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# Climate change impacts on investment in crop sowing machinery\*

Ross Kingwell and Imma Farré<sup>†</sup>

A model of investment in crop sowing machinery is applied to wheat production under current and projected climatic conditions at several locations in south-western Australia. The model includes yield responses to time of sowing at each location given current and projected climatic conditions. These yield relationships are based on wheat growth simulation modelling that in turn draws on data from a down-scaled global circulation model. Wheat price distributions and cost of production data at each location, in combination with the time of sowing yield relationships are used to determine a farmer's optimal investment in crop sowing work rate under each climate regime. The key finding is that the impacts of climate change on profit distributions are often marked, yet mostly modest changes in investment in work rate form part of the profit-maximising response to climate change. The investment response at high versus low rainfall locations mostly involves increases and decreases in work rates, respectively. However, changes to investment in work rate within a broadly similar rainfall region are not always uniform. The impacts of climate change on investments in work rate at a particular location are shown to require knowledge of several factors, especially how climate change alters the pattern of yield response to the time of sowing at that location.

**Key words:** climate change, farm machinery, farm management, machinery investment.

## 1. Introduction

There is a burgeoning literature on climate change and its possible impacts on Australian agriculture (Pittock 2003; Kingwell 2006; Heyhoe *et al.* 2007). Some studies (e.g. Howden and Jones 2001, Pittock 2003; 2004; Kocic *et al.* 2005; van Gool and Vernon 2005) focus on wheat production, a principal component of broadacre farming in Australia, and these studies often point to spatially diverse projected impacts of climate change on wheat yields. Howden and Jones (2004), for example, suggest that the projected climate regime towards 2070 poses a significant downside risk for the Australian wheat industry with marked spatial variation across regions. They suggest wheat production in south-western Australia will be affected deleteriously while southern Queensland and higher rainfall regions of New South Wales could benefit.

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To date the literature on climate change impacts on wheat production in Australia has included some adaptation responses such as varietal change (e.g. Heyhoe *et al.* 2007). However, an adaptation issue yet to be investigated is: what is the likely impact of climate change on wheat farmers' investment in crop machinery? This issue has been over-looked; so this article focuses on farmers' investment in crop sowing machinery in response to projected climate change.

The article is structured as follows. The next section examines briefly the nature and role of crop sowing machinery for wheat production in Australia. Then a conceptual model of investment in crop sowing machinery is introduced. The model draws on relationships derived from climate and wheat production simulation models, wheat price distributions and other cost parameters derived from farm survey data. This model is applied to some wheat growing locations in south-western Australia to illustrate how climate change may affect investments in crop sowing machinery. After presenting and discussing the output from the investment model a final section gives a set of conclusions.

## 2. Farm machinery for wheat production in Australia

Broadscale mechanised operations underpin wheat production in Australia, with wheat being by far the main crop sown on Australian broadacre farms. Each year, on average, around 13 million hectares are sown to wheat and average wheat production is around 23 million tonnes (ABARE 2007). Most wheat grown in Australia is a winter temperate crop (Foster 2000). Sowing usually occurs anywhere from late April to late June, depending on seasonal conditions. Typically crops are sown after opening rains, using reduced tillage methods and herbicide technology. Large tractors pulling wide cultivator bars, airseeders and spray rigs are commonplace. Often the sowing of all crops is completed within a three-week period and typically involves a single pass operation.

The need for speedy crop establishment arises from the desire to provide plants with favourable growing conditions for as long as possible. Also the sheer size of some farmer's cropping programs dictates their need to sow quickly in order to then switch to other tasks such as post-emergent spraying of weeds. In the temperate regions, crops sown late tend to have worsening light and temperature conditions that limit their early vigour and reduce their potential yield (Anderson and Garlinge 2000). By illustration, Shackley (2000) reported time of sowing trials for wheat grown at several sites in Western Australia over a 10-year period and found that the average yield penalty for delays to sowing ranged from 17 to 35 kg/ha/day across the sites. In some years at some sites the yield penalty was as high as 50 kg/ha/day which, at a farm-gate wheat price of \$300 per tonne, translates to foregone revenue of \$15/ha/day. With farmers' large investments in crop sowing machinery being commonplace in broadacre cropping in Australia, the question arises as to

how might climate change affect yield and time of sowing relationships and thereby affect farmers' investments in crop sowing machinery?

### 3. An investment model for crop sowing machinery

Kingwell (1996) provides a conceptual model for investment in crop sowing machinery. We revise and extend this model to consider the likely consequences of climate change, to allow for yield and price variation and to include variation in the size of a farmer's cropping program. In Kingwell's original model the size of a farmer's cropping program was fixed and wheat yield was assumed to be a non-stochastic linear function of the day of sowing. We alter and relax these assumptions. The linear yield response:

$$Y_x = Y_s - bx \quad (1)$$

where

$Y_x$  is the yield (t/ha) of wheat sown on day  $x$

$Y_s$  is the yield (t/ha) of wheat at commencement of sowing (day = 0) and

$b$  is the rate of yield decline per day's delay in sowing (t/ha/day)

is replaced by the more commonly observed quadratic form where, in tonne  $t$ :

$$Y_{xt} = Y_{st} + b_t x - c_t x^2 \quad (2)$$

noting that  $Y_{st}$ ,  $b_t$  and  $c_t \geq 0$ .

