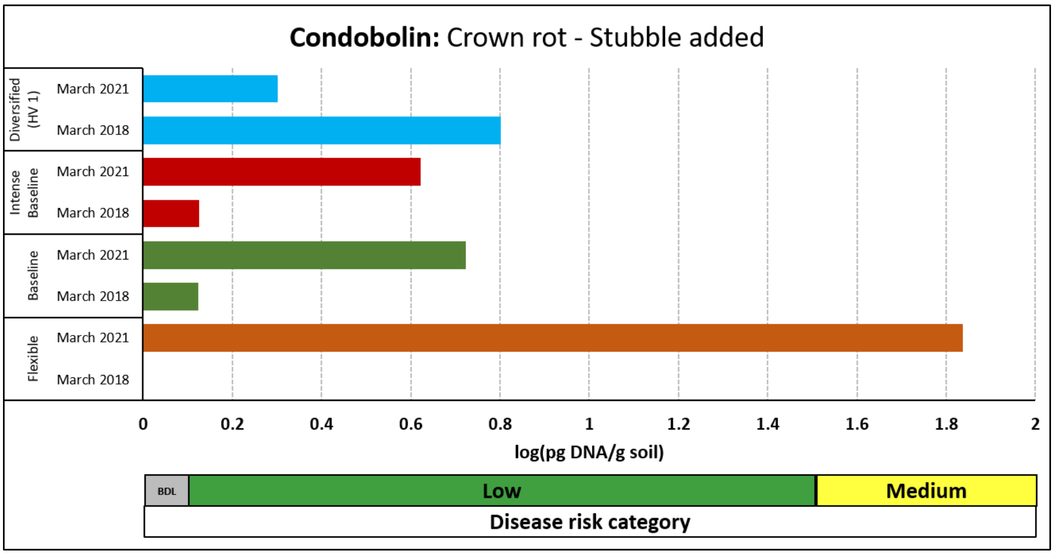
Plant Available Water Capacity – crop and varietal differences in soil water extraction

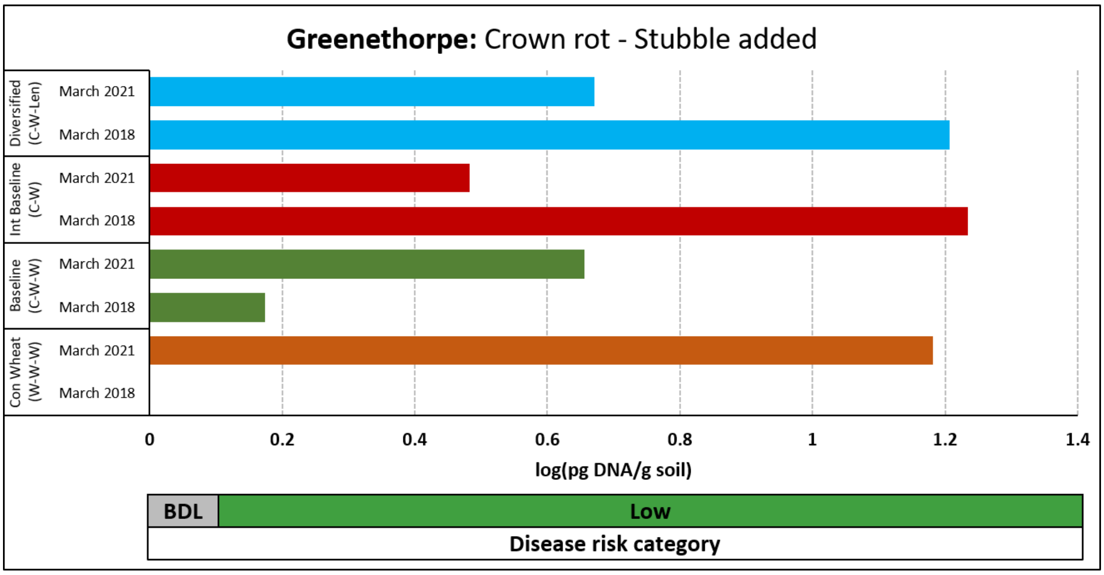
Appendix 1 Disease inoculum changes

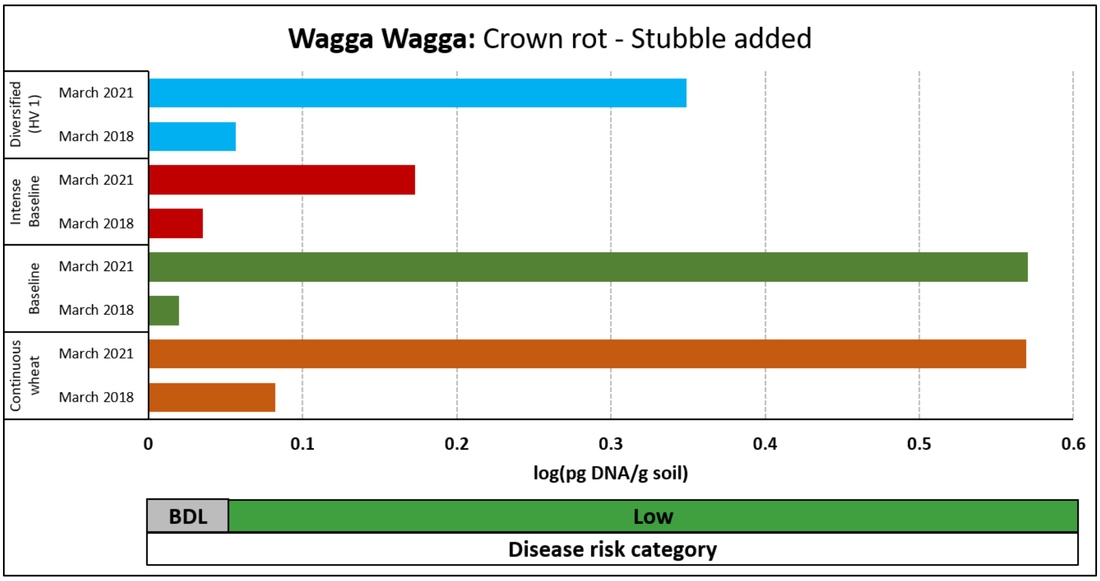
Crown Rot

The Figures below for crown rot show that in general at each site, the levels of crown rot were higher and increased in sequences that had a high proportion of wheat and barley such as in continuous wheat (W-W-W) and Baseline (C-W-B; C-W-W), but were lower and decreased in sequences with less cereal such as the intense baseline (C-W-C) and the Diverse (Le-C-W or Cp-C-W). For example, at Urana where the disease was most prevalent, the disease risk dropped from high risk to low in the Diverse sequence, but remained high in continuous wheat. At the other sites the inoculum levels were in the low risk category for most sequences but tended to remain higher in the continuous and baseline sequences.





