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Factors and scenarios affecting a farmer's grain harvest logistics

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This paper explores how changes in Australia's grain industry supply chains are likely to impact on the nature and profitability of an Australian farmer's grain harvest logistics. A simulation model is used to show how receival site rationalisation, cheaper on-farm storage, larger trucks, higher-yielding crops and new harvest technologies, separately and in combination, affect the nature and profitability of a farmer's grain harvest logistics. Applying the model to a typical Australian grain farm shows that many of these changes unambiguously advantage the farm business, and often, the combination of these changes increases a farmer's harvest profits by at least 10 per cent. For many farmers, the task of efficiently designing and managing harvest logistics will be an increasingly difficult yet important series of choices due to the range of storage options, grain pathways, crop portfolios and market opportunities that are arising. A farmer's decisions about cost-effective on-farm storage and transport, and their judicious use, will be a key contributor to additional profit in future years.

Key words: farm management, farm modelling, grain harvesting, logistics, simulation.

1. Introduction

Agricultural production typically occurs at great distance from the point of final consumption, especially where farm products are exported. Hence, for any farmer, the nature and cost of their supply chains are of practical and financial importance (Stretch *et al.* 2014; Reardon 2015). Supply chain costs affect a farmer's profit margins (Nguyen *et al.* 2016), so farmers have a keen interest in the costliness of their supply chains.

One of Australia's principal agricultural export industries is grains and oilseeds, with average annual exports close to A$12 billion over the last 5 years (ABARES 2018), dominated by wheat exports. The nature and cost of Australia's wheat export supply chains have been examined by White *et al.* (2018) and Stretch *et al.* (2014). These researchers report supply chain costs, from the farm gate to the loading of grain onto ships, are between 30 and 35 per cent of the free-on-board price of wheat. Hence, any reductions in the costliness of wheat or grain supply chains, in general, are potential opportunities for improvement in grain farmers' profits.

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In Australia's grain-exporting regions, the principal supply chain involves large, upcountry commercial storage facilities with farmers delivering grain into these facilities directly from the field. However, as discussed by White *et al.* (2018), there are complementary grain pathways such as placing grain into farm storage rather than upcountry commercial storage or delivering grain directly to port, bypassing upcountry storage. The commercial merit of such complementary supply chains is discussed by Gattorna (2015).

Despite the economic importance of the grains and oilseed industry in Australia, there is a limited literature on Australia's grain supply chains. McClintock *et al.* (1991) examined an Australian farmer's grain harvest logistics in the late 1980s, and Kingwell (2017) provided an historical analysis of broad changes in Australia's grain supply chains from 1986 to 2014. Descriptive studies by Stretch *et al.* (2014) and White *et al.* (2018) outline the recent nature of grain supply chains in various regions of Australia. However, there is no forward-looking study outlining the unfolding changes in the nature of grain supply chains in Australia and investigating how farmers might rationally alter their on-farm harvest logistics and subsequent use of grain supply chains. This paper aims to fill this gap in the literature.

By contrast to Australia, there are many studies of overseas grain supply chains. Typical examples include Ge *et al.* (2015, 2016) who examined strategies to mitigate handling risks in Canada's grain industry. Nourbakhsh *et al.* (2016) studied grain supply chain network design and logistics planning to reduce post-harvest losses in the United States. Sporleder and Goldsmith (2003) similarly investigated how identity preservation requirements might affect supply chains in the United States' grain and oilseed sectors. Nardi *et al.* (2007) examined the optimisation of grain supply chain management in Argentina. Lastly, there are many studies that examine particular components of grain supply chains such as shipping services (Wilson *et al.* 2004; Bilgen and Ozkarahan 2007) or rail services (Hyland *et al.* 2016). However, there is no Australian study that examines the unfolding nature of supply chains in Australia and their impact on a farmer's harvest logistics decisions.

Farmers' decisions about which grain pathways to use during their grain harvest are conditional on many factors. This paper formally explores the relative importance of these factors. Simulation modelling is used to calculate a farmer's net revenues from using the various supply chains and to show how changes in the components of those supply chains affect the farmer's net revenues.

This paper is structured as follows. The next section describes the main factors that affect harvest logistics, highlighting recent major structural changes within the grain industry. Then, a simulation model of harvest logistics is described. This model is applied to various scenarios that typify the commercial environment of farms engaged in harvesting and marketing grain. Modelling results are presented and discussed, after which conclusions are drawn.

2. Factors affecting grain harvest logistics

There has been no formal investigation of an Australian farmer's harvest logistics since the McClintock *et al.* (1991) study almost 30 years ago. Yet many changes have occurred or are underway in the Australian grain industry that affect the nature and cost of grain harvest logistics. These changes, described in the following subsections, are causing harvest logistics to be an increasingly topical issue for many farmers.

2.1 Site rationalisation and site upgrades

Most major providers of grain storage and handling services in Australia have moved from farmer-owned entities to be private or publicly listed companies. All these companies, including the remaining farmer-owned Cooperative Bulk Handling (CBH), have over the last decade announced major rationalisations of their storage and handling networks (Productivity Commission 2010; Stretch *et al.* 2014; Kingwell 2017; White *et al.* 2018). The spread of grain intake for the receival sites operated by these firms is typically highly skewed. For example, CBH in Western Australia recorded in the 2017 harvest that of the 13.2 million tonnes of grain it received, 63 of its sites received only 12 per cent of that volume, whilst 30 sites received 66 per cent of the volume. Noting such skewness and the overhead and operating costs associated with receival sites, CBH has announced a plan of site rationalisation and facility upgrades at some remaining sites. In mid-2018, CBH also implemented staged reductions in its workforce to lower its overhead and operating costs. Viterra in South Australia and GrainCorp in Victoria and New South Wales have applied the same rationalisation and reinvestment strategy (Griggs 2014; Fogden 2019).