The fixed size of the sowing program is replaced by a state-contingent specification. In years that in prospect are favourable (unfavourable), due to already observed weather and price conditions before the commencement of sowing, the size of the cropping program increases (decreases). These tactical changes in the size of a cropping program are known to be an important feature of profitable farm management in various regions of Australia (Kingwell *et al.* 1993; Kingwell 1994).

$S_t$  is the size of the intended cropping program (in hectares) in tonne  $t$  such that:

$$S_t = \alpha + \beta p_t Y_{st} \quad \text{with} \quad S_{\min} \leq S_t \leq S_{\max} \quad (3)$$

$S_{\min}$  and  $S_{\max}$  are the minimum and maximum sizes of the cropping program, respectively, as determined by issues such as rotational considerations, land suitability for cropping and farm size. Also  $p_t$  is the anticipated farm-gate price of wheat (\$/t) in tonne  $t$  as may be provided through a forward contract.

The profit from crop production in tonne  $t$  is:

$$\pi_t = p_t q_t - h_t S_t - m - g \quad (4)$$

where

$\pi_t$  is the profit (\$) from sowing  $S_t$  hectares of wheat in tonne  $t$   $p_t$  is the farm-gate price of wheat (\$/t) (a forward price contract in tonne  $t$ )

$q_t$  is the quantity (tonnes) of wheat harvested in tonne  $t$ ,  $h_t$  is the variable production costs (\$/ha) associated with wheat growing in tonne  $t$ ,  $m$  is the fixed or overhead cost (\$) incurred when growing  $S_t$  hectares of wheat (apart from seeding machinery investment)

$g$  is the cost of investment in seeding machinery (\$)

In Equation (4) the size of the cropping program ( $S_t$ ) and the variable costs of production ( $h_t$ ) are assumed to depend on the anticipated revenue at the start of sowing. Also  $q_t$  is a function of the yield parameters in Equation (2) and the work rate ( $R$ ) of the farm machinery for crop sowing (ha/day).  $g$  is assumed to be a linear function of  $R$ ; that is,  $g = d + eR$ , making the marginal cost of work rate constant. In other words the cost of acquiring a further unit of sowing capacity (1 ha/day) is identical across the range of sowing gear likely to be considered by the farmer.

In Equation (4)  $q_t$  can be re-expressed as:

$$q_t = \int_0^{S_{\min}/R} R(Y_{st} + b_t x - c_t x^2) dx \text{ for years where } S_t = S_{\min};$$

$$\int_0^{(\alpha + \beta p_t S_t)/R} R(Y_{st} + b_t x - c_t x^2) dx \text{ for years where } S_t = \alpha + \beta p_t Y_{st} \text{ and}$$

$$\int_0^{S_{\max}/R} R(Y_{st} + b_t x - c_t x^2) dx \text{ for years where } S_t = S_{\max}$$

The farmer's decision problem is to select an investment in sowing capacity (i.e. work rate  $R$ ) that maximises profit from wheat production across a range of production years; noting that the size of the cropping program  $S_t$  can vary from  $S_{\min}$  to  $S_{\max}$ , conditional on a production year's revenue prospects at the commencement of sowing and similarly, variable costs of production can range from  $h_{\min}$  to  $h_{\max}$ , depending on revenue prospects at the commencement of sowing. The probabilities of occurrence across  $T$  years of production years of the cropping programs of  $S_{\min}$  and  $S_{\max}$  hectares are  $u/T$  and  $w/T$ , respectively, each initially set at one-sixth. This assumption is later subject to sensitivity analysis. Hence one-third of years are classed as being in prospect high or low revenue years, with crop areas and variable costs of production accordingly being set at various limits, characteristic of the location, in response to these prospects.

The farmer's expected profit from wheat production across  $T$  years, where  $T = u + v + w$ , is:

$$\begin{aligned} \pi = & \frac{u}{T} \left( \int_1^u \left( p_t \int_0^{S_{\min}/R} R(Y_{st} + b_t x - c_t x^2) dx - d - eR - h_{\min} S_{\min} - m \right) dt \right) + \\ & \frac{w}{T} \left( \int_1^v \left( p_t \int_0^{S_{\max}/R} R(Y_{st} + b_t x - c_t x^2) dx - d - eR - h_{\max} S_{\max} - m \right) dt \right) + \\ & \frac{v}{T} \left( \int_1^v \left( p_t \int_0^{(\alpha + \beta p_t Y_{st})/R} R(Y_{st} + b_t x - c_t x^2) dx - d - eR \right. \right. \\ & \quad \left. \left. - (\alpha_h + \beta_h p_t Y_{st})(\alpha_s + \beta_s p_t Y_{st}) - m \right) dt \right). \end{aligned} \quad (5)$$

To find the level of  $R$  that maximises profit requires differentiation of Equation (5) with respect to work rate and solving for the  $R_{\text{opt}}$  that causes  $(\partial\pi/\partial R) = 0$ .  $R_{\text{opt}}$  in this study is found through a non-linear programming re-formulation of the decision problem. Denoting the right hand side of Equation (5) by the symbol  $\varphi$ , the non-linear programming formulation of the decision problem is to find the level of  $R$  that maximises the profit from wheat production, subject to various logical restrictions, as follows:

Max  $\varphi$

Such that

$T = n$  (i.e. a sample of  $n$  years under each climate scenario)