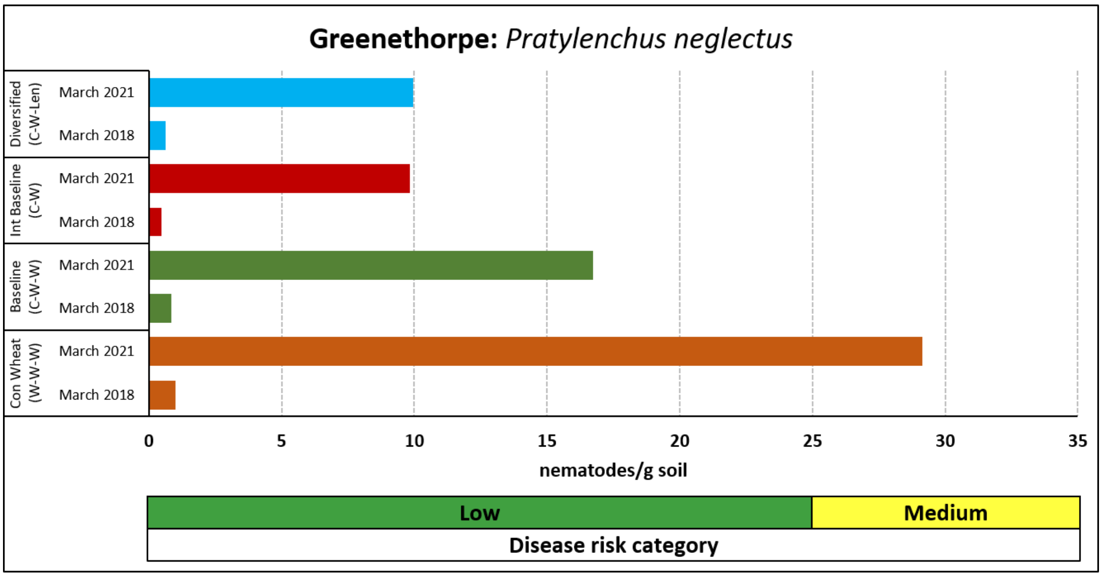




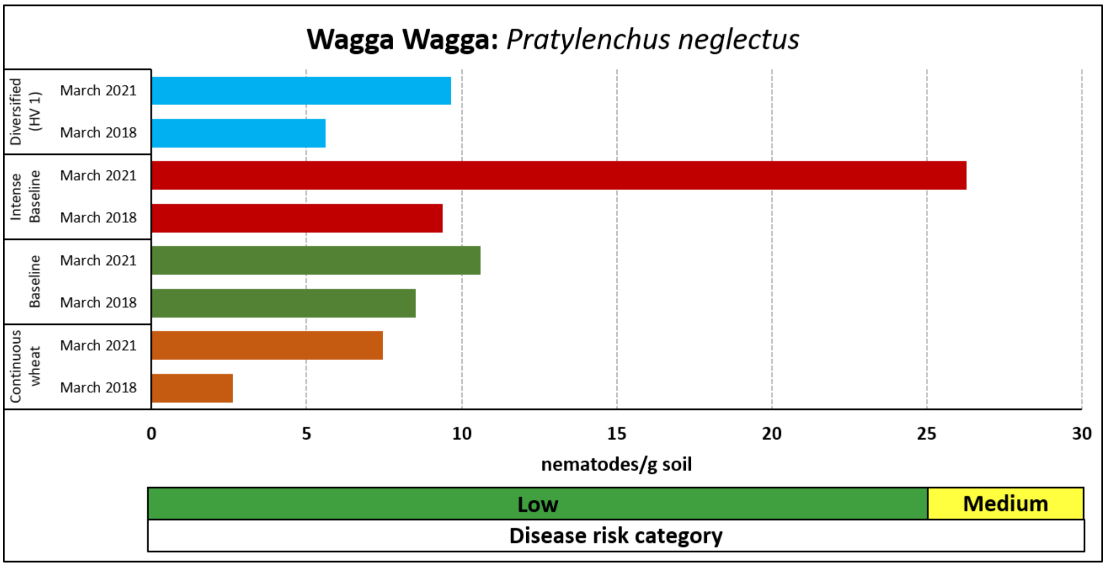
Pratylenchus

Pratylenchus neglectus increased over the course of Phase 1 at all sites and as it hosts on both wheat and canola it tended to have higher populations in Continuouse wheat, Baseline and Intense Baseline systems. Numbers tended to be lower in Diverse systems.

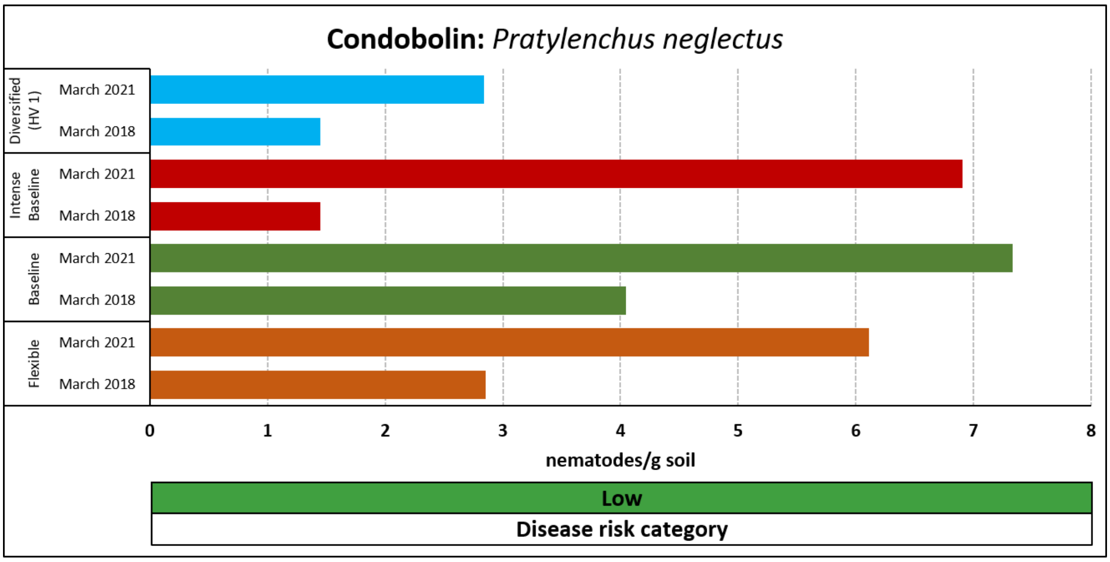
Pratylenchus thornei does not host on canola, but hosts on wheat and some legumes and so at Urana populations increased in Baseline (C-W-B) and Diversified (Le-C-W) systems with 2 hosts in 3 years, compared to the Intense Baseline (c-W-C) with only 1 host in 3 years.



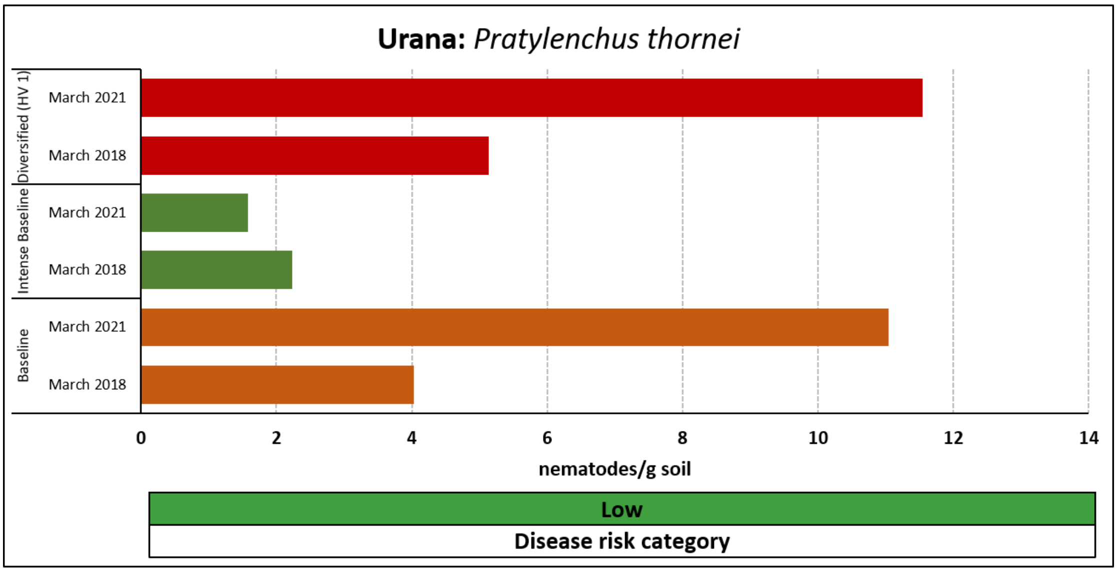
Greenethorpe: Pratylenchus neglectus
Diversified (C-W-Len)
March 2021
March 2018
Int Baseline (C-W)
March 2021
March 2018
Baseline (C-W-W)
March 2021
March 2018
Con Wheat (W-W-W)
March 2021
March 2018
0
5
10
15
20
25
30
35
nematodes/g soil
Low
Medium
Disease risk category



Wagga Wagga: Pratylenchus neglectus
Diversified (HV 1)
March 2021
March 2018
Intense Baseline
March 2021
March 2018
Baseline
March 2021
March 2018
Continuous wheat
March 2021
March 2018
0
5
10
15
20
25
30
nematodes/g soil
Low
Medium
Disease risk category



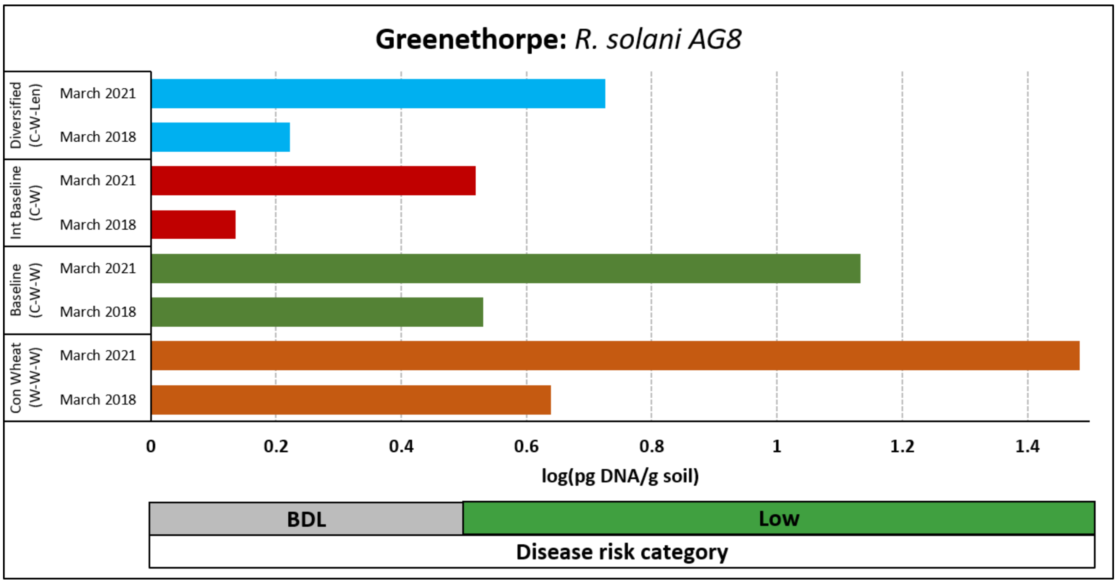
Condobolin: Pratylenchus neglectus
Diversified (HV 1)
March 2021
March 2018
Intense Baseline
March 2021
March 2018
Baseline
March 2021
March 2018
Flexible
March 2021
March 2018
0
1
2
3
4
5
6
7
8
nematodes/g soil
Low
Disease risk category