The rationalisation of site and staff resources, and reinvestment at strategic sites, by the major commercial storage and handling firms in Australia has major implications for farmers' harvest logistics. Farmers whose local receival point closes need to travel further to place their grain into an upcountry facility. For some other farmers whose local receival point receives an upgrade that increases its intake and outturn speeds and storage capacity, those farmers experience faster turnaround times and the likelihood that all the types of grain they grow will be accepted at the enlarged site. Moreover, if the rationalisation activity lowers the overall cost of moving grain from upcountry to an end-user, then a farmer's farm-gate price of grain will be higher (Stretch *et al.* 2014) provided there is sufficient trader competition for their grain. As an illustration, CBH's focus on cost-efficiency in its grain network has in recent years resulted in CBH's grower members receiving substantial rebates that effectively lower the cost of grain handling and storage services to those growers (White *et al.* 2018).

2.2 Grain marketing deregulation

Statutory marketing of Australian wheat ended in 2008. Removal of the single statutory exporter, the Australian Wheat Board, triggered an influx of international grain trading companies, several of which then invested in port terminals and/or upcountry grain storage. By 2010, there were 29 companies accredited to export wheat in bulk from Australia. The deregulatory change made farmers responsible for marketing their wheat.

A common response from farmers was to sell for cash at harvest rather than rely on Australian Wheat Board pool payments often spread over two years after harvest. Many farmers also increased their investment in on-farm storage so that they could capitalise on any price spikes after harvest offered by grain marketers.

2.3 Varietal improvement and farm size

The introduction of end point royalties since the early 2000s encouraged the commercialisation of plant breeding in Australia (Gray *et al*. 2017), especially in the supply of varieties of major crops such as wheat, barley and canola. The result has been release of higher-yielding crop varieties that have supported the shift in land use towards more cropping during the 2000s. The combination of better varieties, crop-dominant farming systems and the continued growth in farm size made for very large crop harvests in some years. For example, when the farm model MIDAS (Kingwell and Pannell 1987) was first constructed in the mid-1980s to represent a typical farm business in the eastern grainbelt of Western Australia, the farm size was 2,500 ha, whereas the current average farm size in that region is almost 6,000 ha (Planfarm 2019).

Across Australia, during the 1980s, the average area sown to wheat, Australia's principal grain, was 10.9 million hectares yet in the decade ending in 2017/18 the average area sown to wheat was 12.9 million hectares. Moreover, the average wheat yields in each respective period were 1.36 and 1.93 t/ha. Resulting from these trends was an average wheat harvest of 14.7 mmt in the 1980s versus an average harvest of 24.8 mmt in the most recent period, that is, a 69 per cent larger harvest. These larger harvests have placed greater demands on the services and assets in grain supply chains: on-farm grain storage, grain transport, upcountry grain storage and port grain terminals.

2.4 Harvest equipment

The combination of increases in crop yields, farm size and cropping dominance has encouraged farmers to adopt larger planting and harvesting machinery. The higher work rates of harvesters have necessitated complementary investments in chaser bins, mother bins, larger grain trucks and additional temporary and permanent grain storage on farms. Most farmers own and operate their own harvest machinery, although some farmers rely on complementary contract harvesters.

One factor influencing some farmers' choice of harvest machinery is the exposure of the crop to adverse weather events at harvest. Rain events during harvest can have impacts ranging from trivial to catastrophic. The latter includes flooding that prevents grain harvest. Other problems caused by adverse weather include crop lodging, grain sprouting, weather-staining and mould problems when stored grain is too damp. Quickly harvesting a crop has the advantage of lessening the standing crop's exposure to adverse weather. The risk of this damage needs to be weighed against the capital and operating costs of grain-drying, on-farm storage to facilitate harvest logistics, crop insurance and/or harvest machinery with greater work rates.

A further complication at harvest, arising from farmers' increased reliance on herbicides, has been the need to incorporate methods of harvest weed seed control (Jacobs and Kingwell 2016). These methods of control can be as simple as forming harvest windrows that subsequently are burnt to kill embedded weed seeds. Other more expensive yet more effective control methods include use of chaff carts that capture weed seeds in the harvest chaff, or use of the Harrington Seed Destructor that mechanically renders weed seeds unviable. Use of these equipment-based technologies reduces the field efficiency of harvesting in fields where problematic weeds exist, with implications for harvest logistics. However, to lessen the impact of weeds in crops, especially herbicide-tolerant weeds, these weed control options at harvest are essential.

2.5 Methods of grain storage

As outlined by White *et al.* (2018), a range of types and costs of on-farm storage are available. There are temporary storage options such as silo bags or concrete pads. There are field bins and chaser bins for mobile grain storage. There are more permanent structures, such as circular-walled open bulkheads with telescopic poles that hold a tarpaulin and allow grain to be augured into the bulkhead (GGHS 2018). These permanent structures, including the traditional steel or steel and concrete silos with cone or flat bottoms, can be sealed to allow effective fumigation of grain insects.

Grain storage performs a range of functions: storing seed for subsequent planting, being a source of feed for animals, assisting in harvest logistics, permitting moisture management, facilitating grain blending, and enabling grain marketing opportunities.

2.6 Grain cartage

Grain is moved from the farm into storage by truck, usually by a combination of the farmer's truck(s) and contract cartage. Grain transported at harvest into commercial upcountry storage mostly relies on contract cartage. The pricing of this contract cartage reflects the peak load problem (Brennan 1992) whereby in years of large harvests trucking rates during the harvest are high due to the greater demand for trucking services. By contrast, trucking rates are far less in the off-peak period after harvest or in years when low yields are commonplace.

Some commercial storage and handling firms and grain marketers encourage grain to be trucked directly to port, bypassing upcountry storage, either to relieve congestion at particular sites and/or to delay the filling of sites, or to avoid the costs of upcountry storage and handling. As noted by Kingwell (2017), the real cost of the road transport of grain has reduced in recent decades due to increases in the carrying capacity of trucks, more fuel-efficient truck engines and upgrades to the quality of regional roads.

