How resilient is your farming system strategy for the long haul? Long term simulations of risk and sustainability of various farming systems experiments using APSIM.

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Take home message

- Increasing cropping intensity can improve profitability but can increase the risk of a negative gross margin
- An increased cropping intensity removes fallows within the system, reducing the ability to buffer both the biological and logistical complexities of the farming system
- Using long term simulation of management decision rules highlights the limitations of each rule and identifies the long-term consequences of each decision.

Introduction

Deciding what to plant, when and where, is a complex decision that all farmers face. Personal preference, enthusiasm for a crop type and its historic success are often tempered by weed control strategies, disease issues, seasonal outlook, financial outlook, current soil water, summer verses winter split, seed availability and logistics. To reduce the complexity of these decisions, two alternative approaches have emerged. Firstly, the fixed rotation where a sequence of compatible crops are arranged in an agronomically sensible order that helps manage the major constraints, provide logistical certainty, while offering diversity of crop type, sowing date and season. This approach aims to give each crop the best opportunity of success while constraining the populations of pests, weeds or disease. The major criticism of the fixed rotation is its lack of flexibility, which limits the ability to capitalise on high prices of particular crops or respond to particularly good (or bad) seasons. The polar opposite of the fixed rotation would be a purely opportunistic system, where the most suitable crop is planted whenever the opportunity arises. In reality, this is probably a utopian description of a cropping sequence, because good agronomics, availability of seed and personal crop preference will add a degree of structure to all sequences. However, between these two extremes lie reality, most farmers have a degree of structure that they opportunistically vary based on their personal risk profile.

Our previous modelling compared different fixed cropping rotations to see if some are more profitable than others (Whish *et al.,* 2018; Hochman *et al.*, 2020) and how adaptable they are across environments. The conclusion was that increasing crop intensity by reducing or removing the long fallows, used to switch between summer and winter phases of the rotation, increased annual gross margins. The downside to this increased intensity and depending on the environment, was an increase in the number of crops retuning a negative gross margin. In addition, the extra crops reduced the average yields of the existing crops and annual return on investment per crop decreased. In short, increasing intensity had the potential to improve system profitability over the long term, but resulted in extended periods of time generating negative gross margins.

Adding flexibility to the sequence by means of specific sowing rules (such as sow on PAW of 100mm) identified a way these structured rotations could have their intensity increased without significantly increasing risk (Whish *et al.,* 2019). This concept of using rules to develop the cropping sequence has been presented as a series of leavers that can manipulate the farming systems and is being tested within the field experiments of the northern farming systems project. This rule-based approach to crop selection has now run in the field for 6 years, but how will they work over the long term?

The value of modelling has often been stated as taking our experiences from a few years and exploring their performance over many. This has been the case with the original rotation modelling and then the combined flexible modelling, but these both have a specific copping pattern that is followed. To capture the management of the farming systems rule-based field trials has proven a greater challenge.

In this paper we report on the success of simulating some of the farming systems cropping strategy with APSIM. We then present a scenario analysis that uses this new approach to compare the economic returns for Goondiwindi and Pampas from 4 different rotation strategies that use the same four crops.

Modelling the farming systems teams decisions

Method and approach

The farming systems experiments have over 80 crop sequences covering different cropping, nutrition and pasture options across sites. In this paper we will focus only on one of these systems as an example to demonstrate how APSIM modelled the rule-based decisions made by the farming systems team.

Different rules were combined to imitate the complex decisions made when deciding what and when a crop could be sown. Hence, we specified in the model a series of 'decisions' that dictate the timing of crop sowing, and the choice of crops that can be made. This was compared to the actual crop sequence and timings deployed in the experiments.

In all simulations sowing occurred, when the minimum rainfall (e.g. 15mm over 3 days) and plant available water (90mm) triggers were exceeded during the sowing window for that crop. For example, the available water threshold could be varied, i.e. a higher intensity system had a lower plant available water (PAW) requirement (90 mm) compared to the baseline system (150 mm).