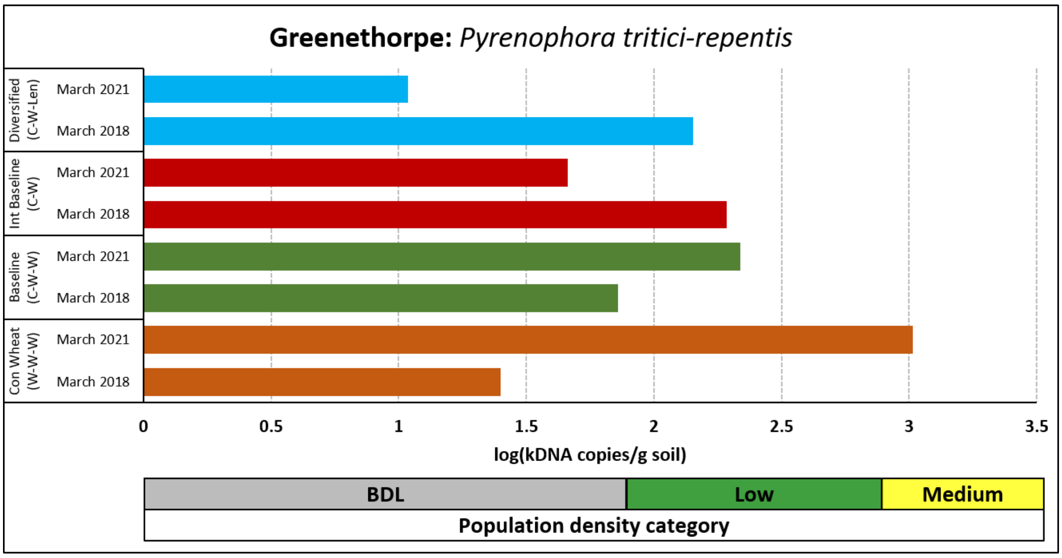


Rhizoctonia and Yellow Leaf Spot at Greenethorpe

Rhizoctonia at Greenethorpe increased in all systems during the experiment from below detection to low risk, but the increase was greatest in systems with a greater intensity of wheat (i.e. host) in the system (Continuous wheat and Baseline) compared to Intense Baseline and Diverse systems with a lower frequency of wheat.

Yellow leaf spot also tended to increase in inoculum in systems with higher intensity of wheat increasing from BDL to Medium risk in continuous wheat. Inoculum declined in the systems with lower intensity of wheat fro Low risk to BDL.




Greenethorpe: Pyrenophora tritici-repentis
Diversified (C-W-Len)
Int Baseline (C-W)
Baseline (C-W-W)
Con Wheat (W-W-W)
March 2021
March 2018
0
0.5
1
1.5
2
2.5
3
3.5
log(kDNA copies/g soil)
BDL
Low
Medium
Population density category

Appendix 2 GRDC Update Papers 2021

Managing water and N across years and crop sequences to drive profit

John Kirkegaard[1], Tony Swan[1], Mat Dunn[2], Graeme Sandral[2], Jeremy Whish[1], Ewan Leighton[2], Daryl Reardon[2], Mel Bullock[1], Kelly Friske[2] and Russell Pumpa[2]

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Key words

risk, water use efficiency, early sowing, nitrogen, diversity, legumes

GRDC code

CFF00011

Take home messages

- Matching N supply to water limited yield targets annually is an ongoing challenge. But with legacies of carry-over N and water, how do these decisions play out over a crop sequence?
- Our system experiments investigate interactions of crop sequence and early sowing systems (+/- grazing) with two N fertiliser strategies (decile 2 (low); 7 (high)) on WUE, production and profit
- In the consecutive dry seasons of 2018/2019, grain yield did not respond to the higher N fertiliser strategy, but grazed forage and hay yields were increased by applied and carry-over N. In the wet 2020 season, responses to N fertiliser were strongly influenced by crop sequence – less response to N in more intense sequences, and in sequences with legumes
- As for the dry 2018-19 seasons, there were legume options as profitable as wheat and canola in 2020 despite higher disease management costs, although canola was the most profitable option at the higher rainfall Greenethorpe site where subsurface acidity may impact some legumes
- Overall average annual earnings before interest and taxes (EBIT) over 3 years were higher for early-sown, grazed systems ($600-$1400/ha) than for timely-sown, un-grazed systems ($200 - $800/ha). Grazed systems responded profitably to higher N, while the profitability of ungrazed systems depended on the crop intensity and the N strategy.

Background – changing the water and N-use paradigm from crop to crop sequence

Australian farmers have been enthusiastic adopters of crop benchmarking tools (e.g. French and Schultz or Yield Prophet®) to compare the performance of **individual crops** to water-limited potential. However, in dryland farming systems, it makes sense to consider the efficiency of water use **across the crop sequence**, to account for the inevitable legacy effects of one crop to the next (i.e. carry over effects on water, N, weeds and disease).

In southern NSW, significant improvements in the water-use efficiency and profitability of crops have been achieved in recent years with improved crop sequences, better fallow management and new earlier sowing systems with suitable varieties (including grazed crops). Diversifying the crop sequence to maintain profit and manage biotic constraints can increase the average profitability across 3-4-yr crop sequences by $150 to $200/ha compared with common sequences, even when individual crops were well managed. Earlier sowing systems are also proving efficient and profitable for individual wheat and canola crops (including grazed crops), but the legacy of dry or low-N soils left by these higher-yielding crops may affect following crops. Our experiments and simulation studies suggest earlier sowing strategies can provide benefits across the crop sequence, but this is influenced by rainfall, crop sequence and **modified by N management**.

Our farming systems project is unique in exploring these interactions to develop strategies to convert annual rainfall into more profit across a crop sequence while managing costs, risk, soil fertility, weeds and diseases. Here we provide a brief overview of the overall project, and the focus of this paper is on understanding how nitrogen strategies play out in terms of productivity and profitability across a range of different systems involving different sequence, sowing time and grazing choices.

The Southern Farming Systems Project – a brief description

To cover the range of soils and climates in southern NSW, sites were established at Wagga Wagga (core site), Greenethorpe (higher rainfall), Condobolin (lower rainfall) and Urana (different soil type). A range of different sequences were established to compare with the common baseline of canola-wheat-wheat sequences typical of the area (Table 1). These included more intensive cereal sequences (wheat and barley), a range of high value (lentil, chickpea) and low-value (lupin, faba) legume options and a forage option (high density legume, mainly vetch) grazed and/or cut for hay. The treatments generated different water and N-use patterns as well as weed, disease and cover legacies monitored by the team. For some sequences, we included interactions of early sowing (March-early April) and timely sowing (mid-April-mid May) of the wheat and canola options. The early-sown options at Wagga and Greenethorpe were grazed by sheep in winter, a recent and profitable management choice on mixed farms with significant implications for water and N use.

Together with the experimental measurements at the 4 sites, we are validating and running APSIM simulations to extrapolate the results across more seasons and explore the data more fully.

N strategies

The N management strategies compared across some systems were based on either a conservative (decile 2) outlook, or a more optimistic (decile 7) outlook for spring in each season. For each non-legume crop in each year of the sequences, the soil N was measured pre-sowing and a potential yield estimate was made in winter based on the starting soil water and N and the seasonal conditions up to that time. Nitrogen was then top-dressed as urea assuming either a decile 2 or a decile 7 finish to the season. Assuming an average season is decile 5, this means that often the decile 2 N strategy would be too low, and the decile 7 treatment too high for the yield potential in any year. Using this approach, the legacies of carry-over N from either legumes or unused fertiliser N would be accounted for in the pre-sowing tests, and less N required accordingly. This approach (compared to set N rates) better mimics farmer practice, and also allows consideration of the risk and reward for conservative or robust N strategies. In the following sections we will focus on selected results that explore the consequences of these strategies in terms of productivity, efficiency and risk in the different systems outlined in Table 1.

Table 1. Selected treatments common to most sites including crop sequence, time of sowing and N strategies. Early-sown treatments included winter grazing of the crops at Wagga and Greenethorpe.

Treatment description	Sequence	Sowing time	N strategy (decile 2 or 7)	Grazing
Baseline	Canola-wheat-barley	Timely	2, 7	
Intense baseline	Canola-wheat	Early, timely	2, 7	Yes
Diverse high value 1	Lentil-canola-wheat	Early, timely	2, 7	
Diverse high value 2	Chickpea-wheat	Timely	2	
Diverse low value	(Faba/lupin)-canola-wheat	Timely	2	
Diverse (mix)	HDL*-canola-wheat	Early, timely	2, 7	Yes
Continuous wheat	Wheat-wheat-wheat	Timely	2, 7	
Fallow	Fallow-canola-wheat	Early, timely	7	

* HDL = high density legume dominated by vetch

A brief recap on the dry 2018-2019 seasons

The 2018 and 2019 seasons were consecutive decile 1 seasons across the sites, while 2020 was decile 7-9 across the sites (Table 2).

Table 2. Annual rainfall (irrigation in brackets) at the experiment sites in 2018 and 2019 and the long-term median rainfall.

Site	2018	2019	2020	LTM
Greenethorpe	359	353	726	579
Wagga Wagga	403	320	557	526
Urana	276	222	488	449
Condobolin	218 (120)	162 (118)	685	434

As would be expected, the productivity and profitability of the individual crop options differed significantly between the decile 1 conditions in 2018 and 2019, and the wetter conditions in 2020. A detailed consideration of the productivity and profitability of the different crops and systems under the dry conditions in 2018 and 2019 was provided in two previous papers which can be found here:

As a brief summary of the results, despite the decile 1 conditions, the annual earnings before interest and taxes (EBITs) for different crop options varied from -$500 to $1700/ha in 2018, and -$500 to $1200/ha in 2019, with the 2 year average annual EBITs varying from $-50 to $1000/ha across the sites.