3. A model of grain harvest logistics

There has been no formal investigation in the literature of how the above-mentioned factors currently affect a farmer's harvest logistics in Australia. Hence, given the grain industry's current structural adjustments, such as a reduced number of upcountry receival sites, higher-yielding crops, increases in truck capacities, greater work rates of grain harvesters and new forms of grain storage, it is worth undertaking such an investigation. Accordingly, this paper uses simulation modelling to examine how different industry scenarios and associated changes in the factors listed above affect a farmer's net returns from logistic operations associated with the sale of their grain after harvest.

The simulation model considers the grain flows or supply chains shown in Figure 1. The solid lines represent possible grain flows from the farm, which are the responsibility of the farmer. The dashed lines are other possible flows of the farmer's harvested grain, but are usually the logistic responsibility of a commercial bulk handler, with the costs of those logistics effectively being

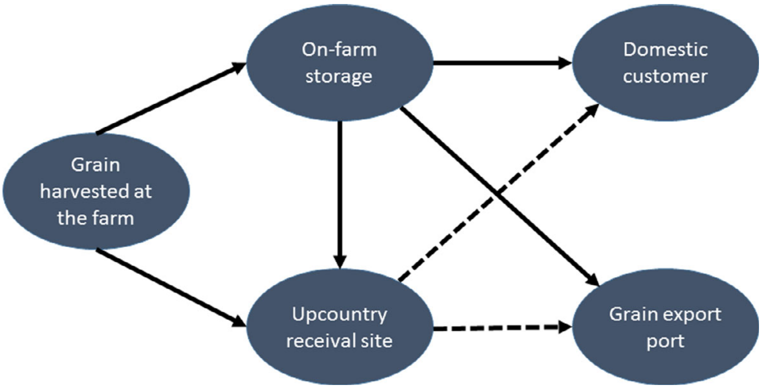

Figure 1 Grain flows characterised in the logistics model.

paid for by the farmer as reflected in the net sale price of the farmer's grain when in commercial storage.

For farms whose grain principally goes to export, the main grain pathway is from the farmer's field to an upcountry receival site and from there to a port. A less frequent path to port is grain moved directly from on-farm storage to a grain port. By contrast, for a farmer who principally sells their grain to a domestic user, the grain flows from the field into on-farm storage and subsequently on to the end-user.

The model describes a farmer's grain harvest and subsequent storage, transport and selling options with one or more crops able to be considered. The harvest operation is conceptualised as in Figure 2 with an example of three crops being consecutively harvested. If on-farm storage is available for a particular crop, then the grain of that crop is harvested and placed first in on-farm storage. When that storage is full, then the remaining grain is transported to a nearby upcountry storage facility. The kinks in the lines in Figure 2 indicate when a grain's on-farm storage is full, at which point the harvesting rate typically slows due to restrictions on receival site opening times, transport journey times and grain moisture limits.

The duration of the harvest of a crop depends on several factors: crop area, initial yield of the crop, the number of days without yield decline (such a decline is usually due to weather events, desiccation or pest damage), harvest hours, harvesting rate, truck load capacities, truck speeds, speed of truck loading and unloading, distance to the upcountry receival facility, and opening hours of the facility. A range of routines in the model describe all these factors and how they affect the harvest, storage and transport of each crop.

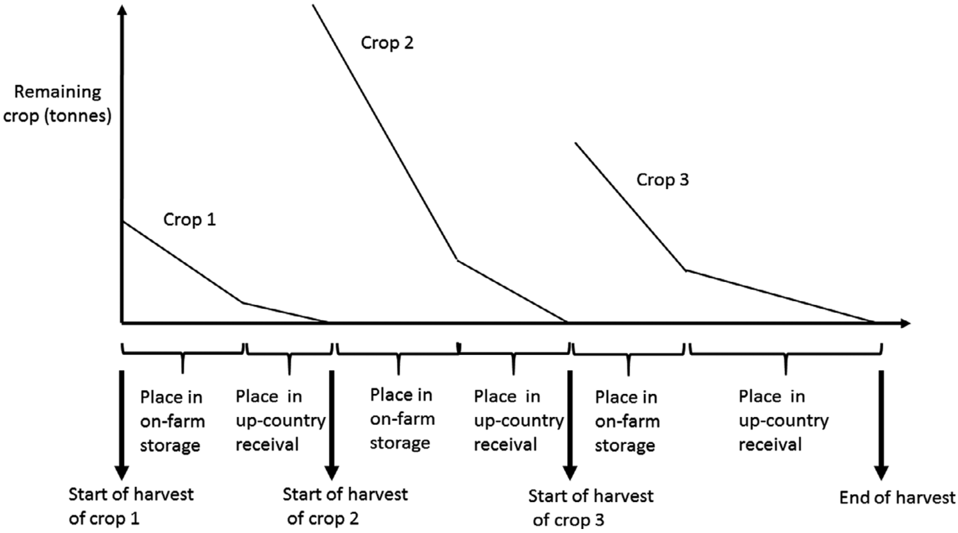

Figure 2 Conceptual flow of grain being extracted from the farmer's fields at harvest.

The model assumes the crops are harvested sequentially; when the harvest of one crop is finished, harvesting of the next crop starts immediately on the next day. For each crop, the model proceeds day-by-day determining the daily harvesting hours, the area harvested, and the weight delivered to on-farm storage and/or the receival site. As shown later in several equations, account is taken of the moisture content of grain and the quality of grain at harvest, as there are opportunities to use grain already stored on farm to blend with grain just harvested in order to meet grain quality targets. A full mathematical description of the model is available in Loxton *et al.* (2017).

