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The socio-economic impact of fungicide resistance in West Australia's Wheatbelt

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Abstract

Farming is a risky business, demanding daily decisions on farm input expenditure and best practices while operating in an uncertain climate. One of these decisions regards agro-chemical inputs for disease control, a decision increasingly challenged by fungicide resistance for many pathogens of agricultural significance. To understand disease management decision-making and the importance of fungicide resistance, we surveyed 137 barley growers from West Australia's Wheatbelt. On average, this group spent \$42/ha on fungicide application. Our survey found that growers were willing to invest an additional \$18/ha to delay resistance of the pathogen to fungicides. Qualitative data show that barley growers perceive fungicide resistance as a growing issue in the region with a significant economic and emotional impact. Growers also expressed concern that fungicide resistance could become a long-term threat to the sustainability of their agribusiness. This study demonstrates that understanding growers' financial motivations and the economics of plant diseases is vital.

Keywords: Mode of action, Net blotch of barley, Pesticide, Return on investment, Sustainable agriculture.

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1 Introduction

Net blotches of barley are considered economically significant diseases due to their ability to cause yield losses of between 10 to 40 percent. In situations where susceptible varieties are grown, control measures fail or are not adequately implemented and environmental conditions favour pathogen growth, the disease can lead to crop failure. Additionally, net blotches can also cause substantial quality losses leading to grain downgrades (Liu et al., 2011; McLean et al., 2010; Murray and Brennan, 2010; Jayasena et al., 2007). A study by Murray and Brennan (2010) evaluated the economic impact of crop diseases in Australia. The study revealed that spot form net blotch (SFNB), the most common foliar disease affecting barley in Western Australia, caused an average annual loss of $43 million to the Australian barley industry with a potential annual loss of over $300 million attributed to both SFNB and net form net blotch (NFNB) if the diseases were not well managed. Since barley contributes about $3 billion per annum to the Australian economy (ABARES, 2021; ABS, 2020), it is important to effectively manage disease epidemics to minimise the risk of undesired economic outcomes.

The extent of losses due to net blotches has led to the adaptation of different disease management strategies. These include cultural practices such as crop rotations and stubble management, planting resistant varieties, and using fungicides (Turkington et al., 2012; Walters et al., 2012; Stuthman et al., 2007; Liu et al., 2011). However, the rate of infection will depend on factors such as host genetics, environmental conditions and disease management interventions (Newlands, 2018; Ishii and Hollomon, 2015; Cooke, 2006; Anderson et al., 2004). Carlson (1970) noted that a grower's disease management decision is often complex and needs to consider the probability of disease development in the absence of perfect information.

Given that fungicide is the main method of controlling NFNB in barley, due to their low cost and effectiveness against a range of pathogens, it is common for growers to prophylactically apply fungicides to crops in order to insure themselves against the negative impacts associated with crop disease (van den Berg et al., 2013). However, fungicides create selection pressure for tolerant strains and extensive use of one mode of action group, using more fungicides than required or incorrect application of fungicides can lead to fungicide resistance (Lopez-Ruiz et al., 2018; Mair et al., 2016; Ishii and Hollomon, 2015). Moreover, the practice becomes prohibitively costly in cases where the cost associated with managing the disease outweighs the expected benefits.

Fungicide manufacturers are also faced with business risks if fungicide resistance becomes widespread. These include loss of current compounds leading to a reduced range of effective fungicides from their portfolio, loss of sale of less effective fungicide groups, and the length of time before new fungicide products come to market. Similarly, fungicide manufacturers would incur additional costs associated with developing new fungicide groups and compliance with regulatory approval requirements when developing new fungicide products (Oliver et al., 2021; Ishii and Hollomon, 2015). According to Ishii and Hollomon (2015), fungicides that were frequently used in the field created selection pressure for mutant strains leading to resistance problems. As a consequence, growers would have a supply risk with limited options of fungicides resulting in further selection pressure and widespread fungicide resistance issues (Rehfus et al., 2016; Ilbery et al., 2012).

Regulatory uncertainty and differences in implementing plant protection products regulations in different countries can negatively affect growers' competitiveness in the global markets. There is a long history of past decisions having impacts. For example, varied timing in the withdrawal of various fungicides from the market in different countries within the European Union (EU), without considering the cost and effectiveness of alternative measures, has left some farmers more vulnerable to disease impacts, thereby impacting their gross margins (Gullino and Laetitia, 1994). Furthermore, the pressure to meet strict regulatory frameworks due to increasing health and environmental concerns has resulted in a ban of various fungicides.

In 2009, the EU implemented a hazard-based regulatory assessment framework to regulate plant protection products (PPP) registration. By this time, several authorised plant protection actives in the EU had fallen by 63% in the past decade. That is, from 900-1000 actives to about 350 actives (Dehne et al., 2011). The impact of EU regulation on plant protection products used in the United Kingdom (UK) was projected to lead to a 36% decline in total farming profits, potential losses of about £2.5 billion (AUD $4.7 billion) of gross added value and 35,000 – 40, 000 job losses in the food processing and manufacturing sector (Andersons Centre, 2014). Similarly, Mason and Harris (2018) reported overall yield losses of between 4% - 50% if actives classified as "high risk" were deregistered and an estimated gross value-added loss of £1.6 billion (AUD $3 billion) per annum.

A reduction in plant protection products, without the availability of appropriate alternative measures, would impact three key areas: (i) the production and viability of farm enterprises resulting in loss of livelihoods throughout the food supply chain, (ii) the affordability of food prices (Rickard, 2008) and (iii) crop disease management in the presence of pesticide resistance (Oliver et al., 2021; Lopez-Ruiz et al., 2018). Whilst regulatory frameworks are important, pathogens continue to evolve and increase the agriculture industry's vulnerability to disease outbreaks. Therefore, management solutions aimed at minimising chemical use and optimising return are essential for a sustainable farm production.

The emergence of fungicide resistant strains and reduced efficacy of multiple fungicide modes of action groups pose a significant economic risk to the Australian barley industry (Lopez-Ruiz et al., 2020, 2018; Mair et al., 2016). For example, the emergence of fungicide resistance on the farm could affect the costs associated with disease control, in the sense that growers may be forced to use higher doses or more expensive fungicides (van den Bosch et al., 2020, 2018; Ishii and Hollomon, 2015). Moreover, resistance to fungicides would result in yield and quality losses when growers cannot achieve adequate disease control (Ireland et al., 2021; Tucker et al., 2015; Damicone, 2014) as well as food security threats (Cooper and Okello, 2021).

Fungicide resistance in Australia has been identified in two major fungicide groups used to manage barley diseases. Specifically, there have been reports on resistance or reduced sensitivity to (i) demethylase inhibitor fungicides (DMI; Group 3) in powdery mildew, NFNB and SFNB and (ii) succinate dehydrogenase inhibitor fungicides (SDHI; Group 7) in both SFNB and NFNB in barley (Ireland et al., 2021; Lopez-Ruiz et al., 2020). In Australia, resistance or reduced sensitivity to fungicides in barley has an average development time of 14 years (see the list of fungicides and the first recorded detection of resistance in Table 1). These results are consistent with the findings which have been reported in the crop protection literature (see, e.g., van den Bosch et al., 2020; Elderfield et al., 2018; Grimmer et al., 2014). A study by Price et al. (2015) in the UK estimated an economic loss of €4.6 billion (AUD $7.2 billion) if DMI fungicides became ineffective. However, the economic losses resulting from fungicide resistance in Australia has received limited attention (Tucker et al., 2015). Research to date has not yet determined growers' willingness to invest to prevent or delay the development of fungicide resistance problems.

This research uses both analytical and empirical analyses to (i) assess the impact of fungicide resistance on grower's return on investment, (ii) establish growers' willingness to invest to prevent or at least delay fungicide resistance problems and (iii) understand growers' current perception and attitudes towards fungicide resistance management. To the best of our knowledge, this is the first study to investigate growers' perceptions and attitudes towards fungicide resistance and their willingness to invest to manage fungicide resistance problems. The remaining part of the paper proceeds as follows: Section 2 gives an outline of the theoretical framework. Section 3 introduces the case study and presents the survey results. We then discuss our findings followed by concluding remarks in Section 4.