Early-sown grazed crops were highly profitable (double to triple non-grazed equivalents) even without grain harvests, while many grain-only crops were low yielding or cut for hay. Both barley grain and hay were profitable options in the dry years, and there was a noticeable effect of the amount of stubble cover remaining over summer (range 0.9 to 9 t/ha depending on crop and sequence).

Legumes and N fertiliser in the dry years

Grain legume crops, and diverse sequences including legume options outperformed baseline canola-wheat sequences at all sites during the dry 2018-2019 seasons. This resulted from both the profitability of the legumes in their own right, and the legacy of water (20-60 mm) and N (50-100 kg/ha) that influenced subsequent crops in the sequence.

The higher N strategy (decile 7) generally provided increased biomass for grazing crops or hay cuts but had either no effect or a negative effect on grain yield and profit in the dry years. However, the N carried over from one season to the next to influence biomass (positively) and yield (variable effects) in subsequent years.

At the completion of the first two years of the project there were systems at all sites achieving annual average EBITs across the 2 dry years $200 - $600/ha above the Baseline C-W-W system.

The 2020 season – major crop responses observed

At the time of writing, the 2020 data set for Wagga and Greenethorpe had been finalised so examples for those sites are included. Data for the other sites will be available for the presentation. The high rainfall in 2020 shifted the agronomic management focus from water management and decisions on graze-out and hay cutting in spring, to a focus on higher N fertiliser requirements and disease management.

Overall yield and profit levels were high in 2020, but some observations were consistent

The excellent seasonal conditions meant that both the yield and EBIT of the individual crop options across the sites were generally higher in 2020 than in the previous seasons (Table 3). The ranges in yield and profit for the crops shown in Table 3 are driven by effects of different crop sequence and N strategy which will be discussed further in following sections.

Table 3. Summary of overall yield and EBIT range for different crops in 2020. Highest yields did not correspond to highest profit at either sites for the different crop types. (compare grey squares).

Crop	Sowing (date)	Graze	Variety	Grazing (dse.d/ha)	Yield range (t/ha)	EBIT range ($/ha)
			Wagga Wagga			
Canola	E (10/3)	G	Hyola® 970CL	730 - 1780	2.1-3.6	$1220 - $1630
Canola	E (31/3)	NG	Hyola 970CL	-	3.6-3.9	$1290 - $1500
Canola	T (23/4)	NG	43Y92	-	3.5-4.3	$1202 - $1590
Wheat	E (10/3)	G	Bennett⚘	1360 - 2070	5.3-6.1	$1250 - $1370
Wheat	E (31/3)	NG	Bennett⚘	-	5.4-6.1	$455 - $657
Wheat	T (12/5)	NG	Beckom⚘	-	5.2-7.5	$645 - $1120
Barley	T (12/5)	NG	LaTrobe⚘	-	7.5-8.0	$720 - $780
Chickpea	T (12/5)	NG	Captain⚘	-	3.3	$988
Lentil	T (12/5)	NG	HallmarkXT⚘	-	4.2-4.4	$1708 - $1851
Lupin	T (12/5)	NG	Bateman⚘	-	4.8	$1453
HDL vetch	E (10/3)	G	Timok⚘	1200	-	$1260
			Greenethorpe			
Canola	Early	G	Hyola970CL	2690 - 3600	3.2 - 3.9	$2700 - $2800
Canola	Early	NG	Hyola970CL	-	2.9 - 3.1	$1,100
Canola	Timely	NG	HyTTec® Trophy	-	4.4 – 4.9	$2000 - $2200
Wheat	Early	G	Bennett⚘	1600 - 2150	3.7-6.2	$1,100 - 1700
Wheat	Early	NG	Kittyhawk⚘	-	8.0-8.3	$1400 - $1500
Wheat	Timely	NG	Coolah⚘	-	6.8-8.7	$1080 - $1550
Chickpea	Timely	NG	Captain⚘	-	4.1	$1331
Lentil	Timely	NG	HallmarkXT⚘	-	3.1	$1100
Faba	Timely	NG	Samira⚘	-	5.3	$652
HDL vetch	Early	G	Morava	1480	4.4 (hay)	$1468
HDL vetch	Timely	NG	Morava		4.9 (hay)	1,050

HDL=High Density Legume dominated by vetch, E=early sowing, T=timely sowing, G=grazed, NG = ungrazed and dse.d/ha = dry sheep equivalents per day per hectare.

Some consistencies in crop performance in 2020 with 2018 and 2019 include:

- Overall yield and profit levels are higher at Greenethorpe than Wagga reflecting the higher rainfall and longer growing season. However, yields and profit levels of some crops (e.g. lentils) were superior at Wagga
- Early sown grazed crops were among the most profitable at both sites and outperformed early-sown grain-only options in most circumstances. Grain-only crops of wheat at the Wagga site had similar yields to grazed crops, while the same comparison for canola yield at Wagga showed grazing reduced grain yield. At Greenethorpe the results differed with grazing canola producing higher yield than un-grazed crops of the same variety
- Timely-sown grain legume options at Wagga matched or exceeded the profit generated by un-grazed timely canola and wheat, while at Greenethorpe grain legumes matched the cereals, but not canola, which was

the most profitable option (by ~$500/ha). Lentils were the most profitable at Wagga, while the chickpea and vetch did best at Greenethorpe

- The top barley yield was higher than that of wheat at Wagga however the profit was higher for the wheat.

Responses to crop sequence and N fertiliser strategies in 2020

Early-sown grazed crops

The early-sown wheat and canola crops both responded significantly and similarly to crop sequence and N fertiliser at Greenethorpe and Wagga in 2020. Table 4 summarises the key responses using the data from Greenethorpe. In the canola-wheat-canola sequence, the additional N (in soil and applied) in the decile 7 strategy (~extra 100 kg N /ha) increased canola grazing and yield by 765 dry sheep equivalent (dse) days/ha and 0.2 t/ha respectively, and wheat grazing and yield by 515 dse days/ha and 2.5 t/ha. This generated an increase in EBIT of $103/ha for canola and $598/ha for wheat.

Diversifying the sequence with a high density legume (HDL) (with decile 2 N strategy) compared to the canola-wheat-canola strategy with decile 2, increased the grazing of canola by 906 dse days/ha but reduced canola grain yield by 0.5 t/ha so that the EBIT was similar. In contrast in the grazed wheat, the diversified sequence had an increase in grazing (387 dse d/ha), yield (0.6 t/ha) and EBIT ($278/ha) but did not match the EBIT of the decile 7 N treatment, predominately due to the higher grain yield.

The N legacy of the HDL measured at sowing was 34 kg N/ha in the canola and 67 kg N/ha in the wheat, and it is likely to provide further benefits from greater in-season mineralisation.

Table 4. Response to crop sequence and N strategy in early-sown grazed canola and wheat crops at Greenethorpe in 2020. Data for soil N at sowing (0-2m) and applied fertiliser N are shown.

Sequence 18-19-20	Crop variety	N strategy	Graze (dse.d/ha)	Yield (t/ha)	EBIT ($/ha)	Nitrogen supply (kg/ha)		
						Soil	Applied	TOTAL
Canola								
C-W-**C**	C = Hyola 970	D2	2689	3.7	$2708	210	100	310
C-W-**C**	C = Hyola 970	D7	3454	3.9	$2839	167	259	426
W-HDL-**C**	C = Hyola 970	D2	3595	3.2	$2774	244	65	309
Wheat								
W-C-**W**	W = Bennett⊕	D2	1631	3.7	$1137	227	15	242
W-C-**W**	W = Bennett⊕	D7	2146	6.2	$1735	196	137	333
HDL-C-**W**	W = Bennett⊕	D2	2018	4.3	$1414	294	15	309

W-Wheat, C=Canola, HDL=high density legume, D2= nitrogen treatment for a decile 2 rainfall projected from mid-winter and D7 = nitrogen treatment for a decile 7 rainfall projected from mid-winter.

Timely sown un-grazed crops

The timely-sown wheat and canola crops also responded significantly to crop sequence and N fertiliser at the sites in 2020, demonstrated here in data from Wagga Wagga (Table 5).

In the canola, a positive yield response to N was only observed in the canola-cereal systems but no yield response in sequences that included legumes. The lowest canola profit ($1232/ha) was generated by the intense baseline low N system, while the equal highest profit occurred in the baseline with decile 7 N ($1578/ha) and the diverse HDL with decile 2 N ($1590/ha). In this case, the diverse treatment profit was generated at lower total cost ($650/ha *vs* $700/ha) reducing production risk.

Table 5. Effect of previous sequence and N strategy on the yield and profit of timely sown canola (upper Table) and wheat crops (lower Table) at Wagga Wagga in 2020. Diverse sequences that include a legume are shown in grey. Total Min N at sowing (0-1.4m) and top-dressed N are shown.