The simulation model of the farmer's grain harvest follows these steps:

(i) start on day one ($d = 1$) and the first type of crop ($c = 1$);
(ii) on each day d, deliver as much of the harvested grain as possible into on-farm storage with any excess grain sent to the upcountry receival site;
(iii) if grain blending is permitted, then mix higher quality grain stored on farm with harvested lesser quality grain to avoid, where possible, price downgrades; and
(iv) keep repeating steps (ii) and (iii) until crop c has been completely harvested and then move to the next crop and the next day

The parameter inputs of the model, using wheat as the example, are listed in Table 1. The model's other crops that form the farmer's cropping program are defined by the user. In many grain-exporting regions of Australia, these other crops would typically be from the following options: barley, canola, oats or a pulse crop such as chick peas or lupins. In this paper, we consider two other main crops grown in Australia (ABARES 2018), barley and canola, with their key respective parameter values listed in Appendix S1. The order of harvest, as suggested in Figure 2, is based on industry practice and is canola ($c = 1$), wheat ($c = 2$) and then barley ($c = 3$).

The areas and yields of each crop type represent a typical grain-producing farm in Western Australia (Planfarm-BankWest 2018). These farms are responsible for almost 40 per cent of Australia's wheat production and over 40 per cent of Australian exports of all types of grain over the last 5 years (ABARES 2018). Many technical and cost parameters of the various supply chains in Table 1 and Appendix S1 are sourced from White *et al.* (2018), Cooperative Bulk Handling's fee schedules for 2017/18 and industry experts. Grain prices are based on forecasts for the 2018/19 crop as of mid-2018.

The simulation model's net revenue function considers the farm's entire grain harvest. The farmer's net revenue from the harvest, storage, transport and sale of grain is maximised subject to a range of logistical constraints and assumptions. The farmer's harvest net revenue is the sum of the net revenues obtained through the four possible supply chain pathways: export direct from farm; export through bulk storage; domestic sale direct from farm; and domestic sale through bulk storage – minus on-farm storage costs. For each pathway, the net revenue is calculated according to the formula:

$$\varphi_c W_c,$$

where φ_c is the average sale margin of crop c (in \$/t) through this pathway and W_c is the weight of grain transported through this pathway. The average sale margin is the revenue received from selling grain minus costs of grain transport, on-farm and upcountry storage, and associated handling costs.

The analysis assumes the crops have been produced, harvested and are then all sold. On-farm storage is treated as a fixed-fee service whereby for crop c, R_c tonnes of storage capacity is available at a fixed fee of ø_c dollars per tonne.

The calculations of φ_c, the net margin, and W_c, the sale weight, are described below for each supply chain pathway. First, for φ_c, the net margin per tonne is equal to the average sale price of grain minus the cost of trucking and minus the cost of grain handling. For a domestic sale via farm storage, the cost of grain handling is zero, but for the other supply chain pathways there is typically a non-zero grain-handling cost (which may be time-based or fixed). Even sending grain direct from farm to port will potentially incur grain-handling costs due to the use of third-party infrastructure at port. For grain sent through the bulk storage system, the average sale price of grain takes into account the relative amounts of target and secondary grades, and blending of the two grades to receive an uplift, through the following formulas:

$$\varphi_c^{\mathrm{rcl:exp}} = P_c^{\mathrm{rcl:exp}} + \left(\tilde{\theta}_c^{\mathrm{rcl}} - 1\right)\rho_c^{\mathrm{rcl:\,exp}}, \varphi_c^{\mathrm{rcl:}dom} = P_c^{\mathrm{rcl:}dom} + \left(\tilde{\theta}_c^{\mathrm{rcl}} - 1\right)\rho_c^{\mathrm{rcl:}dom},$$

where $\tilde{\theta}_c^{\mathrm{rcl}}$ is the proportion of grain sent through the receival system that is of target grade (after blending). The calculation of this variable is explained in the Appendix S3.

For the W_c terms, which are the tonnages of crop of type c that flow through each grain path, their calculation depends on the choice of $\xi_c^{(\mathrm{ofs:exp})}$, $\xi_c^{(\mathrm{ofs:dom})}$, $\xi_c^{(\mathrm{rcl:exp})}$, and $\xi_c^{(\mathrm{rcl:dom})}$ (see Table 1) and a correction factor that adjusts for weight increases/decreases through moisture management in on-farm storage.

The model is applied to a range of industry scenarios described in the next section. The scenario analyses are contrasted against a base case which is the *status quo* in 2018. The scenario analyses are based on likely changes in key parameters in Table 1 and the modelling results show the impacts of changes in these key parameters. For example, the model calculates the farmer's maximum harvesting hours per day based on how many round trips each truck can complete between the farm and receival site. This algorithm is described in the Appendix S2. The model also calculates the weight gain or grain value increases obtained from grain deliveries to receival facilities, if the farmer uses blending for moisture and grain quality management. Grain in on-farm storage is sent to the receival site via two pathways: (i) blended with downgraded grain being harvested in the field to lessen downgrade penalties;

Table 1 Parameters in the grain logistics model for crop type *c* in the base case