$T = u + v + w$

$Y_{st} + b_t x - c_t x^2 \geq 0$  (i.e. wheat yield cannot be negative)

$u \geq 0, v \geq 0, w \geq 0, R \geq 0, P_t \geq 0$

At each farm location  $R_{\text{opt}}$  is found for two different climate scenarios: current climate and the projected climate regime towards 2070. Note that the specification of the decision problem invokes several assumptions including:

1. the farmer is risk-neutral, seeking to maximise profit from wheat production over their  $T$  years of crop management.
2. wheat prices and wheat yields are independent. Note the Pearson rank correlation coefficient of Australian wheat prices and wheat production over the period 1985–2006 is only  $-0.033$ .
3. the portfolio of yield responses to time of sowing are known by the farmer. This assumes the farmer has access to relevant time of sowing trial data or validated simulation model output and that such information influences their machinery investment decisions. This is a bold assumption as many other influences are likely to figure in a farmer's machinery investment choice.

4. the price of wheat in each production year is known by the farmer at the start of crop sowing. Given the emergence of forward pricing options this assumption is reasonable.
5. all costs of wheat production are known with certainty. Most cropping input purchases (fertilisers, chemicals, fuel) are made prior to crop sowing so many farmers are aware of their likely costs of wheat production.
6. the date of the commencement of crop sowing in any particular production year is known by the farmer who then, in light of the known wheat price, makes state-contingent adjustments to the size of their wheat program in that year.

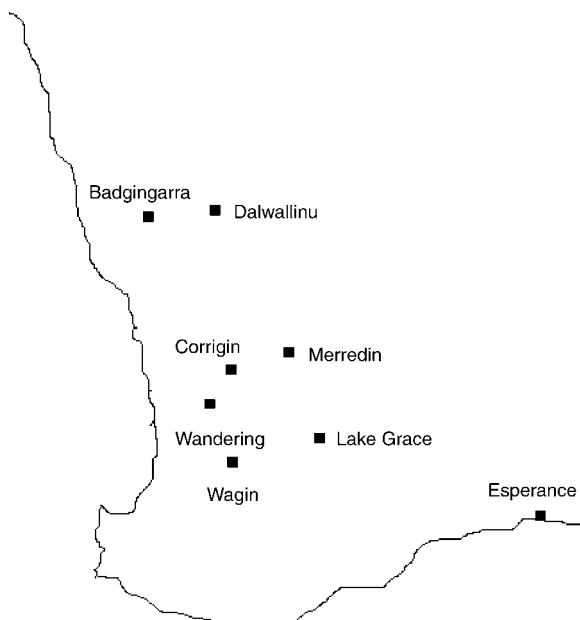
#### 4. Application of the investment model

This investment model is applied to a range of locations subject to climate change. The locations considered are in south-western Australia. This region is used for several reasons. First, it is a major source of Australia's cereal grain production, supplying almost 40 per cent of the nation's cereal production over the last decade. Second, it is a region where crop production is acknowledged as being particularly exposed to the impacts of projected climate change (ACG 2005; Hennessy and Jones 2007), although much uncertainty remains about the timing, size and variation of impacts of the climate change (Reyenga *et al.* 2001; Howden and Hayman 2005; Farré *et al.* 2007; Heyhoe *et al.* 2007). Finally, the region is well-served by validated crop simulation models of wheat production that draw on long time series of daily weather data available for many locations. The region also has down-scaled global circulation model datasets for key climate scenarios. These datasets are 30-year periods of climate data that represent first the period 1976–2005 with current concentrations of CO<sub>2</sub> (350 p.p.m.) and second, the period 2035 to 2064 with an expected higher CO<sub>2</sub> level (440 p.p.m.). Sites within the region selected for this study are shown in Figure 1.

##### 4.1 Parameter estimation for the investment model

Estimates of  $Y_{st}$ ,  $b_t$  and  $c_t$  at each location for each climate scenario were determined by crop simulation modelling and were included in the non-linear programming formulation previously described to determine the relevant  $R_{opt}$  for each location and climate scenario. The APSIM-Wheat model (Meinke *et al.* 1998; Keating *et al.* 2003; Asseng *et al.* 2004; Wang *et al.* 2006; Farré *et al.* 2007) was used. This model simulates a wheat crop's development, yield, water uptake and nitrogen accumulation in response to temperature, radiation, day length, soil water and nitrogen supply. The model is a daily time-step crop growth simulation model that calculates the climate-limited yield of each characterised site.

The APSIM-Wheat model in this study has been validated against experimental data from various sites in Western Australia and is the same as used



**Figure 1** Study sites in the grainbelt of the south-west of Australia.

**Table 1** Characteristics of selected sites in the wheatbelt of Western Australia

Site	Agricultural zone	Annual rainfall (current climate 1976–2005) (mm)	Annual rainfall (future climate 2035 to 2064) (mm)	Reduction in annual rainfall associated with climate change (%)
Badgingarra	North	576	524	9.0
Dalwallinu	North	386	355	8.0
Merredin	Central	353	329	6.8
Corrigin	Central	389	368	5.4
Wandering	Central	597	534	10.6
Lake Grace	South	367	336	8.4
Wagin	South	462	413	10.6
Esperance	South	664	622	6.3

Source: adapted from Farré *et al.* (2007).

by Farré *et al.* (2007). Daily weather data used by the APSIM-Wheat came from the Cubic Conformic model (CCAM), which is a higher-resolution nested model of the CSIRO GCM MK3. It provided downscaled samples of daily climate data for the current (1976–2005) and future (2035–2064) periods at each of the eight sites (Table 1). These sites represent the range of rainfall zones and agricultural sub-regions that form the wheatbelt of Western Australia.