Table 1: List of fungicides and their first recorded detection of resistance in Australia (Ireland et al., 2021) and initial registration (APVMA, 2021). Note: DMI, demethylase inhibitor. SDHI, succinate dehydrogenase inhibitor fungicides. QoI, quinone outside inhibitors. FDR, First detection of resistance. LD, Lab detection, RS, Reduced sensitivity. R, Resistant. NSW, New South Wales. QLD, Queensland. SA, South Australia. Tas, Tasmania. Vic, Victoria. WA, Western Australia.

Fungicide group	**Fungicide resistance risk**	**Crop**	**Pathogen**	**Region**	**LD, RS, R**	**Initial registration (year)**	**FDR (year)**	**Time to FDR (year)**
Group 3 (DMI)								
Cyproconazole	Moderate	Wheat	*Zymoseptoria tritici*	Tas Vic NSW SA	RS RS RS RS	2004	2011 2011 2014 2014	7 7 10 10
Epoxiconazole	Moderate	Barley	*Pyrenophora teres* f. *teres*	WA	RS	2002	2013	11
		Barley	*Pyrenophora teres* f. *maculata*	WA WA	RS R		2016 2017	14 15
		Wheat	*Zymoseptoria tritici*	Tas Vic NSW SA	RS RS RS RS		2011 2011 2014 2014	9 9 12 12

Table 1 continued from previous page

Fungicide group	**Fungicide resistance risk**	**Crop**	**Pathogen**	**Region**	**LD, RS, R**	**Initial registration (year)**	**FDR (year)**	**Time to FDR (year)**
Flutriafol	Moderate	Canola	*Leptosphaeria maculans*	NSW	LD	2002	2014	12
				SA			2014	12
				Vic			2014	12
				WA			2014	12
		Wheat	*Zymoseptoria tritici*	NSW	LD		2011	9
				QLD			2011	9
				Tas			2014	12
				Vic			2014	12
Fluquinconazole	Moderate	Canola	*Leptosphaeria maculans*	NSW	RS	2011	2013	2
				SA			2013	2
				Vic			2013	2
				WA			2013	2
Propiconazole	Moderate	Barley	*Pyrenophora teres* f. *teres*	WA	RS	1996	2013	17
				WA	R		2017	21
				Vic	R		2019	23

Table 1 continued from previous page

Fungicide group	Fungicide resistance risk	Crop	Pathogen	Region	LD, RS, R	Initial registration (year)	FDR (year)	Time to FDR (year)
		Wheat	*Zymoseptoria tritici*	Tas	RS		2011	15
				Vic	RS		2011	15
				NSW	RS		2014	18
				SA	RS		2014	18
		Wheat	*Blumeria graminis* f. sp. *tritici*	NSW	R		2020	24
				Vic			2020	24
Triadimenol	Moderate	Wheat	*Zymoseptoria tritici*	Tas	RS	1996	2011	15
				Vic	RS		2011	15
				NSW	RS		2014	18
				SA	RS		2014	18
Group 7 (SDHI)								
Fluxapyroxad	Moderate - High	Barley	*Pyrenophora teres* f. *teres*	SA	R	2012	2019	7
		Barley	*Pyrenophora teres* f. *maculata*	WA	R		2020	8

Table 1 continued from previous page

Fungicide group	**Fungicide resistance risk**	**Crop**	**Pathogen**	**Region**	**LD, RS, R**	**Initial registration (year)**	**FDR (year)**	**Time to FDR (year)**
Group 11 (QoI)								
All chemicals	High	Wheat	*Blumeria graminis* f. sp. *tritici*	NSW	R	2009	2015	6
				SA	R		2015	6
				Tas	R		2015	6
				Vic	R		2015	6

2 Theoretical framework

This section will focus on a simplified model framework of a grower implementing crop protection decisions in the presence of fungicide resistance risk. Consider a grower whose objective is to implement cost-effective crop protection strategies which maximise the return on investment while minimising the risk of fungicide resistance developing. The initial stage, such as the decision leading up to sowing, represents the opportunity cost assessment stage. This decision occurs during the planning for crop establishment, which may be several months ahead of actual physical sowing. Here, a grower must weigh the benefits of planting one crop type, for example, barley, instead of an alternative option.

Additionally, the grower will select an appropriate crop variety. With respect to disease, we assume that three main components influence the decision to plant a given barley variety, i.e., the availability of disease management options, anticipated disease infection levels which signifies disease pressure, and within-season weather conditions that favour disease spread. Figure 1 provides a summary of the fungicide resistance risk assessment framework for a grower evaluating the efficacy of different disease management options.

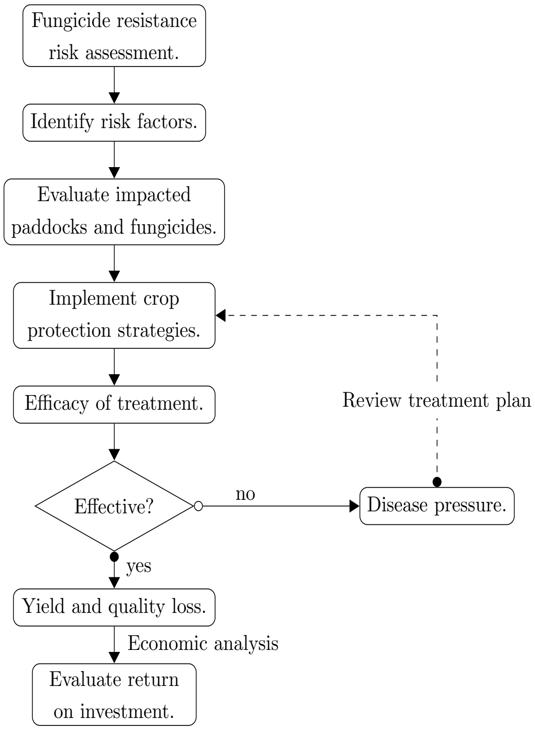

Figure 1: Grower's return on investment decision flowchart illustrating sequence of events when managing the risk of the emergence of fungicide resistance.

From Figure 1, a grower starts by identifying the risk factors associated with the emergence of fungicide resistance. The risk factors include the timing of fungicide application, climatic conditions, susceptibility of the host plant, frequency of fungicide use, the rate of fungicide application (Hollomon and Brent, 2009), suitability of selected fungicide product(s) for the targeted disease and known history of fungicide resistance within the site or region. In the second stage, the grower evaluates the cropping area at risk of fungicide resistance and the affected group of fungicides. As Ireland et al. (2021) suggest, good record-keeping is essential in order to employ suitable risk management strategies. Therefore, the grower needs to assess possible fungicide resistance risk factors to ensure appropriate action is taken, thereby minimising the risk of resistance building up.

The third stage involves the implementation of suitable crop protection strategies. For example, a grower may decide on whether to adopt a preventative or tactical fungicide treatment regime. By adopting a preventative fungicide treatment regime, a grower applies fungicide based on known timing (usually date or growth stage). Conversely, a tactical fungicide treatment regime requires a grower to withhold fungicide application as long as the level of infection is below a pre-defined disease threshold (also called economic threshold). The economic threshold can be seen as the level where control measures should be implemented to mitigate the risk of economic damage. A grower would have to intervene either at the beginning of the cropping season (using non-chemical integrated pest management practices such as stubble management) or throughout the season (using fungicide applications based on economic threshold levels) (Savary et al., 2012; Pedigo et al., 1986; Zadoks, 1985; Tammes, 1961).

To establish whether it is profitable to use preventative or tactical fungicide treatments in the current growing season, a grower will have to decide on a number of factors that will influence the decision to adopt a given fungicide treatment regime. For example, decisions such as cultivar selection; residue management; rotation, time of sowing and fungicide choice; the time of fungicide application; frequency of fungicide use and the rate of fungicide application(Hollomon and Brent, 2009); and the efficacy of fungicide product for the targeted disease. Other factors include environmental conditions, known history of fungicide resistance within the site or region, fungicide resistance risk and growers' perception of fungicide resistance risk.