System	Sequence 18-19-20	N strategy	Yield (t/ha)	Crop intensity	EBIT ($/ha)	Nitrogen supply (kg/ha)		
						Soil	Applied	TOTAL
Timely canola (43Y92) sown 23 April								
Baseline	W-B-**C**	D2	3.7	1 in 3	$1355	86	80	166
Baseline	W-B-**C**	D7	**4.3**	1 in 3	**$1578**	123	170	293
Intensive baseline	C-W-**C**	D2	3.5	1 in 2	$1232	79	106	185
Intensive baseline	C-W-**C**	D7	**4.0**	1 in 2	**$1440**	150	138	288
DivHV1	W-Le-**C**	D2	3.8	1 in 3	$1383	111	106	217
DivHV1	W-Le-**C**	D7	3.6	1 in 3	$1202	105	178	283
DivMix	W-HDL-**C**	D2	4.1	1 in 3	$1590	124	53	177
DivMix	W-HDL-**C**	D7	4.2	1 in 3	$1356	99	188	287
DivLV	W-Lu-**C**	D2	4.0	1 in 3	$1475	67	106	173
Timely wheat (Beckom⊕) sown 12 May								
Baseline	B-C-W	D2	7.3	1 in 3	$1095	51	101	152
Baseline	B-C-W	D7	7.0	1 in 3	$1013	111	101	212
Intensive baseline	W-C-W	D2	6.9	1 in 2	$960	52	101	153
Intensive baseline	W-C-W	D7	6.9	1 in 2	$917	61	147	208
ContW	W-W-W	D2	5.2	1 in 1	$645	111	41	152
DivHV1	Le-C-W	D2	7.0	1 in 3	$1014	57	87	144
DivHV1	Le-C-W	D7	7.4	1 in 3	$1079	81	129	210
DivMix	HDL-C-W	D2	7.0	1 in 3	$1007	73	78	151
DivMix	HDL-C-W	D7	7.5	1 in 3	$1114	79	129	208
DivLV	Lu-C-W	D2	7.0	1 in 3	$1049	89	60	149
DivHV2	W-Ch-W	D2	6.4	1 in 2	$901	88	60	148

W-Wheat, C=Canola, B=Barley, Le=lentil, Lu=Lupin, HDL=high density legume, D2= nitrogen treatment for a decile 2 rainfall projected from mid-winter and D7 = nitrogen treatment for a decile 7 rainfall projected from mid-winter. Soil nitrogen is measured pre-sowing and applied nitrogen is spread as urea. DivHV1 = Diverse high value 1, DivMix = Diverse (mix), DivLV = Diverse low value, DivHV2 = Diverse high value 2.

In contrast to the canola, the timely wheat only responded to higher N in the diverse sequences and not in the canola-wheat sequences, and it appears sequence and crop intensity had a much more significant overriding effect on wheat yield than nitrogen. For example, the yield of the continuous wheat (1 in 1 intensity, decile 2) was only 5.2 t/ha, the yields in the sequences that were 1 in 2 intensity and with decile 2 nitrogen were 6.4 to 6.9 t/ha, while the yields in sequences that were 1 in 3 and D2 nitrogen were 7.0 to 7.5 t/ha. The highest yields of 7.4 to 7.5 t/ha were in diverse sequences with decile 7 N. In most cases the extra cost of N was not reflected in higher profit, while the effects of crop intensity on profit were clear.

System performance across the 3-year sequence

Overall average annual EBITs across the 3 years were higher at Greenethorpe (Figure 1) than at Wagga Wagga (Figure 2) as would be expected by the higher rainfall and yield potential at the site.

Grazed crops remain the most profitable option at both Greenethorpe and Wagga Wagga (see green (lighter) bars) at both sites across the 3-year period and were also the most profitable in individual years (not shown). The grazing income was significant in all years, including the drought years and more than offsets any impact on grain yield. The profits from grazed crops were also responsive to fertiliser N in both the intense C-W sequence and in the diverse sequence with the HDL, however the return on investment and on N was generally improved in the diverse sequence with decile 2 N strategy at both sites.

The 3-year average annual EBITs among the un-grazed treatments were relatively consistent except for the early-sown un-grazed sequence at Greenethorpe and the early-sown fallow and ley-phase at Wagga Wagga. These treatments suffered as a result of the poor performance of the early-sown winter wheat and canola which generally flowered too late and suffered badly in the drought, and to income forgone in fallow and ley phase.

Of the other ungrazed treatments, there were several at both sites with EBITs that exceeded the baseline system (black in Figures 1 and 2) and these included diverse options with decile 2 N strategy at both sites. In the diverse systems at both sites, the decile 2 N strategy has been more profitable than the decile 7 N strategy. The same trend is also the case for the intense baseline and baseline systems at Greenethorpe, while at Wagga the decile 7 N strategy has been marginally more profitable, suggesting a greater responsiveness to N at that site. The decile 2 N strategy generally has a marginally better return on investment overall, but a much higher return on N investment. The response to nitrogen should be considered in the context of two decile 1-2 seasons and one decile 5-6 season.

The continuous wheat system (timely wheat with decile 2 N) has performed well at Greenethorpe though not as well at Wagga Wagga, and this is presumably due to the lack of significant disease pressure during and after the consecutive droughts in 2018-2019, and lack of significant weed pressure. Fungicides were cost effective in controlling disease in the wheat year and high stubble loads retained water in the dry seasons.

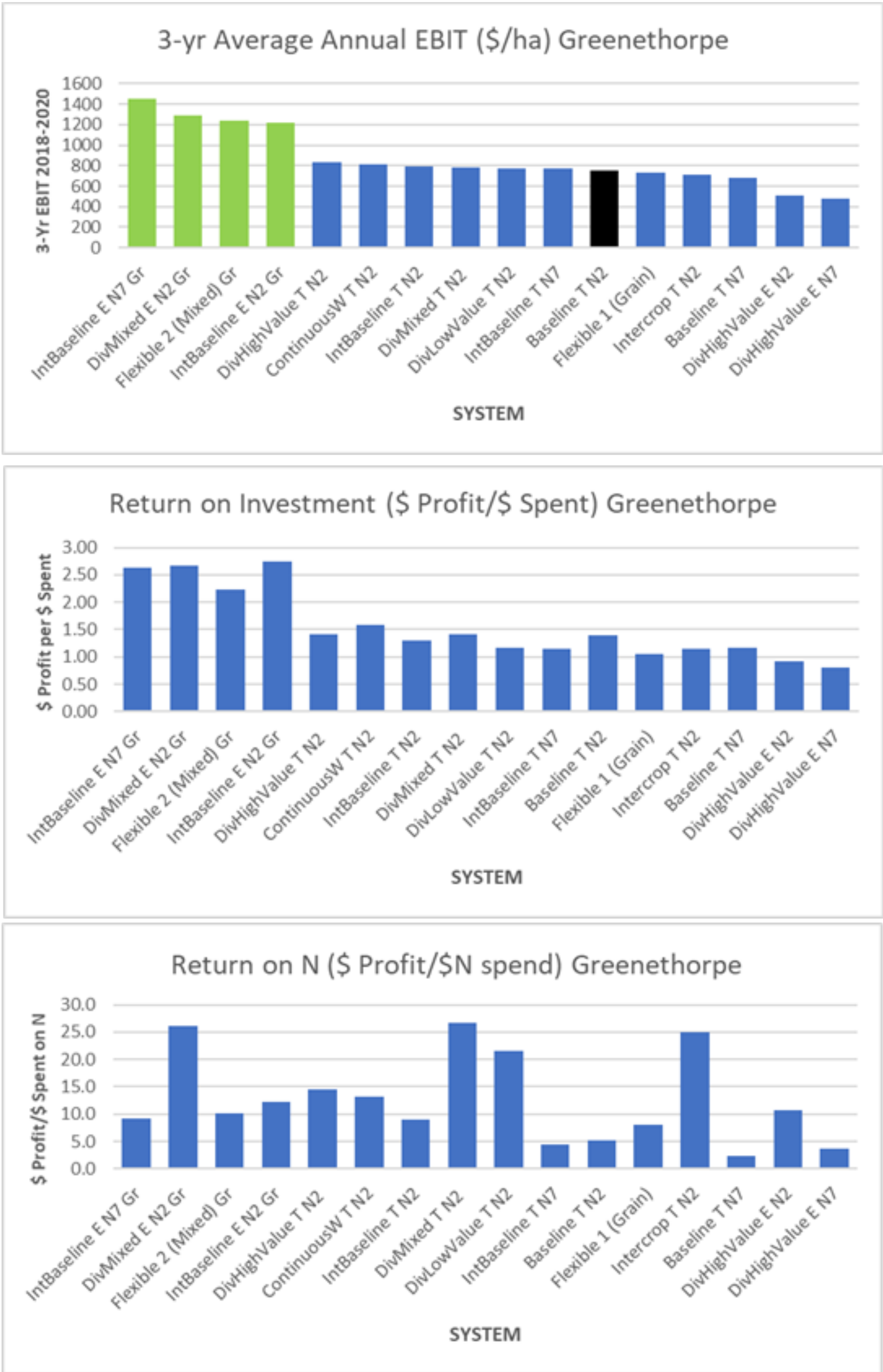

Figure 1. Average annual EBIT (top), return on investment (centre) and return per $ spent on N fertiliser across 3 years (2018-2020) for a range of systems at Greenethorpe. Systems are arranged in order of highest to lowest annual average EBIT in all panels. (green=grazed; black=baseline)