At all sites the future climate scenario simulations point to a decline in average annual rainfall, with the percentage decline ranging from 5.4 to 10.6 per cent. Farré *et al.* examined the seasonal composition of these declines in rainfall and reported that the greatest rainfall reductions (up to 30 per cent)



were simulated to occur in the period April to June which is the period during which crops are sown.

In dryland wheat production, rainfall is a key determinant of grain yield. Hence, it may be anticipated that a decline in annual, and more particularly growing season rainfall, caused by climate change would lessen grain yield. However, other features of the future climate scenario, such as higher concentrations of CO<sub>2</sub> and changes in temperatures, also affect plant growth and grain yield. How these factors interact to alter grain yield is captured by the APSIM-Wheat model.

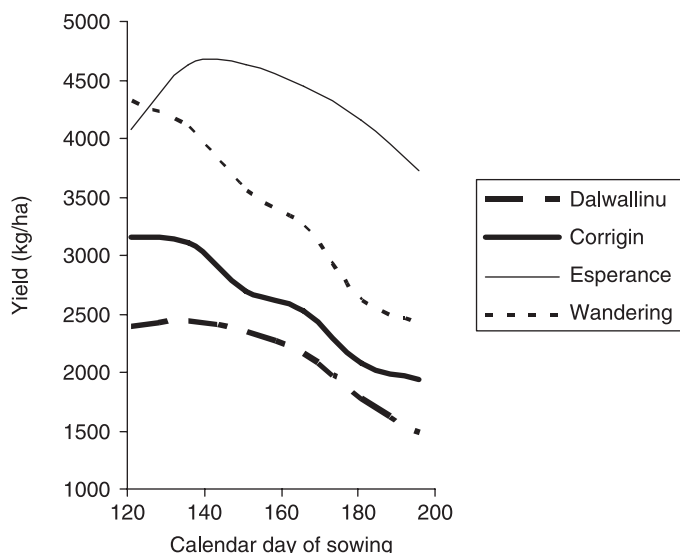
To use APSIM-Wheat to identify yield impacts of climate change required invoking a range of assumptions regarding soil characteristics, starting conditions, varietal characteristics and crop sowing rules. The data used in this study relied on the following assumptions. First, only clay soils at each site are considered and the soil at each site is assumed to be dry at 1 January of each year. The first available day for sowing in any year is determined by the following sowing rule:

Between 25 April and 19 June, sow if rain over 3 consecutive days is greater or equal to  $(25 \text{ mm} - 0.36 \text{ mm} * (\text{day} - 115))$  where day is the numeric calendar day (e.g. January 1 = 1). Effectively this rule is a linearly decreasing rain requirement as the growing season progresses. After 19 June, the sowing rule becomes; sow if there is at least 5 mm of rain over 3 consecutive days.

The variety sown is a function of the date of sowing whereby a long season cultivar is assumed to be planted if sowing occurs before 20 May, whilst a medium season cultivar is sown between 21 May and 9 June, and a short season cultivar is sown after that date. Hence, in using this varietal sowing rule a degree of adaptation to climate change is assumed insofar as farmers are assumed to alter the portfolio mix of varieties sown in accordance with changes to the dates of sowing.

Using these assumptions the APSIM-Wheat model was used to generate yield estimates for a range of sowing days at each site for each climate scenario. A quadratic form was fitted to this data on yield versus time of sowing at each location. Examples of the simulation data for one year at four locations, assuming current climate are shown in Figure 2. Estimates of  $Y_{st}$ ,  $b_t$  and  $c_t$  were generated at each location for each year  $t$  in the period of current climate 1976–2005 and for the projected climate, 2035–2064. In virtually all years and at all sites the adjusted  $R^2$  values were  $>0.95$  for the fitted quadratic form. The estimates of  $Y_{st}$ ,  $b_t$  and  $c_t$  were included in the non-linear programming decision model to determine the relevant  $R_{\text{opt}}$  for each location and climate scenario.

The output from APSIM-Wheat showed that at almost all sites, projected climate change causes crops to be sown a few days later (Table 2) with the delay to the start of sowing being up to almost a week at Badgingarra,



**Figure 2** Examples of the APSIM output of wheat yield versus time of sowing for one year at four locations.

**Table 2** Average potential yields on the first day of sowing on clay soil at each site (kg/ha)

Site	Average potential yield (current climate 1976–2005) (kg/ha)	Average potential yield (future climate 2035 to 2064) (kg/ha)	Change in average potential yield (%)
Badgingarra	3527	3615	-2.4
Dalwallinu	1806	1627	-10.0
Merredin	1308	1160	-11.3
Corrigin	1775	1698	-4.3
Wandering	3143	3314	+5.4
Lake Grace	1569	1388	-11.5
Wagin	2584	2294	-11.2
Esperance	4061	4100	-0.9

Merredin and Wagin. Second, at all sites except Wandering the average potential yield, based on the first day of sowing, declines in the face of climate change. Wandering is a high rainfall site on the western edge of the wheatbelt and the reduction in waterlogging, combined with higher CO<sub>2</sub> concentrations and warmer winter temperatures, that form part of the suggested climate change, allow grain yield to be higher on average. The output from APSIM-Wheat in Tables 2 and 3 shows that it is the change in climate, rather than just the delay in sowing, that is the principal cause of the yield reductions at most sites. The projected reductions in initial yield at a majority of sites range from 200 to 600 kg/ha. The APSIM output for the current climate scenario is also consistent with field experiments at a range of locations within the wheatbelt of Western Australia (Garlinge 2005).