When evaluating a suitable strategy to manage fungicide resistance risk, a grower will find it important to consider the current investment capacity to implement a given fungicide resistance management strategy. Failure to do so can lead to undesired outcomes such as costly disease management options as well as possible environmental impacts (Cooper and Okello, 2021). Finally, the last stage requires growers to re-assess the efficacy of fungicide treatment by evaluating the level of disease pressure and the return on investment under different fungicide management strategies, fungicide resistance risk status and disease severity levels.

2.1 Model formulation

Consider a grower who wishes to evaluate the benefit of implementing a preventative or tactical fungicide treatment strategy under varying levels of disease pressure and fungicide resistance risk. Following Carlson's (1970) decision theoretic framework, our model assumes that the grower selects from two fungicide management strategies: (i) one mode of action and (ii) two or more modes of action (including fungicide mixtures). If a grower uses at least one mode of action fungicide group, the total cost of adopting a fungicide management strategy is:

$$\sum_{i=1}^{m} c(t_i, t_a). \tag{1}$$

The term $c(\cdot)$ is a function of the fungicide treatment cost t_i (\$ per hectare, \$/ha); where $i = 1, \ldots, m$ denotes the number of fungicide application, and the corresponding fungicide application cost t_a (\$/ha). The expected net benefit in the absence of disease-induced loss π_0 (\$/ha) is given by:

$$\pi_0 = P\ y_e - \sum_{i=1}^{m} c(t_i, t_a) - c_0, \tag{2}$$

where P represents the commodity price (\$ per unit ton, \$/t), y_e denotes the estimated yield (tons per hectare, t/ha); which represents the attainable yield in the presence of limiting factors such as water and nutrients (Rabbinge et al., 1989; Savary and Willocquet, 2014). The variable c_0 represents other costs of production (\$/ha) not directly linked to disease management. Furthermore, we assume that fungal pathogens are sensitive to fungicide treatment, and there is no risk of fungicide resistance developing over time.

In order to assess the impact of disease-induced yield loss on a grower's profit margin, suppose a grower is faced with two discrete disease risk states: (i) a state of low disease pressure with low levels of expected yield losses and (ii) a state of moderate to high disease pressure with moderate to high levels of expected yield losses. The expected yield loss is defined as the reduction in both yield quantity and quality (Zadoks, 1985). If a grower manages foliar diseases using either a single or multiple fungicide mode of action groups, the expected yield lost to disease (t/ha) is calculated as (van den Bosch et al., 2020; Savary and Willocquet, 2014):

$$\xi_l = \lambda \, y_e \, \beta, \tag{3}$$

where $\lambda \in [0, 1]$ is the proportion of disease-induced yield loss in the area affected by the disease. Note that $\lambda = 0$ represents a scenario where the grower experience zero yield loss due to disease. Conversely, $\lambda = 1$ denotes complete field failure. The term $\beta \in [0, 1]$ represents the proportion of the farming area affected by the disease. For a given commodity price, P, the value lost to disease is calculated as:

$$\begin{aligned} v_l &= P \; \xi_l, && \text{(4a)} \\ &= P \; \lambda \, y_e \, \beta. && \text{(4b)} \end{aligned}$$

Suppose a grower wishes to maximise the return on investment (ROI) by selecting a given fungicide management strategy. ROI is defined as the ratio between the expected net benefit from implementing a given fungicide management strategy and the total cost of production. If we assume that a grower chooses from three different fungicide management strategies; that is, (i) no fungicide application, (ii) one mode of action (MoA) and (iii) two or more MoA, the grower's ROI maximisation problem is given by:

$$\begin{aligned} \max \quad & \frac{P(y_e - \xi_l) - \sum_{i=1}^{m} c(t_i, t_a) - c_0}{\sum_{i=1}^{m} c(t_i, t_a) + c_0}, \\ \text{subject to:} \quad & P(y_e - \xi_l) - c_0 \geq \sum_{i=1}^{m} c(t_m, t_a), \\ & y_e > 0; m \in \Re^+; \xi_l \geq 0. \end{aligned} \tag{5}$$

The objective function in Eq. (5) seeks to maximise a grower's ROI in the presence of disease-induced yield loss risk. The constraint $P(y_e - \xi_l) - c_0 \geq \sum_{i=1}^{m} c(t_i, t_a)$ ensures that the expected net benefit from adopting a fungicide management strategy, $i \in \{1, m\}$, offsets the fungicide treatment cost. However, in cases where growers continuously use the same fungicide mode of action group, increased selection pressure can lead to a build-up of resistant fungal populations (Hollomon and Brent, 2009), resulting in high levels of disease pressure and hence low yields. Therefore, we will assess a grower's return on investment in the presence of fungicide resistance risk.

To simplify our analysis, let us classify fungicide resistance risk into two broad categories: low and high fungicide resistance risk. In a scenario with a low risk of fungicide resistance, a grower's disease management action results in a slow development of fungicide resistance over time. By contrast, a scenario with a high risk of fungicide resistance results in moderate to rapid development over time. Figure 2 illustrates a slow (linear) and a fast (exponential) fungicide efficacy decay curve in the presence of fungicide resistance risk.

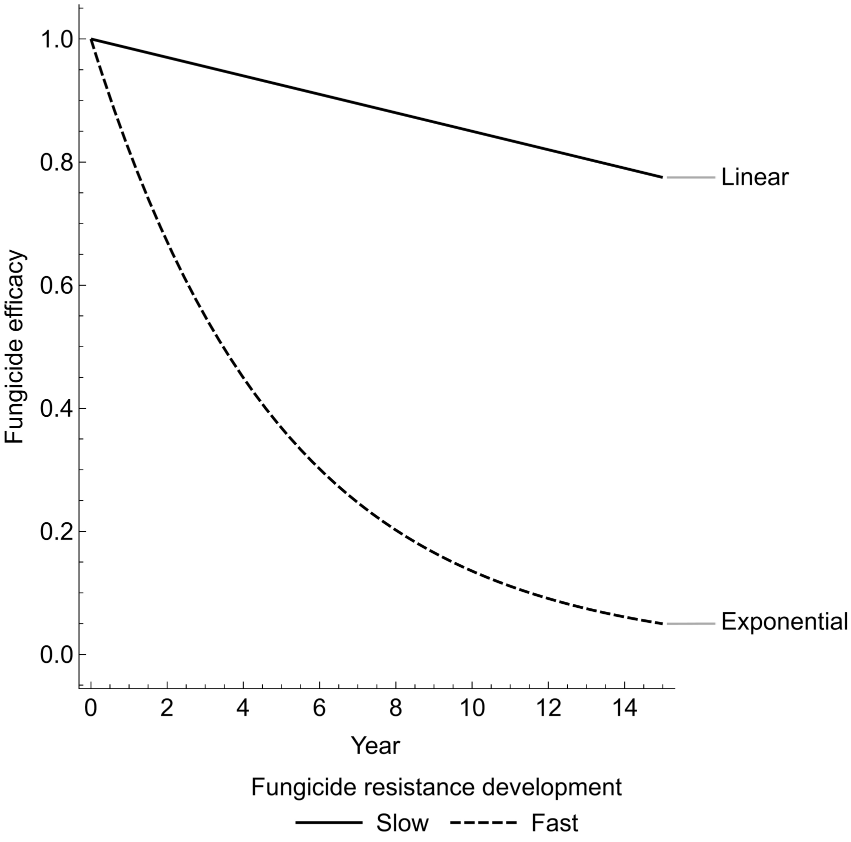

Figure 2: Fungicide efficacy decay plot based on linear and exponential fungicide resistance risk.