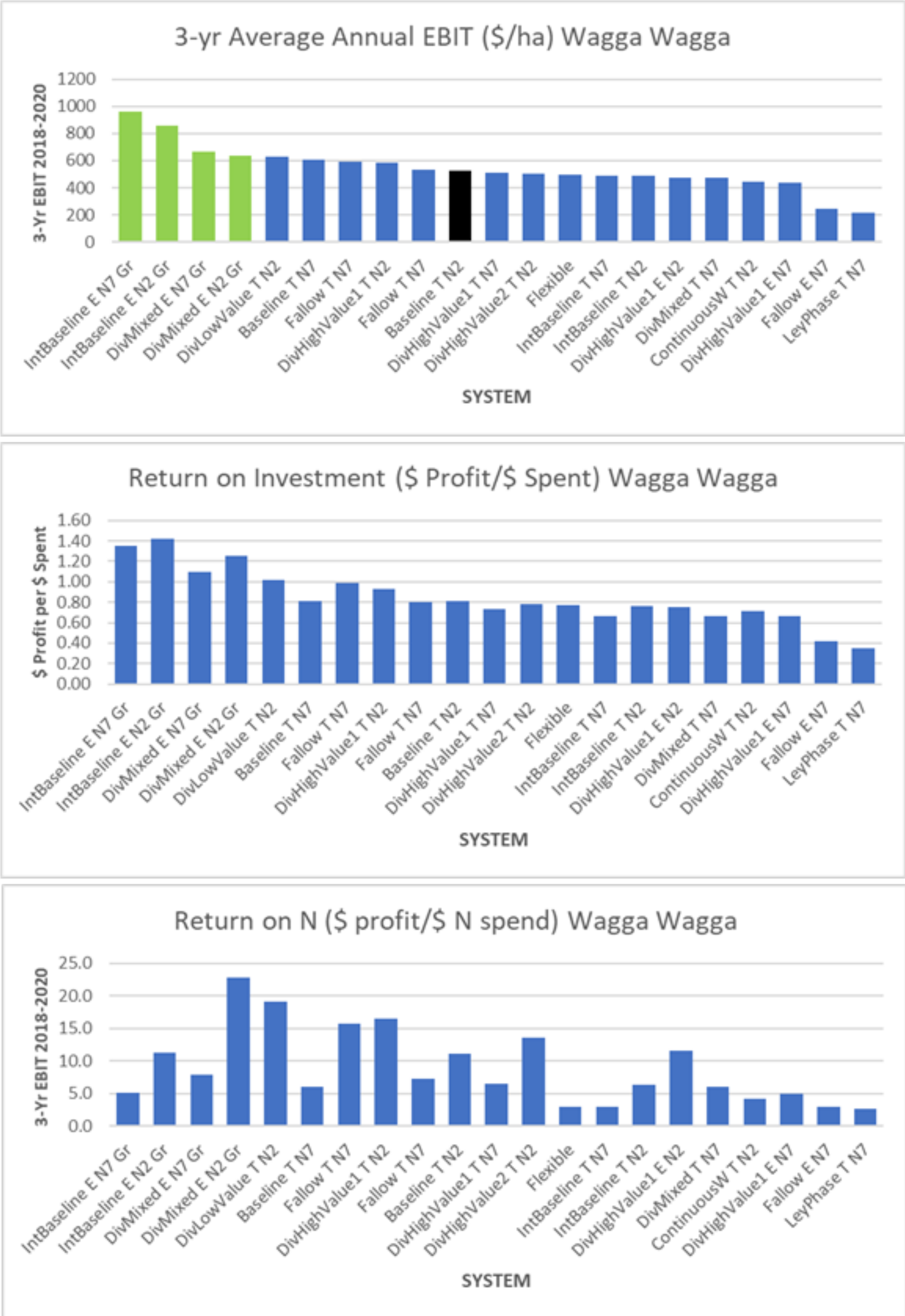

Figure 2. Average annual EBIT (top), return on investment (centre) and return per $ spent on N fertiliser across 3 years (2018-2020) for a range of systems at Wagga Wagga. Systems are arranged in order of highest to lowest annual average EBIT in all panels. (green=grazed; black=baseline)

Conclusions

The results of these system experiments show that both sequence and N strategies have significant effects on crop productivity, profitability and risk in individual years, and these effects can differ depending on individual seasonal conditions. However, the significant legacy effects of crop sequence (crop intensity and legume inclusion) and N strategy across seasons mean that the profitability of the systems over 3 years can play out differently to responses observed in a single season. Further analysis and simulation of this data set will explore this in more detail.

The current area sown to wheat in cropping systems of NSW varies between 55 and 60% which approximates one wheat year every two growing seasons. Years like 2020 represent opportunities to maximise farming systems profits. Results from this farming systems research indicate that on-farm income could be increased if the wheat area were reduced to 30% or approximately one wheat year in every three growing seasons. Profit in this sequence (1:3) are maximised for wheat where more aggressive nitrogen strategies are pursued.

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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 especially thank Mr Rod Kershaw at “Landra” Greenethorpe and Warakirri Cropping “Karoola Park” Urana for the use of land for experimental purpose and for management advice at the sites. We also thank Peter Watt (Elders), Tim Condon (DeltaAg), Greg Condon (Grassroots Agronomy) and Chris Baker (BakerAg) for the many useful discussions in their role on the Project Advisory Committee.

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Appendix 1: Determining earnings before interest and tax (EBIT)

To calculate the annual EBIT for all treatments, we have initially used the following assumptions/prices.

A. Expenditure

1. All herbicides/fungicides/insecticides, seed dressings, fertilisers, GRDC levies and crop insurance costs were obtained from the annual NSW winter cropping guide or the annual SAGIT farm gross margin and enterprise planning guides with links at:
   i. *https://www.dpi.nsw.gov.au/agriculture/broadacre-crops/guides/publications/weed-control-winter-crops*
   ii. *https://grdc.com.au/resources-and-publications/all-publications/publications/2019/farm-gross-margin-and-enterprise-planning-guide*
2. All seed was priced according to purchasing as pure treated seed from seed companies. i.e. In 2019, prices used were wheat seed at $1/kg, faba bean seed at $1.20/kg, chickpea seed at $1.80/kg and canola seed ranging between $23-30/kg
3. All operations costs (sowing, spraying, spreading, haymaking, harvest) were based on the principal that a contractor performed the task. These costs were extracted from the yearly SAGIT Farm gross margin and enterprise planning guides. i.e. In 2019 prices used included sowing at $50/ha, ground spraying at $10/ha, cereal harvest at $70-85/ha, cut/rake/bale hay at $115/ha, with links at: *https://grdc.com.au/resources-and-publications/all-publications/publications/2019/farm-gross-margin-and-enterprise-planning-guide*
4. All variety levies for all crops and varieties were determined from the variety central website at: (e.g. for pulses) *http://www.varietycentral.com.au/varieties-and-rates/201920-harvest/pulse/*

B. Income

1. Wheat, barley and canola grain prices were obtained on the day of harvest from the AWB daily contract sheet for specific regions relating to trial location at: https://www.awb.com.au/daily-grain-prices
2. Pulse grain prices were obtained on the day of harvest from Del AGT Horsham and confirmed with local seed merchants.
3. Hay prices were obtained in the week of baling from a combination of sources including The Land newspaper and local sellers.

Appendix 2: Determining grazing value

To determine the estimated value of grazing the early sown crops, we have used the following formulae:

Winter grazing value ($/ha) = Plant dry matter (kg) removed x Liveweight dressed weight (c/kg) x Feed conversion efficiency (0.12) x Dressing % (lambs) x Feed utilisation efficiency (0.75)

Dressed weight and value:

- Lambs = 22.9kg (3 year average of light, heavy and trade lambs)
- Dressed weight = $6.25/kg (3 year average NSW)
- Dressing percentage = 50%

An example of 45kg lambs grazing winter Hyola 970 canola:

3800kg plant DM removed x $6.25 x 0.12 x 50% x 0.75 = $1069/ha

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Managing crop differences in soil water extraction and legacy impacts within a farming system

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Key words

Legumes, soil water, water-use-efficiency, rotation, legacies

GRDC codes

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Take home message

- Shorter season, faster maturing crops can leave residual surface water from unutilised late season rain and/or residual deep water due to shallower roots and quicker maturity.
- Legumes such as lentils, fababeans, field pea, and chickpea often leave 20-40 mm extra residual soil water compared to canola and winter cereals.
- Higher residual water may not remain at sowing of next crop – fallow efficiency differences between crops and seasons can influence this – e.g. low cover after legumes.
- For summer crops, mungbean typically leaves 20mm more residual water than sorghum/maize while cotton leaves 20mm less (i.e. mungbean > sorghum/maize > cotton)
- Early-sown, slower maturing crops (e.g. early sown winter crops) can dry the profile deeper (>2m) and utilise deep stored soil to support higher yield in dry springs. The legacy of drier soil may warrant changes to crop sequence and management to avoid yield penalties.
- Extra residual water at sowing can increase grain yield of subsequent crops when water is limited during the critical period for yield determination so the marginal WUE (i.e. extra yield per mm of extra soil water available) can be very high (>60kg/ha/mm).
- As the value of the residual water is seasonally dependent, understanding how management (crop choice, sowing dates, N management) can be adjusted to capture value from such legacies across a sequence of crops is the goal of current farming systems research.

Introduction

Stored soil water at sowing is critical for the productivity of grain crops across many parts of Australia's cropping zone, especially when in-crop rainfall is limited. Deep stored water can have a high marginal water use efficiency (i.e. the yield increase per extra mm of soil water at sowing) because it is available for use during the critical period for yield determination. The impact of stored soil water on the yield of subsequent crops is highly season dependent. In very dry seasons, the value may be low because of the low yield potential of highly stressed, low biomass crops, while in very wet growing seasons the reliance on stored soil water may diminish. However, in many intermediate seasons, stored water will add to the total water available for crop growth, especially later in the season with significant productivity benefits. Different management levers (crop sequence, sowing dates, N management) can influence the availability of stored soil water and these legacies can affect the productivity, water use efficiency and profit across a crop sequence.