Then there were rules that dictated the crop types selected, which were largely driven by the requirement for a break between repeat sowings of that particular crop, the selection of crops available and then crop preferences. Hence, for each crop the break between repeat sowings, (e.g. 2 breaks between each chickpea crop) or how many times a crop could be repeated (e.g. 2 sorghum crops in a row; Table 1) were specified. Higher diversity systems had an increased range of crop options to choose from (up to 13 different crop types) and limitations on what crop type could follow each crop (e.g. no cereal following a cereal, no legumes following a legume; Table 1). Finally, all crops included a pre-determined preference to solve conflict (e.g. if wheat and chickpea could be sown at the same time, chickpea would be selected because it has the higher preference value; Table 1).

Table 1. Decision based rules used to determine if a crop could be sown.

Rule	**Variable**
Sowing	Sowing window between dates
	Plant available soil water in mm (PAW)
	Amount of rainfall (mm) over a number of days
BlanketRule	Number of breaks (i.e. 6 month periods) between same crop planting
BlanketRule	The maximum number of that crop that can occur in a row
LastNotLegume	Last crop was not a legume
LastNotWinterCereal	Last crop was not a winter cereal
Preference	Scale of 1-5 priority for crop selection (5 Highest, 1-lowest)

Here we examine how well the model-specified rules replicate the crop sequence grown in the W03 system at the Pampas experimental site. The W03 system is a winter-based system that aims to have a high legume frequency and as such has only winter crop options, but includes more legume options to enable every second crop sown to be a legume (Table 2).

Table 2. Decision based rules applied to the winter crop system (W03) simulation and the selection of crops available, their associated rules specifying when the crops could be sown and the soil water trigger used to instigate each sowing event.

System Code	Details	Crops	BlanketRules	Intensity Rule PAW mm	Diversity Rule
W03	Higher Legume Frequency	Wheat	Up to 2 in row	120	LastNotCereal
		Chickpea	2 crop break	120	
		Barley	3 crop break	120	LastNotCereal
		Faba bean	2 crop breaks	120	
		Fieldpea	2 crop breaks	120	

APSIM's Rule-based crop selection vs the farming systems teams crop selection

Some differences were observed between the model output using the rule-based decisions and the crop choices and timing of farming systems team (Table 3). However, in general the model reproduced the decisions of the farming systems team well. Where the model differed highlights the key differences in the way the model selects a crop and the way the team selects a crop.

The differences can be explained by the decision-based sowing rule. APSIM does not have foresight, so only respond to the conditions of the day (rainfall, stored soil water) .

For example: the barley window opens before the wheat window, so once the soil water level is achieved sowing occurs in APSIM. In 2016, the early sowing of barley was missed by the team (due to logistics and a forecast of little follow-up rain) no additional rain fell until late June, when wheat was sown in the experiment. This difference then had a legacy impacting the future crops. In 2018 the model simulated that the early sown barley crop in 2016 had allowed for a longer fallow compared to the later sown wheat crop in that same year. As a result, more water was stored following barley compared to wheat allowing a crop to be sown by the model in 2018, but not the field. This additional wheat crop then caused the difference in crop selection in 2020 in the modelled crop sequence.

Table 3. Results from observed and simulated crop selection rotation W03 at Pampas experiment over the 6 experimental years.

Year	APSIM sowing date	APSIM crop choice	System trial crop choice	System trial sowing date
2015	2/5/15	Fababean	Fababean	13/5/15
2016	16/4/16	Barley	Wheat	1/7/16
2017	14/6/17	Chickpea	Chickpea	26/6/17
2018	3/7/18	Wheat		
2020	22/5/20	Chickpea	Wheat	27/5/20
2021	12/5/21	Fababean	Fababean	23/4/21

Long-term systems scenario analysis

Method and approach

Since the rule-based decisions were shown to be functioning satisfactorily, a long-term scenario analysis was undertaken to extrapolate these over a wider range of seasonal conditions. The scenario analysis compared four crop sequences at Pampas and Goondiwindi over a 64-year period (1957-2021). All sequences included 4 crops (sorghum, chickpea, wheat and mungbean) and had the same rules required to trigger a sowing event.

The first sequence was fixed (Fixed) where every crop was sown every year, four crops in 4 years. If the sowing rules were not met during the sowing window the crop was sown at the end of the window (Table 4). This is described as the must sow rule.