Therefore, if we include the risk of fungicide resistance in our model formulation, Eq. (3) can be re-written as:

$$\xi_l^r = \lambda(\psi)\, y_e\, \beta, \tag{6}$$

where ξ_l^r denotes the expected yield lost to disease in the presence of fungicide resistance risk. Eq. (6) includes an adjusted yield loss variable, $\lambda(\psi)$, which is a function of the fungicide efficacy factor; where ψ takes any value in the range $[0, 1]$. When $\psi = 0$, the pathogen is considered resistant and unable to respond to fungicide treatment. Conversely, when $\psi = 1$, the pathogen is considered sensitive and fully responds to fungicide treatment. Let us suppose that a grower is faced with the risk of fungicide resistance and quality downgrade. We can reformulate Eq. (4a) to include two components: the value loss to disease and the value loss to quality downgrade. The total value lost to disease and quality downgrade is thus given by:

$$\begin{aligned} v_l^r &= P\ \xi_l^r + \theta(P - P_d)(y_e - \xi_l^r), \qquad &(7a)\\ &= P\ \lambda(\psi)\, y_e\, \beta + \theta(P - P_d)(y_e - \lambda(\psi)\, y_e\, \beta), \qquad &(7b)\end{aligned}$$

where $\theta \in (0, 1)$ denotes the quality loss factor, which represents the proportion of downgraded yield, and P_d denotes the downgraded commodity price. The term $\theta(P - P_d)\,(y_e - \lambda(\psi)\, y_e\, \beta)$ represents the value lost due to quality downgrade. If we reformulate Eq. (5) to include the value lost to disease and quality downgrade, the grower's ROI maximisation problem in the presence of both fungicide resistance and quality downgrade risk is:

$$\begin{aligned} \max \quad & \frac{P(y_e - \xi_l^r) - \theta(P - P_d)(y_e - \xi_l^r) - \sum_{i=1}^{m} c(t_i, t_a) - c_0}{\sum_{i=1}^{m} c(t_i, t_a) + c_0} \\ & \xi_l^r = \lambda(\psi)\, y_e\, \beta, \\ \text{subject to:} \quad & P(y_e - \xi_l^r) - \theta(P - P_d)(y_e - \xi_l^r) - c_0 \geq \sum_{i=1}^{m} c(t_i, t_a), \\ & y_e > 0; m \in \Re^+; \xi_l^r \geq 0; \theta \geq 0. \end{aligned} \tag{8}$$

The objective function in Eq. (8) seeks to maximise a grower's ROI in the presence of fungicide resistance and quality downgrade risks. The constraint $P(y_e - \xi_l^r) - \theta(P - P_d)(y_e - \xi_l^r) - c_0 \geq \sum_{i=1}^{m} c(t_i, t_a)$ ensures that the expected net benefit from adopting a fungicide management strategy, $i \in \{1, m\}$, offsets the fungicide treatment cost.

After setting up the profit maximisation model, the next section will use a numerical simulation experiment to explore the impact of fungicide resistance development on growers' return on investment.

2.2 Model implementation: Numerical simulation experiment

In this section, two scenarios were used to assess a grower's return on investment. In the first scenario, a grower's disease management strategy was assumed to result in a slower decline of fungicide efficacy over time. In the second scenario, the selected disease management strategy resulted in a faster decline of the fungicide efficacy over time. For the purpose of sensitivity analysis, the parameter values for disease impact on profit were randomly generated over a predefined range. Table 2 provides a summary of the parameters that were used in the simulation experiment. The simulations were replicated 20,000 times with randomly drawn parameter values within the General Algebraic Modelling System (GAMS v31.1.1).

Table 2: Parameter values for the numerical simulation experiment

Parameter	**Explanation**	**Value**
$\lambda(\cdot)$	Proportion of yield loss	0% - 80%
θ	Proportion of downgraded yield	0% - 20%
y_e	Estimated yield	1 - 4 t/ha
P	Commodity price	\$225/t - \$385/t
$c(t_m)$	Fungicide treatment cost	\$10 - \$30/ha
$c(t_a)$	Fungicide application cost	\$10 - \$15/ha
c_0	Other cost of production	\$200/ha

Note: t/ha, ton pe hectare; \$/t, dollar per ton; \$/ha, dollar per hectare.

To understand the extent to which the net benefit and the return on investment values differed between the scenarios with a slower (baseline) and faster decline of fungicide efficacy, we computed the relative change in the average benefit from fungicide use. Table 3 shows that, on average, the net benefit and the return on investment values decline by 11% when the fungicide efficacy deteriorates faster (faster rate of fungicide resistance development) compared to the baseline case (slower rate of fungicide resistance development). Overall, the observed deterioration of the ROI value is driven by a faster decline in fungicide efficacy, which leads to greater yield losses and, hence, lower profit margins. The implication is that, as the fungicide efficacy decline (due to fungicide resistance), the yield lost to disease increases, resulting in a lower net benefit and hence a lower return on investment value. These findings suggest that there is value in minimising the negative impact resulting from the loss of fungicide efficacy and fungicide resistance risk. The next section will use a case study of barley growers in West Australia's Wheatbelt (WA) to explore factors promoting behaviour change when managing fungicide resistance.

Table 3: Summary statistics of the numerical simulation experiment

	Mean	**SD**	**Median**	**1Q**	**3Q**	**IQR**
Slow development of fungicide resistance scenario						
Net benefit ($/ha)	490.44	29.68	492.30	471.16	511.20	40.04
Return on investment (ROI)	1.91	0.11	1.92	1.84	1.99	0.15
Fast development of fungicide resistance scenario						
Net benefit ($/ha)	437.10 (↓ 10.9%)*	61.65	447.37	394.37	485.49	91.12
Return on investment (ROI)	1.71 (↓ 11.0%)*	0.24	1.75	1.54	1.89	0.36

Note: SD, standard deviation; 1Q, First quartile; 3Q, Third quartile; IQR, Inter-quartile range; * % change relative to the slow development of fungicide resistance scenario; $/ha represents dollar per hectare.

3 Case study

The theoretical framework specified in Section 2 assesses the impact of disease and loss of fungicide efficacy on growers' return on investment. However, economic modelling is limited in examining the psychological mechanism underpinning growers' decisions toward fungicide resistance management. Beyond economic predictors, prior research shows that growers' willingness to invest and decisions to adopt: bio-pesticides (Al-Hassan et al., 2010), innovative conservative technologies (Mann, 2018), genetically modified crops (De Steur et al., 2019), and reduced usage of pesticides (Vatn et al., 2020) are predicted by different psychological and attitudinal determinants that are not identified through economic modelling. In fact, besides modelling fungicide resistance from a financial perspective, existing research on fungicide resistance management strategies (see e.g., Oliver et al., 2021) has solely focused on growers' current usage and knowledge of different management strategies. Thus, the current research will leverage both a quantitative and qualitative approach to examine barley growers' perceptions and motivators of behaviour change underpinning their willingness to invest and attitudes toward fungicide resistance management strategies.

3.1 Participant recruitment and data collection

During the 2019/2020 growing season, growers participating in the "Barley Disease Cohort Project" sent diseased barley leaf samples to Curtin University's Centre for Crop and Disease Management for disease screening. The project focused on understanding the extent of fungicide resistance in the in WA's Wheatbelt region. After the barley leaf samples were analysed in the laboratory, the participants received the following information: (i) disease diagnosis of two major barley pathogens: spot form net blotch and net-form net blotch, (ii) fungicide resistance status of the samples and (iii) fungicide management recommendations.

From the initial engagement with the growers, it was clear that the fungicide resistance problem was more widespread than initially anticipated. This study wanted to understand the motivators of behaviour change when growers were faced with fungicide resistance risk. The recruitment targeted growers and agronomists who had provided their consent to be contacted about their fungicide resistance management. Growers and agronomists from the WA's Wheatbelt were invited to share information about their fungicide resistance management practices. The primary contact was made through phone interviews. Alternatively, a link to an electronic version of the survey was included in the email communication to the participants. Prior to conducting the survey, we sought ethical approval from Curtin

University Human Research Ethics Committee (HRE2020-0440).

During the phone interview, the interviewer provided participants with the background of the study, followed by participation consent questions. Participants who provided consent to participate in the study were subsequently asked the survey questions. Their responses were recorded or transcribed by the researcher. The process took about 20-25 minutes. Participants who nominated to complete a self-administered online questionnaire had their responses stored in a secured database. To ensure consistency of the survey responses, descriptions of the contents in the electronic version of the survey were consistent with those delivered through phone interviews.