Parameter	Unit	Description	Base values for wheat ($c = 2$)
A_c	ha	Farm's area of crop *c*	2,000
Y_c	t/ha	Initial harvest yield of crop *c*	2
T_c	no.	Number of days of harvest in which no yield decline occurs for crop *c*	14
r_c	%	Daily reduction in yield of crop *c* after period T_c	0.5
R_c	T	On-farm storage capacity for crop *c*	1,000
M_c^{field}	%	Grain moisture content of crop *c* in field at harvest	0.15
M_c^{target}	%	Target value of grain moisture content of crop *c* for grain storage	0.125
B_c	–	Blending ratio	0.7
$[a_{cd}^{ofs}, b_{cd}^{ofs}]$	h	Valid time interval on day *d* for harvesting crop *c* when on-farm storage is the destination	[8 am, 8 pm]
$[a_{cd}^{rcl}, b_{cd}^{rcl}]$	h	Valid time interval on day *d* for harvesting crop *c* when receival site storage is the destination	[8 am, 6 pm]
H_l	t/h	Harvesting rate of harvester *l (assumes 75% field efficiency)*	34
Q_m	T	Capacity of truck *m*	40
S_m	km/h	Average speed of truck	80
L	t/h	Loading rate at farm	250
U	t/h	Unloading rate at receival site	1,000
δ_{load}	h	Set-up/waiting time for grain loading at farm	0.125
δ_{unload}	h	Set-up/waiting time for grain unloading at receival site	0.5
$[\propto_d^{rcl}, \beta_d^{rcl}]$	h	Receival site hours when open on day *d*	[7 am, 7 pm]
$D^{\text{farm:rcl}}$	km	Distance between farm and receival site	30
$D^{\text{farm:exp}}$	km	Distance between farm and port	200
$D^{\text{farm:dom}}$	km	Distance between farm and domestic sale point	180
$\varepsilon_c^{ofs:exp}$	%	Proportion of grain in on-farm storage sent direct to port	0.6
$\varepsilon_c^{ofs:dom}$	%	Proportion of grain in on-farm storage sent direct to domestic customer	0.15
$\varepsilon_c^{ofs:rcl}$	%	Proportion of grain in on-farm storage sent to the receival site	0.25
$\varepsilon_c^{rcl:exp}$	%	Proportion of grain in receival site allocated to export market	0.95
$\varepsilon_c^{rcl:dom}$	%	Proportion of grain in receival site allocated to domestic customer	0.05
d_i	–	Day on which downgrade *i* occurs	Note†
c_i	–	Crop affected by downgrade *i*	Note†
w_i	%	Proportion of target grade of grain affected by downgrade *i*	Note†
$P_c^{ofs:exp}$	$/t	Target grade price for export sale direct from farm for crop *c*	290
$P_c^{ofs:dom}$	$/t	Target grade price for domestic sale direct from farm for crop *c*	285
$P_c^{rcl:exp}$	$/t	Target grade price for export sale via receival system for crop *c*	300

Table 1 (*Continued*)

Parameter	Unit	Description	Base values for wheat ($c = 2$)
$P_c^{rcl:dom}$	\$/t	Target grade price for domestic sale via receival system for crop *c*	290
$p_c^{ofs:exp}$	\$/t	Secondary grade discount for export sale direct from farm for crop *c*	25
$p_c^{ofs:dom}$	\$/t	Secondary grade discount for domestic sale direct from farm for crop *c*	25
$p_c^{rcl:exp}$	\$/t	Secondary grade discount for export sale via receival system for crop *c*	30
$p_c^{rcl:dom}$	\$/t	Secondary grade discount for domestic sale via receival system for crop *c*	25
$\pi^{farm:exp}$	\$/t/km	Trucking rate from farm to port	0.08
$\pi^{farm:dom}$	\$/t/km	Trucking rate from farm to domestic customer	0.08
$\pi^{farm:rcl}$	\$/t/km	Trucking rate from farm to receival site	0.12
ϕ_c	\$/t	Fixed fee for on-farm storage of crop *c*	16
$\lambda_c^{ofs:exp}$	\$/t	Fixed fee for export sale direct from farm	43
$\lambda_c^{rcl:exp}$	\$/t	Fixed fee for export sale via receival system for crop *c*	52
$\Lambda_c^{rcl:exp}$	\$/t/mth	Time-based fee for export sale via receival system for crop *c*	0
$\lambda_c^{rcl:dom}$	\$/t	Fixed fee for domestic sale via receival system for crop *c*	32
$\Lambda_c^{rcl:dom}$	\$/t/mth	Time-based fee for domestic sale via receival system for crop *c*	0
$t_c^{rcl:exp}$	mth	Time spent in receival system before export sale for crop *c*	2
$t_c^{rcl:dom}$	mth	Time spent in receival system before domestic sale for crop *c*	3

Note: †In all scenarios, we considered two weather events that cause the downgrade of a portion of the remaining unharvested grain. These were assumed to occur on days 9 and 18 of the harvest causing 20% and 35% of remaining wheat and barley, respectively, to be downgraded.

and (ii) sent directly to the receival site without blending. The model maximises the amount of secondary grade uplift. The weather-related downgrade of grain and blending algorithms are described in the Appendix S3. Hence, within the structure of the model are some logical and optimisation algorithms that ensure efficient and practical management of supply chain resources.

Applying the model to the scenarios described below assumes that standard farmer practice in the future will be to undertake blending. However, the current *status quo* is assumed to entail no blending but on-farm storage is used to facilitate harvest logistics. To illustrate the value of blending, it is assumed that there are two separate weather events that cause the downgrade of a proportion of wheat and barley crops, as yet unharvested. The opportunities for blending for moisture and quality and the way they are modelled are outlined in Loxton *et al.* (2017). Banks (1999) and Shinners *et al.* (2011), for example, discuss the important role that moisture content can play in affecting harvest logistics. A full description of all aspects of the model, including a full listing of the model's equations, is contained in Loxton *et al.* (2017).

The harvest logistics model, conditional on the inputs specified in Tables 1 and 2, generates the farmer's net revenue from the harvest and post-harvest activities (not including crop inputs). For each type of grain considered by the model, the following outputs are reported:

1. the duration of its harvest (in days),
2. the amount harvested (tonnes),
3. the expenditure on trucking ($),
4. fees paid to the grain receival facility ($),
5. the average daily duration of the harvest (in hours),
6. the extra value generated through moisture management ($),
7. the value of yield losses due to the duration of the harvest ($), and
8. the revenue losses from grain quality downgrades (with and without blending) ($).

The model assumes blending grain is only to minimise quality downgrades. Moisture management is considered insofar as grain can be harvested at one moisture content and is then placed in on-farm storage. If necessary, by opening the top of the silo to allow entry of moist night air, the moisture of the stored grain gradually is raised over the next several weeks so that when the grain is sent to the receival or end-user, it has a higher weight whilst still meeting the moisture limits set by the grain receival standards.