The second sequence was the Flexible (Flex) sequence. This sequence was the same as the fixed rotation with the must sow rule applied to the sorghum, wheat and chickpea crops, but mungbean was only sown if conditions were satisfied.

The third sequence was the free or opportunistic sequence (Free). Here any crop could be sown whenever the rules allowed (Table 4).

The final sequence was the same as the Free sequence but included a rule that prevented two legume crops being sown consecutively (FreeL) (Table 4).

Table 4. Summary of the different management rules applied to the scenario analysis simulations for Goondiwindi and Pampas

System Code	Crops	Must sow	BlanketRules	Intensity Rule PAW mm	Diversity Rule
Fixed	Wheat	yes		90	
	Chickpea	yes		90	
	Sorghum	yes		90	
	Mungbean	yes		60	
Flex	Wheat	yes		90	
	Chickpea	yes		90	
	Sorghum	yes		90	
	Mungbean	no		60	
Free	Wheat	No	2 in row	90	LastNotWinterCereal
	Chickpea	No	2 crop break	90	
	Sorghum	No	2 in row	90	
	Mungbean	No	2 crop breaks	60	
FreeL	Wheat	No	2 in row	90	LastNotWinterCereal
	Chickpea	No	2 crop break	90	LastNotLegume
	Sorghum	No	2 in row	90	
	Mungbean	**No**	**2 crop break**	**60**	**LastNotLegume**

Results

Modelled comparisons between the two sites Pampas and Goondiwindi supported all previous studies. Where by, the higher rainfall site of Pampas can easily sustain a cropping intensity of 1 crop per year or more, with increased cropping intensity in this area not significantly increasing risk (Table 5). For this reason, the remainder of this paper will concentrate on the results from Goondiwindi (Whish *et al*., 2018, Whish *et al*., 2019, Hochman *et al*., 2020).

In contrast at Goondiwindi, the lower annual rainfall increases the risk of experiencing a negative gross margin crop at a rate of 1 crop in ~7 (Table 5). An interesting observation was increasing the intensity by adherence to the rules in the free treatment, increased the intensity to 1.4 crops per year and improved the mean annual gross margin by $79; but did not significantly change the risk. However, an inspection of the cropping sequence showed this result was achieved by regularly planting back-to-back legumes. The inclusion of the legume rule (no legumes following legumes) improve the agronomics of the sequence, but reduced the gross margin to be the same as the flexible system (Table 5). The increased cropping intensity produced the increased annual gross margin in the Free system but individually the returns of each crop were reduced (Table 7). The additional cost of sowing more crops for a reduced value, explains the lower return on investment for these systems.

Table 5. A comparison of the mean annual gross margins for each system after 64 years and an estimate of the risk required to achieve them

Site	Treatment	No. Crops sown	Mean annual gross margin ($/ha/yr)	Percent crops with negative gross margin (%)	Intensity (crops/yr)	Return on investment ($/$)
Goondiwindi	Fixed	65	524	15	1	1.22
Goondiwindi	Flexible	64	533	12	1	1.25
Goondiwindi	Free	87	612	16	1.4	1.11
Goondiwindi	FreeL	78	533	13	1.2	1.05
Pampas	Fixed	65	911	5	1	2.01
Pampas	Flexible	65	911	5	1	2.01
Pampas	Free	107	1143	9	1.7	1.66
Pampas	FreeL	103	1147	8	1.6	1.67

Despite having the same mean annual gross margin, the FreeL system and the Flexible system did not plant the same number of crops or the same crop types at the same time (Table 5). Overall, the 14 additional crops sown in the Free L treatment were predominantly summer crops. This shifted the summer to winter ratio from a potential 50:50 to 66:34. A similar trend towards summer crops was observed in the Free rotation, so it was not exclusively a result of the additional legume rule (Table 6).

Table 6. The difference in summer to winter split within a sequence.