**Table 3** Key characteristics of crop sowing at each site under current and future climate

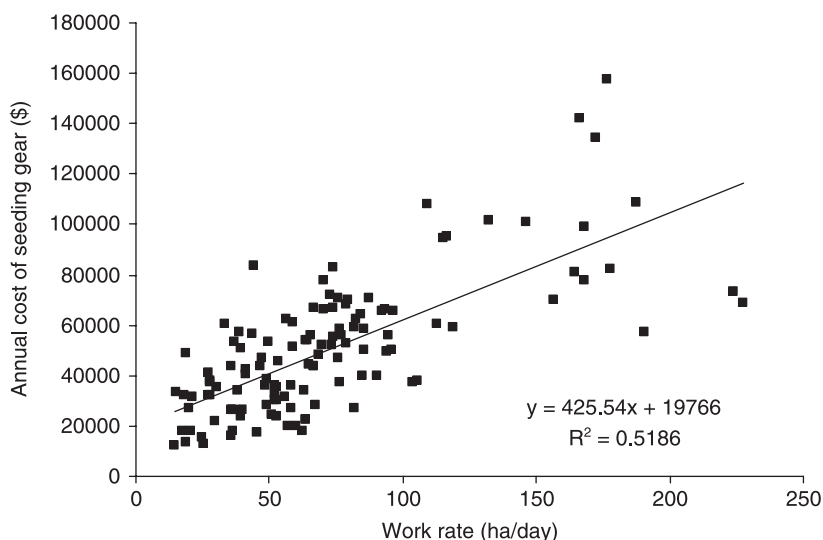
Site	Calendar day of start of sowing	Coefficient of variation of the start of sowing (%)	Calendar day of start of sowing	Coefficient of variation of the start of sowing (%)	Delay to sowing† (days)
	current climate	1976 to 2005	future climate	2035 to 2064	
Badgingarra	139	10.0	146	10.1	6
Dalwallinu	152	10.0	155	10.8	3
Merredin	153	10.3	157	10.4	5
Corrigin	153	9.4	152	9.8	-1
Wandering	142	9.8	145	9.5	3
Lake Grace	153	10.5	155	9.8	2
Wagin	148	10.1	153	9.2	5
Esperance	140	10.2	142	9.9	2

Included in the decision model are prices of wheat. Values for  $p_t$  (wheat price in year  $t$ ) at each location were specified by fitting a probability density function to farm-gate wheat prices at each location. These prices were based on the location's dominant grade (e.g. Australian Standard White or Australian Premium White) and its pool prices over the period 1995/1996 to 2007/2008. The farm gate price at each location in each year of the period was calculated as the published (and forecast for 2007/2008) pool price less cooperative bulk handling (CBH) outturn costs plus port differentials minus Australian Wheat Board Ltd finance costs minus CBH receival and grain assessment costs less grain freight to port less grain cartage to the receival point (also known as silo or bin) less levies (e.g. skeleton weed levy, grain research levy).

The historical handling and silo to port freight costs were obtained for each location from CBH as reported in various issues of the Farm Budget Guide. The farm to silo grain freight was calculated assuming a 20-km journey. For most locations farm-gate prices were well-approximated by lognormal distributions, generated by the Excel-Add in, *BestFit* (Palisade Corporation 2002). For each year in the climate scenarios, at each location, 20 random price draws from the location's lognormal price distribution were used in calculating profit. Hence, for each climate scenario a sample of 600 possible year types ( $30 \times 20$ ) formed part of the decision model to determine  $R_{opt}$  for each location experiencing that climate scenario.

The cost of work rate, depicted as  $g$  in Equation (4) and  $d$  and  $e$  in Equation (5) (noting that  $g = d + eR$ ) was estimated from farm survey data displayed in Figure 3.

At each location the relationship  $S_t = \alpha_s + \beta_s p_t Y_{st}$  was also estimated by drawing on firstly, the APSIM yield simulation data generated for each location; second, the price draws from the lognormal distributions of the farm-gate wheat prices at each location and third, the current size of cropping programs at each location as reported by BankWest farm survey data (BankWest 2007). In calculating profits from crop production, the variable