In this paper we use data collected from recent GRDC farming systems research projects across Queensland and New South Wales to explore the question - How do different crops in a sequence influence the soil water available to subsequent crops? This is influenced by both differences in crop water extraction (as highlighted in paper by Verburg et al. 2021) which can influence the residual soil water left at harvest, but also subsequent fallow water accumulation prior to sowing the next crop. Understanding how different crops influence the available water in the system for subsequent crops is important to (i) design crop sequences that make better use of this limited resource, (ii) to tailor management (e.g. sowing date, fertiliser applications or variety choices) based on previous crop history, and/or (iii) to avoid situations where low soil water could increase the risk of crop failure.

Crop differences in residual soil water & implications for subsequent crops

Grain legumes often leave more residual soil water than cereals or canola

Across a range of experimental comparisons, we have found that legumes such as chickpea, fababean, field pea and vetch often leave more residual soil water at harvest than winter cereals and canola. This is evident in the both summer-dominant (Table 1) and the uniform rainfall zones (Table 2). However, the differences are not always consistent and vary significantly across seasons. In the summer dominant rainfall regions, it seems that in dry winters with limited spring rainfall (e.g. Eastern Darling Downs in 2015) these differences were smaller, suggesting all crops could extract similar amounts of soil water under water-limited conditions. However, in wetter seasons or with higher spring rainfall (e.g. Narrabri and Liverpool plains 2016, Eastern Darling Downs 2017) larger differences between the grain legumes and winter cereals and canola were evident. We believe this occurs because the legumes are beginning to senesce, reducing their water demand earlier in the spring and do not utilise soil water during that period to the same extent. For example, in one such comparison on the Eastern Darling Downs in 2017, legumes such as fababeans and chickpea had around 100 mm more soil water after harvest than wheat (Table 1).

In southern NSW, a range of different legumes also tended to leave more residual water in the soil profile, as shown for 2018 during a very dry spring period (Table 2). This was evident on both the deep red loam soil at Greenethorpe and on the heavier clay sodosol at Urana. The differences were evident in both early-sown winter comparisons at both sites, and in later-sown spring varieties. The differences were in part due to the shallower rooting of later-sown legumes as shown by the differences in measured rooting depth at Greenethorpe (Table 3), which also shows the very deep rooting and drier soil profile following early-sown winter canola sown in early April.

Despite leaving more water, low summer cover can reduce fallow efficiency after legumes

While we regularly find more soil water left after grain legumes compared to wheat or canola, this may not always translate into more soil water at the sowing of subsequent crops, or to significant crop yield benefits (see Table 1 & 2). Across our experiments, despite differences of up to 50 mm of more soil water left after grain legumes, the lower efficiencies of water accumulation during the subsequent fallow, has meant that differences in soil water often diminished prior to sowing subsequent crops. This occurred because drier soil profiles are less prone to evaporative losses of this water, and because the residue cover and enhanced rainfall infiltration following winter cereals and canola compared to the low and shorter-lived ground cover left after grain legumes. Some differences exist between northern and southern regions due to differences in soil types, summer rainfall intensity and frequency.

Within the 6 experimental comparisons in the summer-dominant rainfall region here (see Table 1), higher residual soil water at harvest has only translated into more soil water available in the subsequent crop in a single case. In that case, grain legumes had over 100 mm more soil water after harvest, but by the sowing of the subsequent wheat crop the difference was reduced to only 20-30 mm. Nonetheless, the additional soil water translated into a yield benefit of 0.8-0.9 t/ha. In all other cases, there were no significant yield differences in subsequent crops that could be attributed to soil water at sowing.

Table 1. Comparisons of residual soil water post-harvest of winter crops in the summer-dominant rainfall zone and implications for plant available water at sowing and yield of following crops in the sequence. Note: Only where crops were grown with a similar starting condition (e.g. fallow length) and a common crop following are compared. Other aspects (e.g. soil nitrogen, weeds and pathogens) are also influenced by the previous crop, hence all effects are hard to attribute entirely to soil water availability.

Site – year	Crop	Residual PAW (mm)	PAW prior to next crop (mm)	Following crop & year	Grain yield (t/ha)
Narrabri, 2016	Chickpea	65^{b}	140	Wheat, 2016	2.7
	Fababean	75^{b}	145		2.5
	Canola	70^{b}	155		2.6
	Fieldpea	130^{a}	150	-	-
Liverpool plains, 2016	Chickpea	100^{b}	160	Wheat, 2016	3.4
	Fababean	150^{a}	150		3.6
	Fieldpea	135^{a}	155		3.7
Trangie (Red soil), 2017	Chickpea	50	35	Barley, 2016	1.6
	Wheat	15	25		1.7
Eastern Darling Downs, 2015	Fababean	75	110	Durum wheat, 2016	8.3
	Canola	65	120		8.4
Eastern Darling Downs, 2017	Wheat	-10	140	Wheat, 2020	3.4
	Chickpea	95	160		4.3
	Fieldpea	100	170		4.2
	Wheat	70	200	Sorghum, 2016	7.2

Eastern Darling Downs, 2015	Canola	85	220		7.3
	Chickpea	60	200		7.5
	Fababean	75	200		7.7
	Fieldpea	80	185		7.6

In southern NSW, there were also examples of large differences in residual soil water after legumes compared to non-legumes and these differences diminished by the time the subsequent crops were sown (Table 2). At both Greenethorpe and Urana, differences at harvest of around 25-40mm were reduced to 10-25mm at sowing of subsequent crops. In some cases, the legume retained a small soil water advantage at sowing of the subsequent crop. However, at Greenethorpe the amount of stored water after wheat and canola increased by 56 – 59 mm over the summer fallow, while after chickpea it increased by only 25mm, so that by sowing there was more water available after wheat. In general, the yields achieved by the subsequent crop reflect the differences in water at sowing with small differences in most cases, as 2019 turned out to be another dry year across the sites (Decile 1 -3).

Table 2. Comparisons of residual soil water post-harvest of winter crops in the equi-seasonal rainfall zone of southern NSW and implications for plant available water at sowing and yield of following crops in the sequence. Note: Only where crops were grown with a similar starting condition (e.g. fallow length) and a common crop following are compared. Other aspects (e.g. soil nitrogen, weeds and pathogens) are also influenced by the previous crop, hence all effects are hard to attribute entirely to soil water availability.

Site – year	Crop	Residual PAW (mm)	PAW prior to next crop (mm)	Following crop & year	Grain yield (t/ha)
Greenethorpe, 2018 (Kandosol)	Vetch	75	124	Winter Canola, 2019	4.0 (forage)
	Winter Wheat	48	108		3.6 (forage)
Greenethorpe, 2018 (Kandosol)	Chickpea	76	101	Spring Wheat, 2019	2.6
	Spring Canola	36	92		2.4
	Spring Wheat	59	117		2.8
Urana, 2018 (Sodosol)	Lentil	170	217	Spring Canola, 2019	1.0
	Spring Wheat	130	208		1.0
Urana, 2018 (Sodosol)	Fababean	184	153	Spring Canola, 2019	1.0
	Barley	169	155		1.1
	Wheat	159	147		1.0

Agronomy to manage the legacy of dry soils after high yielding, early-sown crops

Early-sown, high yielding crops can leave a legacy of drier and N-depleted soils in seasons where the spring is dry (as in 2018 and 2019 in much of southern NSW and northern Victoria) (see Figure 1). If the subsequent rainfall during the summer fallow is low, and fails to refill the soil profile, it may be necessary to reconsider the crop sequence plan, or the intended sowing date of subsequent crops in order to avoid high risk scenarios.

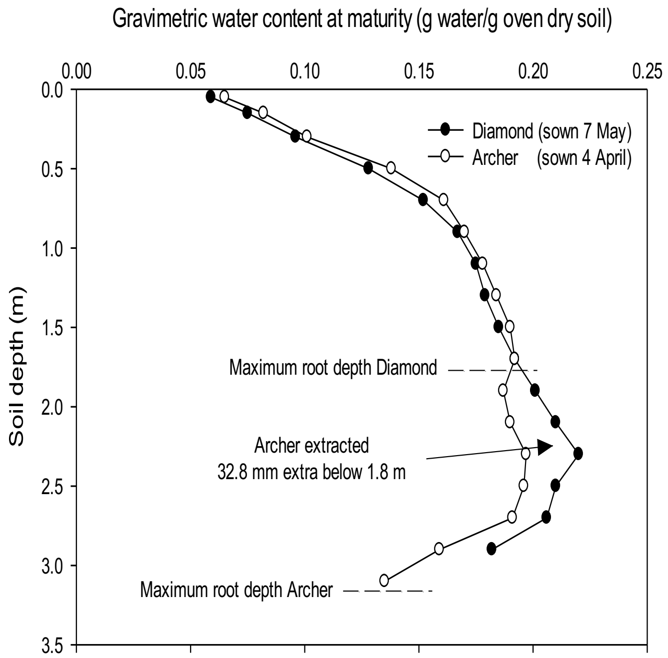

Figure 1. Residual soil water at harvest following a terminal drought in 2018 showed deeper rooting and increased deep water use in an early April sown canola variety (Archer) compared with May-sown variety (Diamond) with similar flowering dates (Kirkegaard et al., 2020).