Site	Treatment	Percent summer crops (%)	Percent winter crops (%)
Goondiwindi	Fixed	50	50
Goondiwindi	Flexible	47	53
Goondiwindi	Free	64	36
Goondiwindi	FreeL	66	34
Pampas	Fixed	50	50
Pampas	Flexible	50	50
Pampas	Free	58	42
Pampas	FreeL	57	43

If the individual returns from each crop are examined, the difference between the Flexible sequence and the FreeL sequence becomes more apparent. Despite both sequences having the same mean annual gross margin, they achieve it differently. The FreeL rotation has more sorghum crops and 5 fewer chickpea crops (Table 7), but more importantly the average returns from these chickpea crops are less (Table 8). The increased cropping intensity has reduced the returns from all crops except sorghum. This is due to the rule that allowed 2 sorghum crops to follow each other, allowing a continuous summer cycle of sorghum and mungbean to occur in low rainfall years.

The reduced opportunity to store soil water before winter prevented the switch from a summer crop sequence back to winter crops until a wet season allowed the winter sowing trigger to be satisfied. When the switch did occur, it was usually as a result of a double crop wheat or chickpea crop following a sorghum or mungbean crop. When the switch occurs, the lower initial starting soil water conditions of the double crop meant a lower yield potential from these crops compared to the flexible sequence, where the winter crops were always preceded by a short or long fallow.

Table 7. The number of individual crops sown in each rotation over the 64 years of simulation

Site	Treatment	Chickpea	Mungbean	Sorghum	Wheat
Goondiwindi	Fixed	16	16	17	16
Goondiwindi	Flexible	16	15	17	16
Goondiwindi	Free	16	22	28	21
Goondiwindi	Free L	11	15	32	20
Pampas	Fixed	16	16	17	16
Pampas	Flexible	16	16	17	16
Pampas	Free	23	22	35	27
Pampas	Free L	16	16	39	32

Table 8. Mean crop gross margins from crops grown in the different rotation systems across 64 years

Site	Treatment	Chickpea	Mungbean	Sorghum	Wheat
Goondiwindi	Fixed	874	662	165	386
Goondiwindi	Flexible	874	725	183	384
Goondiwindi	Free	628	416	430	378
Goondiwindi	FreeL	706	397	402	377
Pampas	Fixed	1192	1145	641	625
Pampas	Flexible	1192	1145	641	625
Pampas	Free	858	782	672	470
Pampas	FreeL	916	632	766	588

This reinforces previous results that show improving profitability by increasing cropping intensity within a water limited environment comes at a cost. Overall profits may increase, but each individual crops value may decrease (Table 8). The advantage of a fixed rotation is it allows resources to be prioritised to high value crops. For example, if a high value crop like cotton is included, then it can always be preceded by a long fallow to improve its odds and reduce risk. Similar strategies can be tested in this rule-based simulation. The examples presented all used the same soil water trigger which is quite low for the region, encouraging a high cropping intensity. If the summer crops had a higher trigger compared to the winter crops, then the dynamics between summer and winter would change and an increase in fallows may occur.

Conclusion

The modelling scenarios presented are different to the types of modelling that we have presented over the last 20 years. Historically, we have shown how the models can reproduce yields observed in the field and then used the model to investigate different management scenarios over time with the hope of improving decisions and reducing risk of individual crops.

The focus of the modelling presented here, is not the yield, but the decision to plant a specific crop where and when we did, and the rules that surround or drive that decision. This can be confronting, as the farming systems team discovered. Why was barley not sown on the early sowing opportunity in 2016? Reasons included seed supply, access to machinery and staff availability. Real reasons that are not dissimilar to why many paddocks are not sown at the optimal time and incur a yield gap. This highlighted that logistics and labour are as important to the creation of a yield gap as biological factors such as nematode burdens or under application of nitrogen. Fallows have a real value in northern farming systems by providing disease breaks, refilling profiles and buffering the system from a biological and management perspective.

The modelling presented here is not designed to optimise a range of variables and produce the perfect sequence that can be rolled out across the country. The aim of this work is to look for new opportunities within existing systems. To understand the importance of different environments and assess different rules for their ability to improve economic potential and reduce risk. To that end this work demonstrates the enhanced capability of simulation models like APSIM to aid in testing farm management decisions. The use of APSIM as a boundary object to help consultants, researchers and growers refine and understand the consequences of crop selection decisions is the future for this work and the best way to practically improve the profitability of crop sequences in the northern-grains region.

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