The particular application of the model in this paper assumes adverse weather events occur on days 9 and 18 of the grain harvest, affecting the quality of unharvested wheat and barley. However, economic opportunities to blend subsequently harvested grain with better quality grain stored on-

Table 2 Change in key parameters for each scenario (using $c = 2$ as the illustration, i.e. wheat)

Scenario	Parameter	Unit	Description	Level
1	$D^{\mathrm{farm:rcl}}$	km	Distance between farm and receival site	38
	U	t/h	Unloading rate at receival site	1,150
	δ_{unload}	h	Set-up/waiting time for grain unloading at receival site	0.45
2	R_c	t	On-farm storage capacity for crop c	1,250
	ϕ_c	$/t	Fixed fee for on-farm storage of crop c	12.8
	L	t/h	Loading rate at farm	275
3	Y_c	t/ha	Initial harvest yield of crop c	2.3
	Q_m	t	Capacity of truck m	44
	H_l	t/h	Harvesting rate of harvester l (assuming 75% field efficiency)	40

farm then arise. The blending allows downgrading penalties imposed at the upcountry or port receival site to be avoided or lessened.

4. Grain supply chain scenarios

The model of a farmer's harvest is applied to various industry scenarios to illustrate their effect on the nature and profitability of a farmer's grain harvest and to show how a farmer is likely to alter key aspects of their harvest operations in response to those scenarios. The farmer's scenarios, examined separately and in combination, are as follows:

Scenario 1: a more distant, more efficient upcountry receival facility {1}.
Scenario 2: more on-farm storage at a lower unit cost {2}.
Scenario 3: higher-yielding crops and larger capacity harvesters and trucks {3}.

Based on these three scenarios, seven combinations are considered: {1}, {2}, {3}, {1,2}, {1,3}, {2,3} and {1,2,3}.

The first scenario is consistent with strategic business decisions already undertaken by all the major commercial grain handlers in Australia. Site rationalisation and upgrades to remaining strategic sites are now commonplace in the grain-growing regions across Australia. The second scenario increasingly is observed, whereby farmers are opting for additional and different on-farm storage. Also emerging are some low-cost on-farm storage options (e.g. Botta 2018; GGHS 2018) that allow fumigation and ease of grain intake and extraction. Reductions in the cost of grain assessment equipment are also permitting farmers to more cheaply identify the quality of their grain and then store or transport it. The third scenario is the continued improvement in crop yields and machinery capability, whereby plant breeders deliver more resilient, higher-yielding varieties and manufacturers supply ever larger, more fuel-efficient and more sophisticated harvesters, trucks and grain-handling equipment.

Under each scenario, the following assumptions apply. For scenario 1, the journey length from farm to the receival site increases by about 25 per cent to be 38 km, yet the receival site's unloading rate increases by 15 per cent and the wait-time reduces by 10 per cent. For scenario 2, the on-farm storage capacity for crops 2 and 3 (wheat and barley) increases by 25 per cent, the fixed costs for storage reduce by 20 per cent, and the rate of loading at the farm improves by 10 per cent. In scenario 3, the yields of each of the three crop types increase by 15 per cent, truck capacity improves by 20 per cent, and the harvester rate improves by 20 per cent. These scenarios are applied to a representative grain farm in Western Australia, which is Australia's principal source of grain exports. The parameter values associated with the assumed scenarios are listed in Table 2 for the main crop, wheat.

In justifying the changes in parameter values that accompany each scenario, the following observations are made. Firstly, under scenario 1, annual reports and media statements from GrainCorp and CBH (e.g. CBH 2018) often describe their upgrades to receival sites. These upgrades increase intake and outturn capacities and reduce waiting times at their facilities. For example, GrainCorp's 'Project Regeneration' is a $200 million capital works expenditure on its network involving a reduction in the number of receival sites from 252 down to 180 whilst generating faster intake and outtake rates and faster turnaround times. In the final consolidated network, the average distance between its receival sites is forecast to still be only 30 km. Similarly, in 2016 CBH announced a $750 million investment over 5 years to improve receival and out-loading facilities, targeting 100 key sites. CBH have stated that growers' journeys from their farms to their closest receival point will only increase by around 10 per cent on average (Fulwood and Brammer 2016). However, the impact of site closures on travel distance is likely to be highly skewed as many farmers will have no change in their journey length whilst others whose local receival site closes will now need to travel much further. Hence, across all farms, although the average increase in distance to an upgraded receival site might be around 10 per cent, the modal increase will be far greater. Already in the early stages of site rationalisation, some farmers are reporting they need to travel much further than previously was the case.

Scenario 2 follows another industry trend of increased investment in on-farm storage (Kingwell 2017; Botta 2018; White *et al.* 2018). Botta (2018) suggests that in eastern Australia most farms can currently store on-farm about half an average year's grain production, and he envisages that this will increase to storing up to 75 per cent of an average year's grain production. Hence, suggesting that on-farm storage for some crops could increase by 25 per cent seems feasible. Furthermore, low-cost storage options (GRDC 2014; Baxter 2017; GGHS 2018) are increasing in popularity. Some of the newer forms of grain storage involve far less capital costs than traditional steel-only silos. White *et al.* (2018), for example, show that silo bags have a fixed cost of $6.9/t compared to $9.4/t for a large flat bottom steel and concrete silo. However, these authors also show the variable costs associated with using a silo bag are far greater and that large built storage overall has much lower unit costs of storage compared to small steel silos.

Scenario 3 considers varietal improvement. By illustration, the wheat variety Scepter, released by Australian Grain Technologies in 2015, in variety trials in Western Australia from 2012 to 2016 out-yielded the popular variety Wyalkatchem by 10 per cent and was 7 per cent higher yielding than Mace, a variety that had rapidly become a dominant variety (AGT 2017; DPIRD 2019). Hence, achieving a 15 per cent increase in crop yields in future years relative to current yields would seem possible, although the drying trend observed in southern Australia presents a key challenge to yield improvement (Stephens 2017). The lift in truck load capacity by 10 per cent seems achievable due to ongoing upgrades of key rural roads and further improvements in engines, design and materials used in truck manufacture. Lastly, increasing the potential harvesting rate to 54 t/h is achievable. Most new headers are capable of harvesting 40–50 tonnes of grain per hour. The base model assumes a harvesting rate of 45 t/h, so increasing that rate to 54 t/h in future years would seem feasible. Already harvesters with 60 foot fronts are available in Australia (Law 2014).