The issue of better managing the legacy effects is the topic of the current farming systems project where a range of crop sequence choices have been combined with early- and later-sown crops with different nitrogen management to investigate the productivity, profitability and risk of different management options. Table 3 shows the residual plant available water and mineral N to 2m depth following a range of crops at Greenethorpe in 2018. The early-sown winter canola had no plant available water left in the top 2m, while the other crop options had between 24 and 57 mm more stored water left in the profile. The legumes also left a legacy of higher soil mineral N. The different rooting depth and water use patterns of these crops may provide opportunities to plan sequences where high value legumes can be grown in sequence with early-sown, deep-rooted grazing crops both to capitalise on the water and N left by the legume, and to reduce the risk of negative legacy effects after early-sown crops, by sowing a less water-demanding crop.

Table 3. Residual plant available water (mm) and mineral N (kg/ha) at harvest to a depth of 2m following a range of different crop options at Greenethorpe in the dry year of 2018.

Crop	Sowing date	Rooting depth (cm)	Plant available water (mm)	Mineral N (kg/ha)
Winter canola (grazed)	3 April	370	0	24
Spring canola (hybrid, grain)	17 April	340	42	16
Spring canola (OP-TT, grain)	7 May	220	24	28
Winter wheat (grazed)	4 April	340	42	31
Spring wheat (grain)	7 May	185	24	39
Lentil	8 May	150	48	79
Chickpea	8 May	150	46	129
Fababean	9 May	150	57	103

A summary of the pros and cons of the various options to precede early sown canola crops is shown in Table 4, as water is not the only aspect of the farming system influenced by crop choice.

Table 4. A summary of the impacts of different preceding crop choices to precede early sown canola crops (the more stars the better for each aspect).

Sequence option	Residual soil water	Nitrogen	Ground cover	Weed control	Relative profit
Grain legume	***	***	***	***	***
Legume hay	****	**	*	****	****
Legume brown manure	****	*****	****	*****	*
Cereal grain	*	*	*****	*	****
Cereal hay	**	*	*	***	*****
Long fallow (with cover)	*****	***	variable	****	*

Summer crops also create soil water legacies in farming systems

We have also found some differences in summer crops in terms of their influence on residual soil water and available water in subsequent crops (Table 5). In our experiments, two direct comparisons (sown on same data on common history) between cotton and summer cereals (maize or grain sorghum) have shown cotton leaving the soil around 20-30 mm drier. However, because of the lower ground cover after cotton, the difference was preserved until the sowing of the subsequent crop following both short (8 month) and long (18 month) fallows. In both cases, the difference in starting soil water resulted in a significant yield difference of 0.7 and 1.2 t/ha in a subsequent sorghum crop. Our data also suggests that mungbean often leaves additional soil water compared to sorghum, though this can depend on the relative timings of the crops. However, as with the winter grain legumes this difference in soil water is often diminished by the time subsequent crops are planted.

Table 5. Comparisons of residual soil water post-harvest of summer crops in the summer-dominant rainfall zone and implications for plant available water at sowing and yield of following crops in the sequence. Note: Only where crops were grown with a similar starting condition (e.g. fallow length) and a common crop following are compared. Other aspects (e.g. soil nitrogen, weeds and pathogens) are also influenced by the previous crop, hence all effects are hard to attribute entirely to soil water availability.

Site – year	Crop	Residual PAW (mm)	PAW prior to next crop (mm)	Following crop & year	Grain yield (t/ha)
Eastern Darling Downs, 2016	Maize	150	150	Sorghum, 2017	5.5
	Cotton	120	120		4.8
Eastern Darling Downs, 2018	Sorghum	-5	130	Sorghum, 2020	3.7
	Cotton	-20	100		2.5
Eastern Darling Downs, 2017	Sorghum	20	100	Mungbean, 2019	1.58
	Mungbean	30	100		1.15
Eastern Darling Downs, 2018	Sorghum	-20	20	Mungbean, 2019	0.58
	Mungbean	0	30		0.60

Long-term predictions of residual water – crop comparisons

While our experimental results provide a diverse range of seasonal and production environments, it is likely that the residual water left by different crops will be highly influenced by seasonal conditions and timing of rainfall. Hence, we have used the APSIM model to predict over 50 different seasons (1957-2012) how wheat, canola and chickpea compare in terms of residual soil water in 2 contrasting environments (Goondiwindi and Wagga Wagga). These predictions are consistent with our observed data. At Goondiwindi, in 3 out of 5 years chickpea is predicted to leave 20-30 mm more soil water at harvest than wheat and canola. These differences are smaller under the wettest 30% of seasons where large rainfall events at harvest or late in the season replenish soil water in the profile in all crops. At Wagga Wagga, differences in residual soil water between chickpea and wheat were small and only occurred in the driest 25% of years. On the other hand, APSIM predicted the canola had a 15-20 mm drier profile than wheat or chickpea in 3 of 4 years.

Simulations also predict less accumulation of soil water after chickpea than following wheat, resulting in very little differences in soil water at sowing of the next crop at Goondiwindi, and more soil water at sowing after wheat at Wagga Wagga. The soil water deficit at harvest of canola compared to wheat was maintained at both sites.

These long-term predictions are consistent with our experimental findings, demonstrating relative differences between wheat, canola and chickpea and these findings are likely to occur in other seasonal conditions. While other legumes such are lentil or fababean have been shown to leave more soil water than chickpea, we are unable to simulate these crops reliably in APSIM at present. However, we would expect differences in soil water at harvest to diminish by sowing of the next crop after lentils in a similar way as measured and predicted for chickpea here.

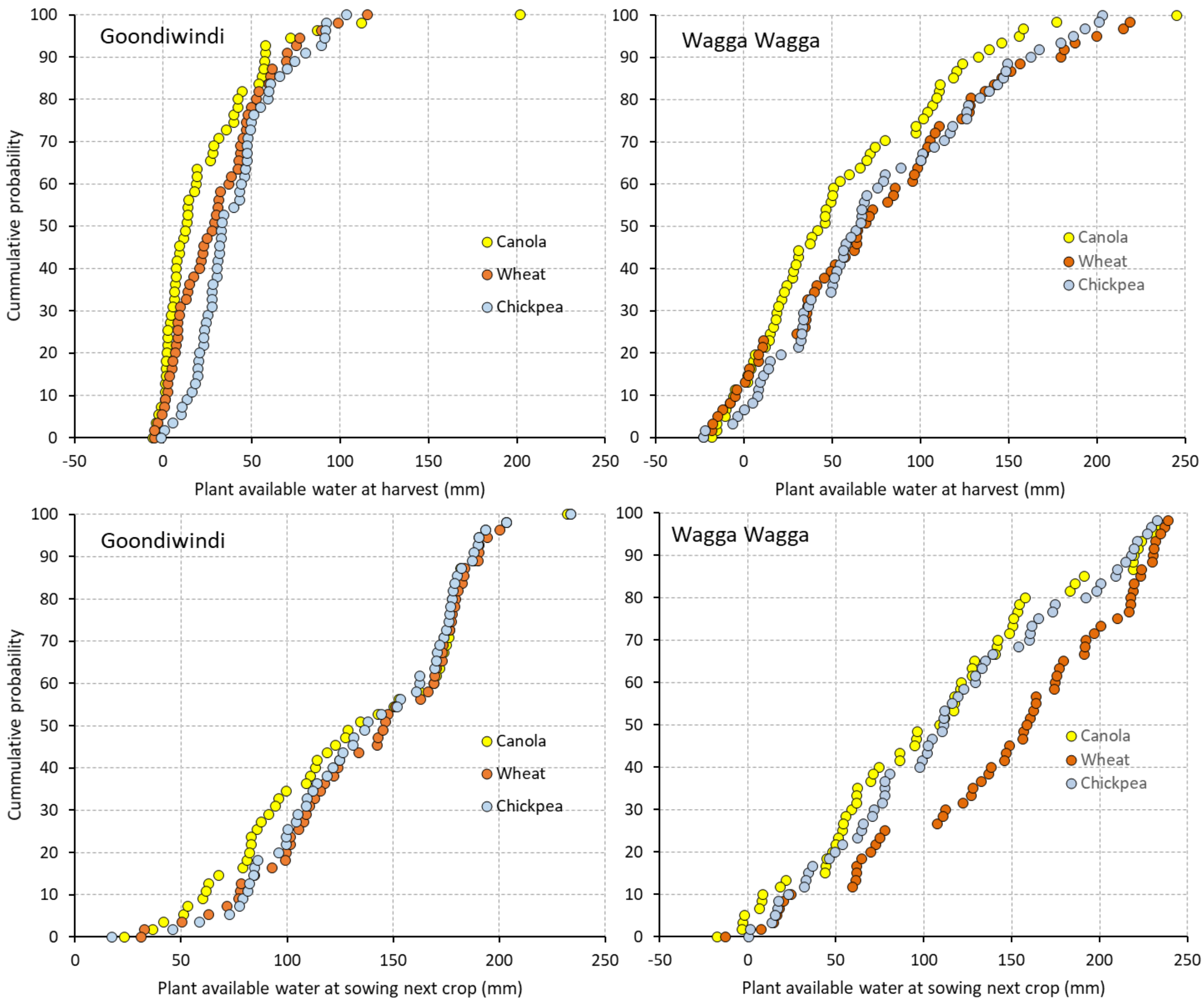

Figure 2. Long-term predictions of soil water remaining at harvest and accumulated prior to sowing the following crop after wheat, canola and chickpea at two locations representing the summer-dominant rainfall zone (e.g. Goondiwindi) and the uniform rainfall zone (e.g. Wagga Wagga). Each point shows the predicted value arranged from the lowest to highest to demonstrate the range of possible outcomes and their relative likelihood for each simulated year for a phased crop rotation involving chickpea-canola-wheat.

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