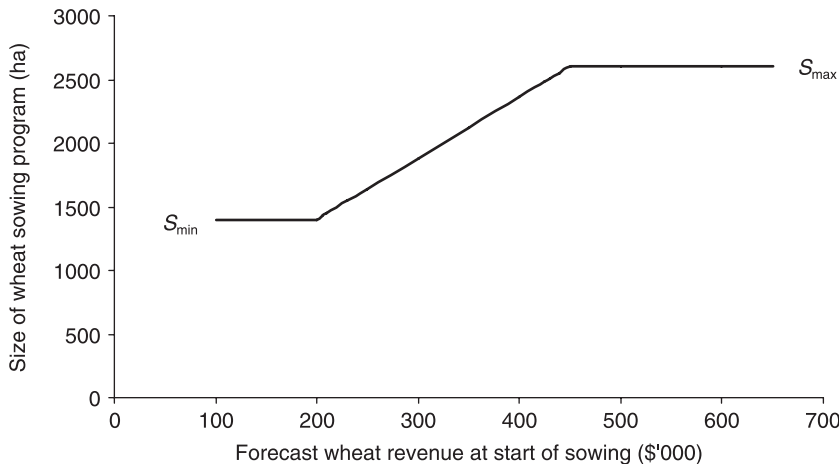
**Figure 3** The relationship between the annual cost of investment in seeding machinery and sowing machinery work rate. Based on 2005/2006 data for 122 broadacre farms in Western Australia.

costs of wheat production,  $h_{\min}$ ,  $h_{\max}$  and  $h_t = \alpha_h + \beta_h p_t Y_{st}$ , and other overhead costs (apart from fixed costs of machinery),  $m$ , were based on BankWest (2007) and DAFWA (2005) wheat gross margins for the locations, or nearest locations, in the grainbelt of Western Australia.

Of the 600 years types ( $30 \times 20$ ) that constituted the sample of years in each climate scenario at each location,  $u$  and  $w$  years were associated with sowing programs of size  $S_{\min}$  and  $S_{\max}$  hectares, respectively. At each location values for  $S_{\min}$  and  $S_{\max}$  were set based on BankWest data, historical data from farm management consultants and local farm adviser opinion. The probabilities of occurrence of the cropping programs of  $S_{\min}$  and  $S_{\max}$  hectares were each set at one-sixth, subject to subsequent sensitivity analysis. Hence one-third of years are classed as being in prospect high or low revenue years, with crop areas and variable costs of production accordingly being set at various limits, characteristic of the location, in response to these prospects. A diagrammatic representation of an example of the relationship  $S_t = \alpha_s + \beta_s p_t Y_{st}$  is shown in Figure 4. The variable cost of wheat production is a similar shaped function, based on variable costs of wheat production at each location as specified in DAFWA (2005) wheat gross margins and adviser opinion. The treatment of variable costs assumes that in years where wheat revenues at the start of crop sowing are anticipated to be high (low) then, within limits, variable costs are increased (decreased).

## 5. Results and discussion

The optimal investments in work rate,  $R_{\text{opt}}$ , for an average farm at each location were derived for current and projected climate regimes and results



**Figure 4** An example of the relationship between the size of the wheat sowing program ( $S_i$ ) and the anticipated wheat revenue at the start of crop sowing ( $p_y Y_{st}$ ).

are presented in Table 4. At five of the eight locations optimal work rates are reduced by climate change impacts, whilst at Esperance, Wandering and Badgingarra work rates increase. The latter locations are in high rainfall parts of the grainbelt and benefit from climate change or experience only small declines in yield potentials (see Table 2).

Lake Grace and Merredin record the largest declines in work rate, 7.6 and 7.4 per cent, respectively. At Lake Grace, Merredin and Dalwallinu farms are large and crop dominant, and these locations are all subject to very adverse impacts of climate change with the average commencement of crop sowing being delayed by several days and average yield potentials at the start of crop sowing being around 10 per cent less than average yield potentials at the start of crop sowing under the current climate regime. These low rainfall regions are the main sources of wheat production in Western Australia so the adverse impacts of climate change have potentially important ramifications for the State's and nation's wheat production.

Directly linked to the very adverse impacts of climate change at these locations are their large reductions in cumulative profit from wheat production. At Merredin, Lake Grace and Dalwallinu where large crop sowing machinery supports wheat production, the cumulative profit from wheat production is reduced in the presence of climate change by 35, 24 and 18 per cent, respectively. The projected climate change causes a leftwards shift in the yield and profit distributions at these locations.

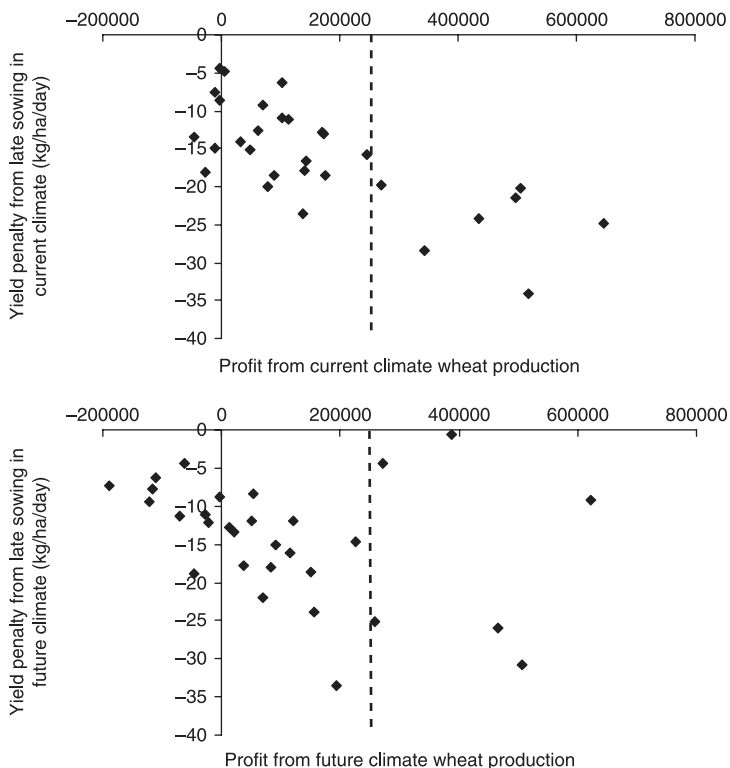
Given the assumption that the area sown to wheat is a state-contingent function of anticipated revenue at the commencement of sowing, then one of the impacts of climate change is a reduction in wheat plantings at these locations. Accordingly, as shown in Table 5, at Merredin, Lake Grace and Dalwallinu the average area sown to wheat is likely to decrease by around 3 per cent, *ceteris paribus*.