To gauge how some of the scenarios may affect different farms, some of the parameter values in Table 2 for each particular scenario were altered. For example, under scenario 1, we examined the impact of farmers having different increases in their journey length to their nearest receival site from no increase to a 30 per cent increase. Under scenario 2, we considered farmers who increased their on-farm storage by only 10 per cent as well as those who increased this storage by 50 per cent. Under scenario 3, we examine even larger work rate harvesters yet also considered a more limited increase in truck capacity.

5. Results and discussion

Results in Table 3 contrast the base case, without blending, against the base case, and other scenarios, where blending minimises the cost of downgrades.

Using better quality on-farm stored grain to blend loads and thereby lessen revenue penalties associated with downgrading of grain following adverse weather events is shown to be a very minor source of additional profit for farm businesses under all scenarios, at least for the events considered. In some situations where strongly adverse weather events occur, then blending is a more important source of additional profit. The ability to access blending in the base case lifts profit by only 0.5 per cent.

Another mechanism for lessening the cost or likelihood of weather-damaged grain is to have faster harvests, achieved by improving the field efficiency of harvest operations, using a harvester with a greater work rate capacity or using more than one harvester. For example, profits in the base case (with blending) can be increased by 3.3 per cent if a harvester with a third greater work rate is employed (i.e. 45 t/h versus 34 t/h). Such a high work rate could be achieved by improved field efficiency, assuming this is relatively costless to achieve. A higher work rate could also be achieved by using a harvester with a wider front but this would likely involve greater overhead and depreciation costs. The additional revenues come from a shortening of the harvest duration by 5 days, thereby avoiding one adverse weather event, and harvesting a slightly greater weight of grain, due to the grain being harvested sooner at a slightly higher moisture content.

Under scenario 1 that considers a more distant, yet more efficient upcountry receival facility, the farmer's profit is almost unchanged. The faster turnaround time at the receival site is insufficient to offset the increased travel time, and thus, the number of trips each day to the receival site stays the same. The very slight reduction in profit is due to more expenditure on

Table 3 Key outputs from the scenario analyses of a farmer's harvest logistics (with blending)

Scenario	Harvest profit ($'000)	Harvest duration (days)	Cost of trucking ($'000)	Receival fees ($'000)	Value of grain moisture management ($'000)	Cost of yield loss due to harvest duration ($'000)	Value of downgrade losses ($'000)	Extra value of blending for grain quality ($'000)	Extra average value of blending for grain quality ($/t)
Base case (no blending)/	1,639	21	88	318	2.5	80.6	38.1	na	na
Base case (with blending)	1,647	21	88	318	3.8	80.6	38.1	7.6	1.2
1	1,628	21	106	318	3.8	80.6	38.1	7.6	1.2
2	1,657	20	90	314	4.8	72.1	32.8	9.6	1.5
3	1,905	20	100	368	3.8	82.6	37.7	7.6	1.0
1 and 2	1,639	20	108	314	4.8	72.1	32.8	9.6	1.5
1 and 3	1,883	20	121	368	3.8	82.6	37.7	7.6	1.0
2 and 3	1,907	20	102	364	4.8	82.6	37.7	9.6	1.3
1, 2 and 3	1,886	20	123	364	4.8	82.6	37.7	9.6	1.3

grain cartage as each journey from the farm to the upcountry receival site is longer (38 km versus 30 km).

If bulk handlers rationalise their receival networks and simultaneously upgrade the efficiency of their remaining storage sites (i.e. scenario 1), then in the absence of yield advancement, farmers on average are likely to be slightly worse off (a 1.2 per cent fall in profit), if there is no change in the real cost of the handling and storage services. In this situation, farmers incur a greater cost of grain transport. Moreover, in some situations, farmers will undertake fewer trips per truck if their nearest receival facility is sufficiently more distant from their farm.

There are some important caveats and implications of the results for scenario 1, especially relevant in WA, where the principal owner and provider of upcountry and port receival, storage and handling services is a farmer-owned cooperative, CBH. Site rationalisation and facility upgrades by CBH are designed to reduce the overall cost of operating the supply chain network (CBH 2018). Accordingly, due to its cooperative status, CBH is likely to pass onto grain growers the benefits of the greater efficiencies of the network, thereby lessen handling costs paid by growers. These benefits are not fully captured in this analysis. Secondly, scenario one assumes that all tiers of government will continue to maintain regional road infrastructure in the face of its greater use by farmers. If government policy changes and higher road user charges are introduced, then higher costs of site rationalisation will be borne by grain farmers. These feasible higher road user costs are not considered in this analysis.

Enhancement in on-farm storage facilitates harvest logistics and the marketing of grain (via blending) (i.e. scenario 2) and thereby slightly boosts a farmer's business profit. However, to use effectively farm storage to deliver those profits adds to the already acknowledged complexity of farm management (Kingwell 2011).

Of all the scenarios listed in Table 3, the more profitable includes scenario 3 that involves higher-yielding crops and increased work capacities of the trucks and harvester. Predictably, higher yields mean greater volumes of grain and greater potential revenues from grain sales. How those greater revenues translate into higher profits depends on harvest logistics and the costliness of on-farm grain storage, grain transport and grain receival. By illustration, scenario {2,3} is the most profitable scenario, lifting profits by 15.8 per cent relative to the base case. The bulk of the increase in profits arises from a 15 per cent increase in the volume of grain harvested, with further incremental additions to profit arising from a shortening of the harvest duration by 1 day and 2 per cent less of the harvested tonnes being subject to downgrading.