3.2 Survey summary

A total of 137 survey responses were obtained through phone interviews (82%) and self-administered questionnaires (18%). The overall response rate was 81% among the participants who sent their barley leaf samples for disease screening. Figure 3 provides the geographical distribution of the survey participants.

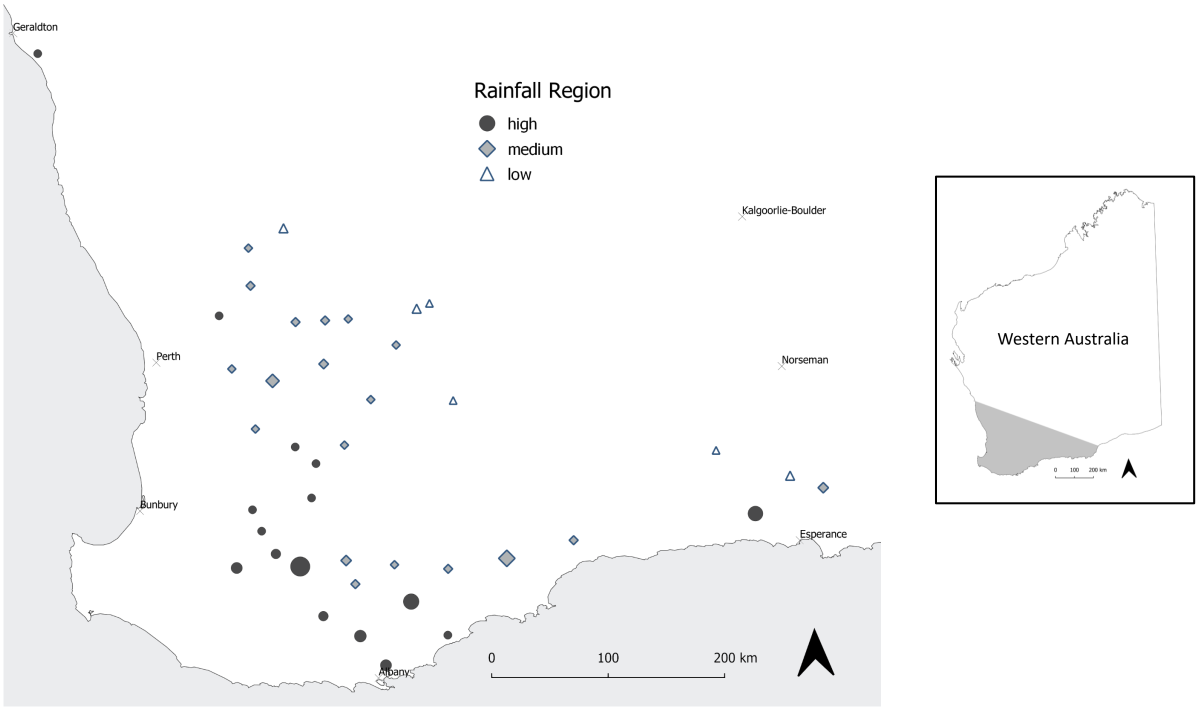

Figure 3: Map of the distribution of survey participants categorised according to postcodes and rainfall zones: Low, Medium and High. The size of the symbols denote the number of participants in each location across the West Australia's Wheatbelt.

The participants were aged between 22 and 69 years, while their agricultural experience varied between 2 and 54 years. See summary statistics in Table 4.

Table 4: Summary statistics of the Barley Disease Cohort Project survey during the 2019/2020 growing season.

Demographic details	**Mean**	**SD**	**Median**	**1Q**	**3Q**	**IQR**
Age (years)	44.1	10.7	44.01	35.0	52.0	17.0
Years in agriculture industry	24.6	11.8	25.0	15.0	33.0	18.0
Barley production program						
Planted area (hectares)	1122	1180	800	450	1500	1050
Total number of paddocks	9.9	8.0	8.0	5.0	12.0	7.0
Number of varieties grown	1.9	0.8	2.0	1.0	2.0	1.0
Number of crop(s) in 2018 rotation	1.6	0.9	1.0	1.0	2.0	1.0
Fungicide treatment program						
Total number of fungicide(s) application	2.4	0.6	3.0	2.0	3.0	1.0
Seed/In-furrow cost ($/ha)	13.6	8.3	12.0	6.0	20.0	14.0
First foliar treatment cost ($/ha)	10.3	5.8	10.0	5.6	15.0	9.4
Second Foliar Treatment cost ($/ha)	11.9	5.3	12.0	8.0	15.0	7.0
Production and harvest statistics (t/ha)						
Potential yield (beginning of season)	3.3	1.0	3.5	2.6	4.0	1.4
Breakeven yield	2.0	0.6	2.0	1.5	2.4	0.9
Actual yield (end of season)	3.1	1.3	3.0	2.1	4.0	1.9
Fungicide resistance management (FRM)						
Maximum acceptable yield loss (%)	5.0	4.8	5.0	1.5	6.4	4.9
Extra investment for FRM ($/ha)	17.9	11.9	15.0	10.0	23.5	13.5

Note: SD, standard deviation; 1Q, First quartile; 3Q, Third quartile; IQR, Interquartile range; t/ha, tons per hectare; $/ha, AUD dollar per hectare; FRM: Fungicide resistance management.

In the following sections, we will: (i) evaluate growers' willingness to invest in preventing or delaying fungicide resistance problems, (ii) assess grower's current perception of fungicide resistance issues using thematic analysis, and (iii) understand motivators of behavior change when growers were faced with fungicide resistance risk. Understanding motivators and barriers of behaviour change would enable effective, practical and economical crop protection strategies while minimising the impacts of fungicide resistance.

3.3 Growers' willingness to invest to prevent or at least delay fungicide resistance

This section will explore growers' willingness to invest in addressing fungicide resistance risk. It was hypothesised that growers would be willing to allocate extra investments to manage or delay fungicide resistance problems. Our study found that, on average, growers currently invest approximately \$30/ha on fungicide treatment (see Table 4). When asked about their willingness to invest in managing fungicide resistance risk, growers indicated that, on average, they were prepared to invest an extra \$18/ha to manage or at least delay the fungicide resistance problem (see Table 5).

When we grouped the willingness to invest in managing fungicide resistance according to the rainfall region, we found the willingness to invest for growers in the low rainfall region to be \$12/ha. In contrast, those in the high rainfall region were willing to invest about \$19/ha.

Additionally, growers who currently find the cost of fungicide treatment to be costly and those with lower profit margins were likely to allocate up to \$10/hectare to manage fungicide resistance (see Figure 4). These results reveal that the affordability of disease management alternatives remains the main factor affecting the growers' willingness to invest in managing fungicide resistance.

Table 5: Growers' willingness to invest (WTI) grouped according to rainfall region.

Rainfall region	**WTI (\$/ha)**	**Actual yield (t/ha)**
High	\$18.98	3.7
Medium	\$17.88	2.7
Low	\$12.29	1
Average	\$17.93	3.1