**Table 4** Optimal investment in crop sowing machinery work rate on an average farm at various sites for current and projected climate regimes; and estimates of cumulative profit from wheat production at each location for each climate regime

Optimal investment crop sowing machinery (in terms of work rate (ha/day))	Dalwallinu	Badgingarra	Merredin	Corrigin	Lake Grace	Wagin	Wandering	Esperance
Current climate 1976–2005	152	56	115	85	123	75	81	65
Future climate 2035–2064	151	58	106	83	113	71	86	71
Percentage change in work rate	–0.8	+2.3	–7.4	–2.2	–7.6	–5.3	+5.8	+9.0
Cumulative profit from wheat production (\$mill)								
Current climate 1976–2005	414.1	371.2	120.7	131.9	217.9	247.6	350.5	708.1
Future climate 2035–2064	341.3	356.9	78.7	117.8	165.0	193.4	386.6	714.2
Percentage change in cumulative profit	–17.6	–3.8	–34.8	–10.7	–24.3	–19.9	+19.3	+0.8

**Table 5** Average areas sown to wheat and the coefficient of variation of the area sown to wheat on an average farm at each location under current and projected climate regimes

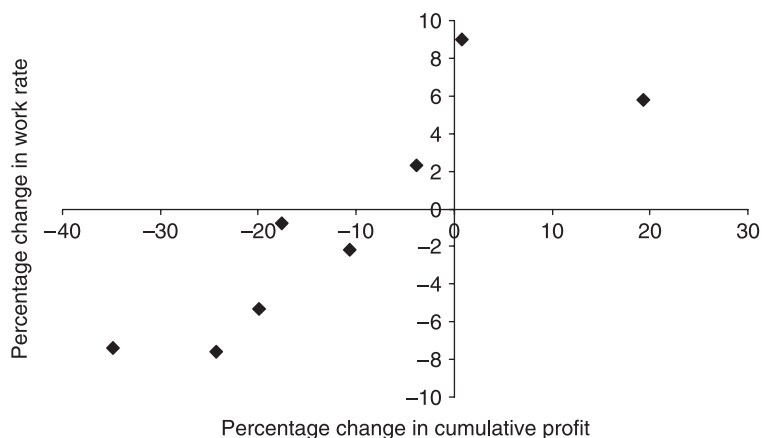
	Unit	Dalwallinu	Badgingarra	Merredin	Corrigin	Lake Grace	Wagin	Wandering	Esperance
Average area sown in current climate 1976–2005 regime	ha	3098	1088	2625	1668	2588	1344	1348	1674
Coefficient of variation in the area sown to wheat in current climate 1976–2005 regime	%	13.0	13.4	11.6	11.4	13.0	13.0	12.9	13.2
Average area sown in future climate 2035–2064 regime	ha	3004	1079	2552	1657	2508	1289	1378	1681
Coefficient of variation in the area sown to wheat in future climate 2035–2064 regime	%	13.6	13.5	11.9	11.6	13.4	13.2	12.4	13.1
Percentage change in area sown	%	–3.0	–0.8	–2.8	–0.7	–3.1	–4.1	+2.2	+0.4



**Figure 5** Yield penalty from late sowing versus profits from wheat production in the current and future climate scenarios at Merredin. The dashed vertical line indicates where annual profit is \$250 000.

This reduction in the average area sown to wheat in the presence of climate change is part of the reason for the decline in work rate. The other reasons for the decline in work rate are the differences in yield responses to time of sowing with current versus future climate conditions and the lesser capital costs associated with owning crop sowing machinery of smaller size. As an illustration, consider the case of Merredin under current and future climate (Figure 5). There are greater yield penalties for late sowing in high return years under the current climate regime compared to the future climate scenario. Hence, there is greater incentive to invest in work rate under the current climate to lessen foregone profit in the 'high' return years. In Figure 5 a dashed vertical line shows where annual profits are \$250 000. For years in which profits exceed \$250 000, the average yield penalty from late sowing is 23.6 and 15.9 kg/ha/day in the current and climate scenarios, respectively.

The general pattern of results is that at locations that are projected to be particularly adversely affected by climate change, a reduction in the work rate of sowing machinery is an element of the profit-maximising strategy. Conversely, at the few locations projected to benefit from climate change then the work rate of sowing machinery increases (see Figure 6).



**Figure 6** A plot of the eight locations' percentage changes in work rate versus percentage changes in cumulative profit associated with climate change. The correlation coefficient,  $r_{x,y} = 0.87$  is significant at the 1 per cent level of significance.