In coming years, the most likely scenario to unfold is the combination of scenarios 1, 2 and 3. This set {1,2,3} involves more distant but more efficient receival sites, greater and less costly on-farm storage, higher-yielding crops, and further improvement in the work capacities of trucks and harvesters. The financial consequence of these trends, relative to the base case, is a 14.5 per cent increase in the farmer's profit with the main source of additional profit being increased grain yields.

An important assumption affecting all the scenario analyses is the maintenance of the real price of grains. If, as seems likely, real grain prices continue to slightly decline in the face of productivity gain (OECD/FAO 2018), then the improvement in profit will be less than suggested in Table 3. Under the most likely scenario {1,2,3}, even if real prices of grains decline by 5 per cent in coming years, then the farmer's profit will still increase by 10 per cent. Hence, over the next several years, as the rationalisation of receival sites continues, and new higher-yielding crop varieties are released and improvement in grain storage and cropping gear occurs, then this study's findings suggest farmers' profits from harvest logistics will increase, in spite of a possible or likely reduction in real prices of grains.

Importantly, however, the modelling results point to a farmer's need to be managerially skilful in order to achieve the possible increases in profit. For example, the model's structure assumes the farm manager embraces opportunities for on-farm blending of grain of different qualities and that the farmer is capable of properly matching machinery and equipment to the various tasks of harvesting, grain storage and grain transport. An annual improvement of the farm's grain net revenue of 10 per cent is worth $160K per annum that, for the typical Western Australian grain farm illustrated in the model, lifts the farm's rate of return to business equity by around 3 per cent. In other words, at a 4 per cent real discount rate, the net present value of a decadal stream of such additional profits is worth $1.3 million to that farm business. Noting that Australian grain farms, by international comparison, receive one of the lowest producer support estimates via government policy and action (OECD 2016), it follows that farmers' own actions rather than government support are the main source of the farmers' profits that are subsequently capitalised into the value of the farm businesses. In the case of a current Western Australian grain farm business, its net worth is $9.8 million (Planfarm 2019), so a decadal stream of additional profits worth $1.3 million in present value terms, as identified in this study, helps bolster the asset value of a farm business.

Table 4 shows the results from a sensitivity analysis of key aspects of the various scenarios. A perhaps unexpected result is that changes in on-farm storage alter net revenues very little. However, this result may be peculiar to the structure of grain handling and storage in Western Australia where the grower cooperative CBH is the dominant provider of storage and handling. Due to its economies of size, CBH storage and handling fees are the nation's lowest (White *et al.* 2018) and growers are not charged time-based storage fees. Hence, permanent on-farm storage is relatively expensive compared to upcountry storage fees charged by CBH. Moreover, CBH allows post-delivery virtual blending of grain classes that lessens the incentive for on-farm blending for quality.

The largest sensitivity impacts on net revenues in Table 4 stem from changes in the travel distance from the farm to the upcountry receival point.

Table 4 Sensitivity analysis results for various changes in components of scenarios 1, 2 and 3: farm net revenue ($’000)

	Scenario						
	1	2	3	1, 2	1, 3	2, 3	1, 2, 3
Change to scenario 1							
No increase in travel distance from farm to bin	1,647	—	—	1,657	1,905	—	1,907
A 40% increase in the travel distance from farm to bin	1,619	—	—	1,630	1,873	—	1,876
Change to scenario 2							
Only a 10% increase in on-farm storage	—	1,650	—	1,650	—	1,908	1,887
A 50% increase in on-farm storage	—	1,656	—	1,656	—	1,906	1,886
Change to scenario 3,							
Larger harvesters (45 t/h)	—	—	1,920	—	1,898	1923	1,903
No increase in truck carrying capacity	—	—	1,905	—	1,883	1,907	1,886

More efficient receival points offset some of the additional costs of travel time, but there is a point at which a farmer is financially worse off by the requirement to cart grain further.

The findings in this paper illustrate an often-stated theme in agriculture (e.g. Alston *et al.* 2009; Kerin 2017) that farming and agriculture are long-term endeavours. The improvement in the productivity of grain production and its supply chains is mostly a long-run game, often built on incremental changes that ultimately deliver benefits to grain industry participants. Hence, innovation in grain handling and storage, varietal improvement and more capable cropping machinery and transport, in concert, deliver efficiencies that enhance the profitability of grain farm businesses.

Another implication is that a potential source of additional profit for farm businesses is not just in crop production improvement, but also in post-production activity. The way grain is stored, blended, transported and sold can be further sources of profit for farm businesses. Yet often grain storage and transport are seen as costs rather than as investments skilful managers use in generating additional profit. Moreover, often the focus of much grains industry R&D is on farm productivity rather than innovation in supply chains beyond the farm gate. Yet, as the results of this study show, farmers can directly benefit from efficiency improvements in grain logistics. The need for vigilance of costs in grain supply chains and the pursuit of innovation and efficiency in those grain paths is often not given the same attention, or level of funding support, as aspects of grain production on farms.

6. Conclusion

This paper describes and applies a model of a farmer’s harvest logistics in grain industry scenario analyses in Australia. The characteristics of various industry scenarios are outlined, and their impacts on the nature and profitability of a farmer's harvest logistics are assessed.

The most likely scenarios involve more distant but more efficient receival sites, greater amounts of on-farm grain storage, a lower unit cost of on-farm storage, higher-yielding crops, and further improvement in the work capacities of trucks and harvesters. The financial consequences of these trends, relative to a current base case, show that even if real grain prices decline by 5 per cent, this still leaves a potential 10 per cent lift in the average farmer's profit which substantially adds to the net worth of the grain farm business.

An important conclusion is that a future source of additional profit for farm businesses will not just be improvement in the farm's production of crops but also in post-production activity. How grain is stored, blended, transported and where it is sold can generate additional profit for farm businesses. In summary, innovation and greater efficiency in grain logistics can contribute to a farmer's profit from grain production in coming years.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Key base case parameters for canola and barley.
Appendix S2. The round trip time of a grain truck at harvest.
Appendix S3. Modelling of crop quality downgrades and blending.