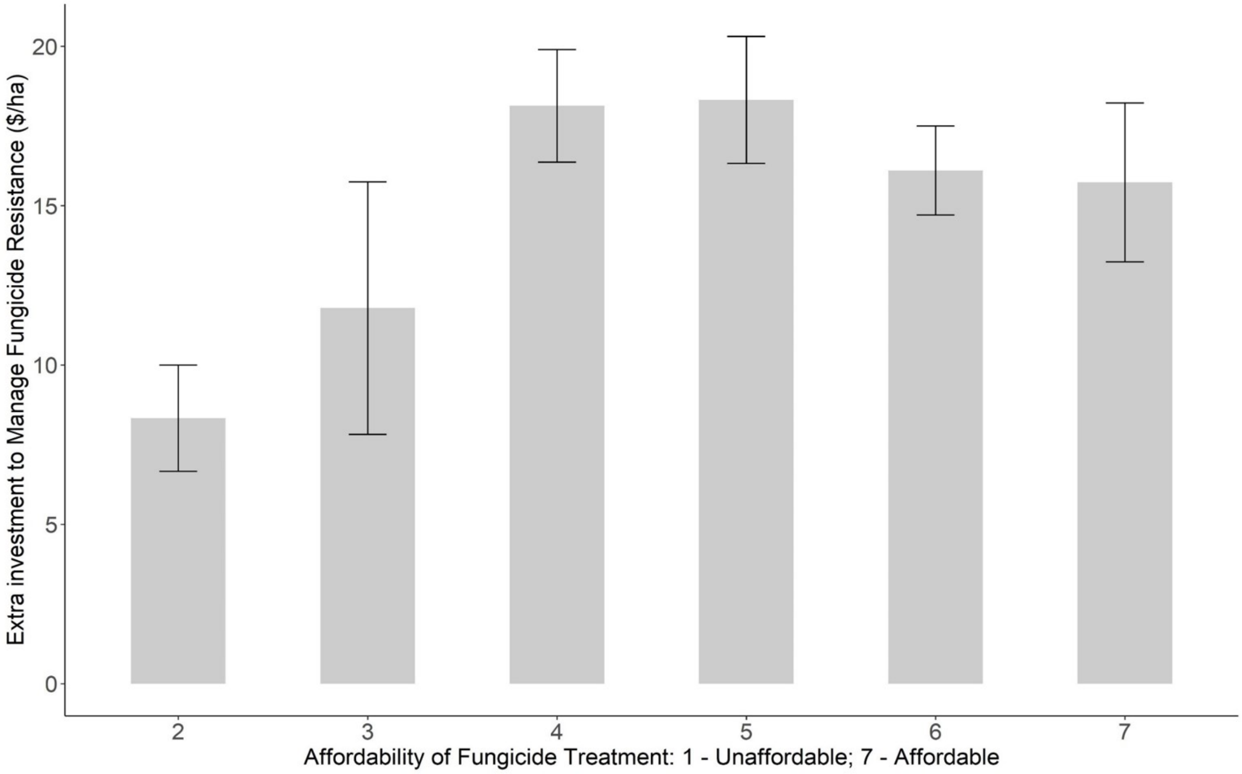

Figure 4: Distribution of the extra investments that growers were willing to invest in managing fungicide resistance problems. The extra investments were grouped according to the affordability of the current fungicide treatment. $/ha denotes dollar per hectare.

3.3.1 Drivers of return on investment (ROI) and extra investment to manage fungicide resistance

Multiple factor analysis (MFA) was used to reduce the dimension of the variables in the dataset and investigate the influence of the variables on the total variance. MFA can be viewed as a weighted principal component analysis (PCA) that compares the differences between several groups of variables and the correlation of the variables (Jolliffe and Cadima, 2016; Abdi et al., 2013; Bécue-Bertaut and Pagès, 2008; Escofier and Pagès, 1994). In our survey data, we normalised related questions by assigning equal weights to each question in the same category.

The original questionnaire data contained 66 variables. In order to reduce the number of variables, we grouped the variables into 20 distinct groups. The resulting variables included (denoted as G1 to G20): area under barley production (G1), crop varieties (G2), yield estimates (G3), age and experience (G4), return on investment (G5), fungicide resistance management (FRM) investment (G6), crop rotation program (G7), rainfall region (G8), education level and association membership (G9), fungicide application decision-maker (G10), type of fungicide used (G11), affordability of disease management options (G12), fungicide application patterns (G13), the importance of FRM to agri-business (G14), disease pressure on the farm (G15), fungicide resistance management practices (G16), factors that drive the adoption of FRM practices (G17), frequency of access to FRM information sources (G18), accessibility of FRM information sources (G19) and timeliness of FRM information sources (G20).

Results from multiple factor analysis reveal that the first 11 components (G1 - G11) explain 55% variability within the dataset. For instance, accessibility of FRM information sources, timeliness of FRM information sources, frequency of access to FRM information sources and the return on investment contribute the most to the first component. FRM investment, yield estimates and rainfall region dominate the second component, while factors driving the adoption of FRM practices, fungicide resistance management practices, and the importance of FRM to agri-business contributes to the third component.

Additionally, multiple linear regression was used to determine the drivers of the return on investment (ROI) and the extra investments growers were willing to invest in managing fungicide resistance. The model indicates the following factors to have significant positive effects on ROI (p-value < 0.05): the actual yield, age of the respondent, rainfall region, the total number of fungicide applications, accessibility of fungicide resistance information source (e.g., agronomists) and the timeliness of the fungicide resistance management information source (e.g., print media). Factors that negatively impacted ROI include: farm size, current fungicide cost, the total cost of production, years in the agriculture industry, types of fungicide resistance management practices (e.g., scouting for disease and varieties used), frequency of use of fungicide resistance management information source (e.g., social media), accessibility of the fungicide resistance management information source (e.g., the Barley Disease Cohort Project) and timeliness of fungicide resistance management information source (e.g., field days).

Regarding growers' willingness to invest in preventing or delaying fungicide resistance problems, the positive drivers included the types of fungicide resistance management practices (e.g., varieties used, scouting for disease, use of fungicide mixtures); the estimated yield; and the first foliar fungicide treatment group. On the other hand, the main factor limiting the allocation of extra investment to manage fungicide resistance includes the actual yield obtained at the end of the growing season.

In the next section, we will use thematic analysis to understand growers' perceptions of the fungicide resistance problem and motivators of behaviour change. Qualitative responses were collected to better understand the factors that promote and impede growers' willingness to invest in mitigating fungicide resistance risks and adopting fungicide resistance management practices.

3.4 Thematic analysis: Current knowledge about fungicide resistance

Thematic analysis was used to identify themes (patterns of meaning) from the qualitative data collected on the survey. Specifically, we adopt Braun and Clarke's (2006) reflexive thematic analysis approach, which is designed to explore an individual's views, attitudes, and lived experience. To ensure the robustness and reliability of the thematic analysis, three researchers conducted the thematic analysis following the recommended analysis process outlined by Braun and Clarke (2006): (1) data familiarisation; (2) coding; (3) generating initial themes; (4) reviewing themes; (5) defining and naming each theme; (6) writing up. The three researchers conducted the first three steps individually, whereby recurring and prevalent themes were coded, extracted, and grouped. The final, synthesised themes were then re-assessed to ensure that the scope and focus aligned with our research question. A consensus was reached through discussion to ensure that they were sufficiently meaningful and informative (Braun and Clarke, 2006).

Growers were asked about their current knowledge of fungicide resistance problem and current agronomic practices. Five major themes emerged from the thematic analysis (Braun and Clarke, 2006) and content analysis Weber (1990) of growers' perceptions of the fungicide resistance problem (see Figure 5).

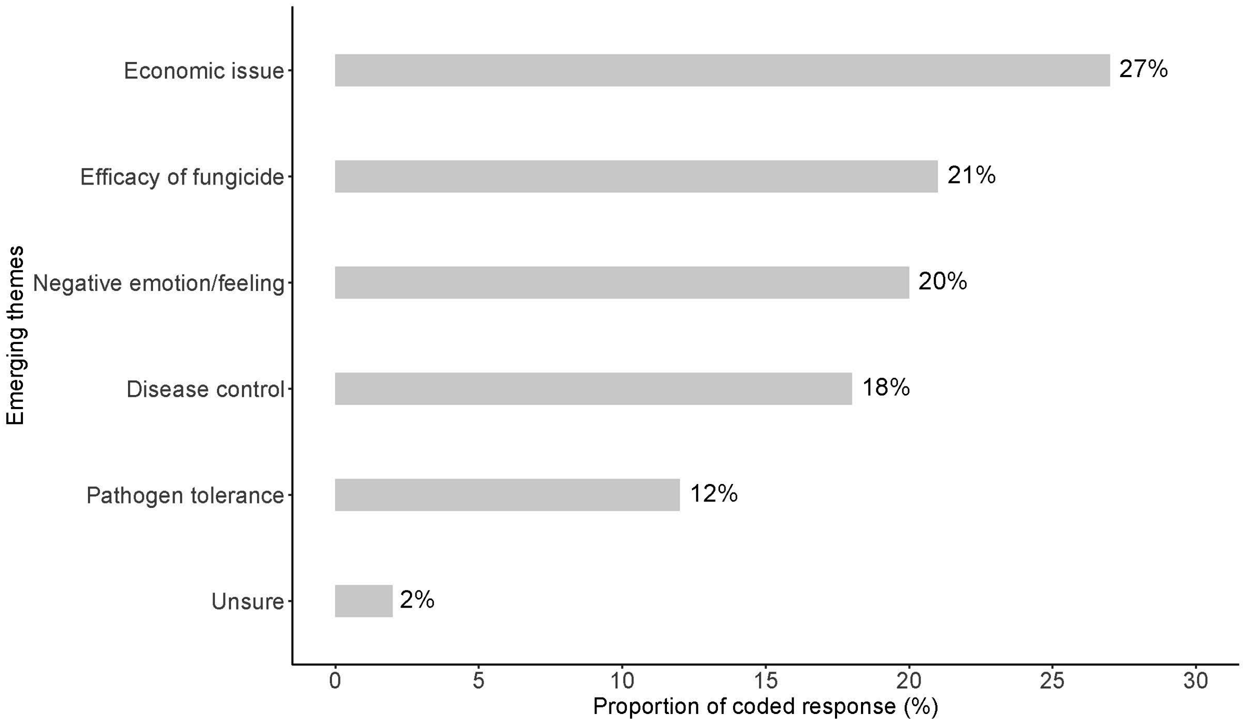

Figure 5: Emerging themes from growers' definition of fungicide resistance.

The top theme emerging from the thematic analysis of growers' definition of fungicide resistance related to the economic impact of fungicide resistance. We find that 27% of the coded responses define fungicide resistance as an economic issue. The respondents were particularly concerned about the threats of fungicide resistance to their agribusiness and the sustainability of their production program. For instance, one grower said: "*Fungicide resistance affects agribusiness state-wide; it doesn't matter where you farm, every area is affected or near affected by diseases. It impacts your business model (tons in the bin) and chemical logistics.*" Interestingly, respondents tend to frame the economic impact of fungicide resistance as a yield loss or a high input cost. From the perspective of yield loss, respondents indicated: "*Fungicide resistance is caused by fungal organisms within productive crops which have yield effect if left untreated"*, "*yield loss*", and "*less yield, small crop, thin crop*". However, other respondents perceive fungicide resistance as a significant input cost to implement fungicide management strategies: *"expensive, making barley less economical to grow*", '*Expensive if it is a failure*", "*annoying, costs money...*" and "*(management strategies) wasting your money.*" These responses highlight growers' concerns about the threat of fungicide resistance risk to the profitability of the Australian barley industry. They also demonstrate the need for fungicide resistance management strategies to positively impact yield in a cost-effective way.

Growers also highlighted the emotional impact of the fungicide resistance problem. The respondents had a sense of urgency to manage fungicide resistance risk. The respondents had a sense of urgency to manage fungicide resistance risk. One respondent stated that: "*Fungicide resistance is scary. It is definitely a looming issue. We haven't got it yet, but it's something that we are very worried about. With herbicide resistance, we've got different options, but we don't really have those options with fungicides.*" Other respondents referred to fungicide resistance as: "*a bad thing*", "*frustrating*", "*stressful*", "*worrying*", "*challenging*", "*Scary, you need to be on your front foot and be preventative rather than reactive*", and "*problematic...stress...*". Another respondent highlighted that fungicide resistance results from the "*lack of knowledge. Expensive if it's a failure and wasting your money*" while another stated that fungicide resistance results in "*spending a lot of money on something that doesn't work, frustration*". These sentiments highlight growers' concern about the long-term threat of fungicide resistance risk and the likelihood of the problem impacting disease management strategies, especially for those operating in marginal areas. Aside from economic impact, the findings show that these threats may also negatively impact growers' emotional well-being.

The second major theme concerned the efficacy and knowledge of fungicide treatment, accounting for 21% of the coded responses (see Figure 5). Generally, fungicide resistance was defined as the state where cheaper fungicides failed to provide adequate protection against fungal pathogens. As one respondent states: "*The pathogen is no longer controlled by the chemistry that we are using.*" Other respondents commented: "*failure with the use of one or more fungicides in crop apart from weather conditions or other factors*"; "*fungus that has become resistant to chemicals*"; "*application of fungicide choice which fails due to resistant factors other than factors under my control such as weather and application techniques*" and "*using a fungicide and not getting a result you were hoping for*". At the same time, other respondents also attribute the inefficacy of fungicide treatment to the lack of knowledge: "*problematic because it's hard to understand whether we've had resistance or failures in fungicides*", '*Fungicide knowledge as a farmer isn't that great and I don't think agronomists have a great handle on fungicide management*", and *"It's a bit of an unknown. Something that you can't see you can't fix"*. These findings suggest that respondents are particularly concerned about the risk to their agribusiness if cheaper fungicides failed to provide adequate protection against fungal pathogens, highlighting the need for fungicide resistance management strategies to demonstrate their effectiveness and efficacy before wide adoption. Knowledge about fungicides, fungicide resistance risk factors and management strategies is essential to tackle resistance issues.

The concerns of fungicide resistance are also attributed to the ongoing inability to control the disease with fungicides (18%) and pathogens developing tolerance to chemicals over time (12%). For instance, when asked about the fungicide resistance challenge that they face, a respondent said *"inability for (current) fungicide to control a disease*" and another indicated "*loss of control over diseases in barley*". In fact, some respondents agreed that fungicide resistance is a growing concern that is not within their control due to the ever-increasing and changing challenge to manage the issue: *"It's increasing and more difficult to control nowadays as products are not working as they used to do*", *"resistant factors other than factors under my control such as weather and application techniques*", and *"loss of control over diseases in barley*". The respondents attribute this lack of control to the development of tolerance in crop disease pathogens: *"When a fungicide has reduced sensitivity or won't work on a pest you're trying to control*", *"When a product used no longer provides the level of control on a target pathogen population.*", and *"increasing tolerance to label rates of fungicide. Reduced expected control period*". Interestingly, about 2% of the coded responses (6 growers) were unsure of how to define fungicide resistance. Taken together, these findings suggest a need to assist growers in regaining control by educating them regarding different facets, causes, and management strategies of fungicide resistance beyond the overuse and resulting tolerance of fungicides.

3.5 Motivators of behaviour change

To further understand patterns in the coded responses, the results were grouped according to the participant's age and experience level (years in the industry). Age was divided into three distinct groups: (i) below 35 years, (ii) 35 to 50 years and (iii) over 50 years. Similarly, the experience level was divided into three groups: (i) 0 to 15 years, (ii) 16 to 30 years and (iii) over 30 years (See Tables 6 and 7).

Growers were asked to indicate their current fungicide resistance management (FRM) practices. Our study reveals that, on average, greater than 70% of the participants use crop rotation and resistant (tolerant) varieties as their top two strategies to manage fungicide resistance. On the contrary, 46% of the participants reported using fungicide mixtures to manage fungicide resistance problems. When FRM practices were grouped by rainfall regions, we find that greater than 80% of growers in all the rainfall regions were likely to adopt crop rotation as their top strategy to manage the fungicide resistance problem. We also see that growers in the high rainfall regions were likely to adopt resistant varieties (74%) or rotate new chemistry (74%) as their top two FRM strategies. On the other hand, growers in the low rainfall region were likely to use stubble management (64%) or rotate new chemistry

(64%) to manage fungicide resistance. Interestingly, only 27% of growers in the low rainfall region were likely to use fungicide mixtures.

In relation to the fungicide application pattern, participants across all age groups implement the following management practices: (i) use label rates (96%), (ii) scout for the disease before applying fungicides (93%) and (iii) alter their fungicide spray programs in response to weather condition (92%) and disease pressure (91%). The average proportion of participants using fungicide mixtures was 57% across all age groups. When asked about their willingness to stick to the spray plan, a smaller proportion of participants under 35 years (6%) were likely to stick to their original spray plans. However, 23% of participants between the ages of 35 and 50 years and 32% of participants over the age of 50 stated that they would stick to their original spray plan. If we considered the participants' level of farming experience, 32% of participants with more farming experience were more likely to stick to their spray plan than participants with less farming experience (11%).

Moving on to factors that would motivate growers to adopt FRM practices, we find that majority of the respondents considered yield and profitability as the two main drivers of adopting FRM practices. In particular, more than 80% of the growers indicated that they would adopt FRM practices if they: (i) received a positive fungicide resistance diagnosis; (ii) lost disease control from current fungicide management practices, and (iii) observed a reduction in productivity relative to the current state. On the other hand, 73% of the respondents indicated that they were likely to change their FRM practices if fungicide treatment costs became expensive. Taken together, these results demonstrate growers' willingness to implement cost-effective FRM practices in anticipation of disease epidemics while maintaining the efficacy of current fungicides and the profitability of their agribusiness.

Table 6: Descriptive statistics showing respondents' fungicide application patterns grouped according to age with Likert scale score of 5 and above (1 – Strongly disagree to 7 - Strongly agree). Note: *FRM, Fungicide resistance management.

		Age group (years)		
Frequency of using *FRM practices	Average	Under 35	35 - 50	Over 50
I rotate crops	88%	94%	87%	83%
I use resistant varieties	70%	65%	75%	70%
I rotate new chemistry	66%	52%	75%	73%
I change mode of action	67%	68%	70%	63%
I use stubble management	55%	58%	53%	55%
I use fungicide mixture	45%	42%	52%	40%
Fungicide application pattern				
I use full label rates	96%	90%	97%	100%
I scout for disease before fungicide application	93%	87%	97%	95%
I alter spray plan depending on weather condition	91%	90%	93%	90%
I have an annual agronomic spray plan	90%	84%	92%	95%
I alter spray plan depending on disease pressure	91%	94%	92%	88%
I use fungicide mixtures	57%	55%	58%	58%
I stick to spray plan no matter what	21%	6%	23%	33%
Factors driving *FRM adoption				
Receipt of positive fungicide resistance results	99%	100%	97%	100%
Loss of disease control from current fungicide use	98%	97%	98%	100%
Reduced productivity relative to current state	93%	87%	95%	98%
Rise in cost of fungicide treatment	74%	77%	72%	73%

Table 7: Descriptive statistics showing respondents' fungicide application patterns grouped according to years of experience with Likert scale score of 5 and above (1 – Strongly disagree to 7 - Strongly agree). Note: *FRM, Fungicide resistance management.

	Experience level (years)			
Frequency of using *FRM practices	Average	0 - 15	16 - 30	Over 30
I rotate crops	87%	92%	87%	83%
I use resistant varieties	69%	55%	80%	73%
I rotate new chemistry	69%	61%	72%	73%
I change mode of action	67%	74%	67%	61%
I use stubble management	54%	55%	52%	56%
I use fungicide mixture	46%	47%	54%	37%
Fungicide application pattern				
I use full label rates	95%	89%	98%	98%
I scout for disease before fungicide application	93%	84%	96%	98%
I alter spray plan depending on weather condition	91%	89%	91%	93%
I have an annual agronomic spray plan	91%	89%	87%	98%
I alter spray plan depending on disease pressure	91%	92%	91%	90%
I use fungicide mixtures	57%	63%	56%	54%
I stick to spray plan no matter what	22%	11%	24%	32%
Factors driving *FRM adoption				
Receipt of positive fungicide resistance results	99%	100%	96%	100%
Loss of disease control from current fungicide use	99%	97%	98%	100%
Reduced productivity relative to current state	93%	92%	93%	95%
Rise in cost of fungicide treatment	72%	71%	74%	71%

4 Discussion and conclusion

This research sought to (i) evaluate the economic impact of fungicide resistance on growers' return on investment, (ii) establish growers' willingness to invest in preventing or delaying fungicide resistance problems, and (iii) understand grower's perception and behaviour towards fungicide resistance management.

Regarding the first objective, numerical simulations reveal that the rate at which fungicide efficacy declines negatively influences growers' return on investment. For instance, we see that as fungicide efficacy decline at a slower rate over time, symbolising a slower development of fungicide resistance, the return on investment value also deteriorates at a slower rate. Conversely, when fungicide efficacy exhibits a negative exponential distribution, the return on investment value declines faster. A study by Deloitte Access Economics (2018) noted that using fungicides contributes about 9% of the yield value in barley. Other studies have highlighted the importance of extending the effective life of fungicides with practices such as optimising the dose and timing of fungicide application, rotating with low-risk fungicides, using fungicide mixtures and changing the mode of action (see, e.g., van den Bosch et al., 2020; Poole and Arnaudin, 2014; van den Bosch et al., 2014; Khoury and Makkouk, 2010; Comins, 1977; Hall and Norgaard, 1973; Hillebrandt, 1960). However, these benefits would likely deteriorate in the presence of fungicide resistant strains (Grimmer et al., 2014). These findings suggest that there is value in integrating different fungicide resistance management practices to protect the current stock of fungicides from losing their efficacy and slowing the rate of the evolution of resistant pathogen populations.

The second objective sought to find the drivers of the return on investment and growers' willingness to invest in managing the fungicide resistance problem. Results from multiple factor analysis and multiple linear regression reveal the importance of diversifying the sources of fungicide resistance management information. This can promote behaviour change among different grower groups. Most growers in the study nominated their agronomists as the primary source of fungicide resistance management information. A study by Ingram (2008) assessed how growers and agronomists receive and deliver information and the dynamics involved in these encounters. They established that trust, credibility and empathy underpin positive agronomist-grower interactions.

We also found that younger growers or growers with less experience use diverse information sources to assist them in managing fungicide resistance. Conversely, experienced growers were more likely to rely on fewer sources of information for their fungicide resistance management. Additionally, in regards to the most preferred media, younger growers favoured social media and online media. In contrast, the older age group favoured more traditional sources of information, such as print media and field days. These results reveal the need to diversify fungicide resistance information sources to cater to diverse grower groups.

The third objective sought to understand growers' attitudes and behaviour towards fungicide resistance management. Using thematic and content analysis, we find that most growers consider the economic impact of fungicide resistance as the main driver of change when faced with fungicide resistance risk. This aligns with the existing literature that has established that fungicide resistance risk impacts growers' ability to control disease outbreaks (see, e.g., Rehfus et al., 2016; Tucker et al., 2015; Ilbery et al., 2012). Furthermore, unsurprisingly, we find that information regarding the impact of fungicide resistance on yield and profitability was the main driver of FRM practice adoption. In fact, the adoption of FRM practice is mainly driven by the cost of implementing the practice. These findings demonstrate the importance of quantifying the financial impact of fungicide resistance risk and considering the cost of implementation in any future effort to influence growers' willingness to adopt FRM practices.

Growers' perception of fungicide resistance is also manifested through fungicide inefficacy and a loss of disease control with current practices. For instance, growers indicated that the adoption of fungicide resistance management practices is influenced by: (1) a receipt of a positive fungicide resistance diagnosis; (2) a loss of disease control with existing fungicide resistance management practices; (3) a reduction in current productivity; and (4) a rise in the cost of fungicide treatment. These findings point to the importance of having active and ongoing support in diagnosing fungicide resistance on-farm, education around FRM practices, and accurate quantification of the financial impact of fungicide resistance issues and FRM practices.

Surprisingly, our findings reveal that fungicide resistance concerns carry significant psychological and emotional impacts. Many growers identified fungicide resistance issues as stressful, frustrating, and worrying. To our knowledge, this is the first study to investigate the impact of fungicide resistance issues on growers' psychological well-being. These findings demonstrate the need to consider fungicide resistance beyond the economic impacts and examine its social and psychological costs to growers. This also prompts further research in examining and devising effective management practices to safeguard growers' psychological and social well-being in the face of growing fungicide resistance issues. We anticipate that by understanding the socio-economic cost of the fungicide resistance problem, the agricultural industry can provide targeted intervention strategies to growers leading to a profitable and sustainable industry.

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