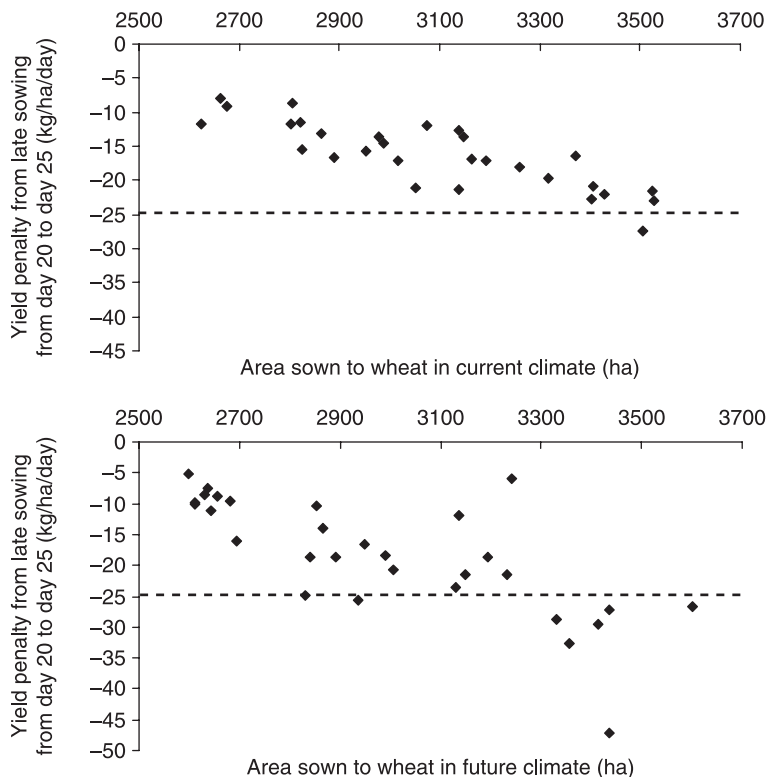
However, there are exceptions. At Dalwallinu there is a projected decline in cumulative profit from wheat production of almost 18 per cent yet there is only a very small reduction in work rate. The explanation for the results at Dalwallinu are that although climate change is associated with a 3 per cent reduction in the size of cropping program, thereby suggesting a slight reduction in work rate, there is a much greater offsetting yield penalty for late sowing after 20 days. In years with large programs when forecast profits are often relatively high, then the costs of late sowing are particularly high, and so investment in higher work rates is warranted. Also at Badgingarra where cumulative profit from wheat production is projected to decline by about 4 per cent, a small increase in work rate is recorded.

The situation regarding yield penalties for late sowing at Dalwallinu is shown in Figure 7. At Dalwallinu the rates of yield decline associated with larger sowing programs are much greater under the future climate scenario. This necessitates maintenance of the investment in sowing capacity as years in which cropping programs are large tend to be years of 'higher' returns and consequently the costs of late sowing are sufficiently large to justify investment in sowing machinery with large work rates. These findings are consistent with those of Kingwell (1996) who showed how yield penalties affect the use of and investment in crop sowing gear at a farm level.

Altering the probabilities of occurrence of the cropping programs of size  $S_{\min}$  and  $S_{\max}$  (see Equation 4) at each location has only a slight impact on the level of  $R_{\text{opt}}$  at each location for current and projected climate regimes. The probabilities were changed from one-sixth to a quarter then one-tenth with little impact on  $R_{\text{opt}}$  at each location. The tendency was for  $R_{\text{opt}}$  to increase (decrease) slightly as the probabilities of occurrence increased (decreased).

There are several caveats to this analysis. First, it is a partial analysis, considering wheat only grown on clay soils with limited adaptation responses





**Figure 7** Yield penalty from late sowing versus area sown to wheat at Dalwallinu in the current and future climate scenarios. The dashed horizontal line identifies where yield penalties are 25 kg/ha/day.

to climate change such as varietal portfolios and alteration of the size of the cropping program. In practice, the rate and degree of yield decline will be altered by technical and managerial innovation. Higher yielding short season or drought tolerant varieties may ameliorate some of the potential loss of yield. Better systems of weed management (Loi *et al.* 2006, 2007; Newman 2008) may allow later sown crops to suffer less from weed competition or enable crops to be sown earlier. Management innovations such as grain soaking (Blackwell *et al.* 2007) will allow a more rapid emergence of crops, compensating for delays to sowing. Technical innovations in various aspects of crop preparation and sowing (e.g. deep tillage, variable rate and spray technology, GM technologies) are likely to generate yield and profit improvements thereby affecting the returns from investment in crop sowing machinery.

Second, by concentrating on the likely yield implications of climate change at the various locations the analysis overlooks other important economic impacts and policy responses to climate change that will affect the relative profitability of wheat production. For example, biofuel subsidy policies, petroleum and natural gas pricing, carbon taxation, regional impacts of climate change and climate-related adaptation in other grain-producing

regions or competing and complementary enterprises in concert will affect the prices of key inputs to wheat production such as fertilisers and fuel and will also affect wheat prices. It is the combination of all such factors that ultimately will govern the costliness of delays to crop sowing. However, to canvass all these possibilities is understandably beyond the scope of this paper.

Third, the study does not consider the backdrop of the trend of increasing farm size that is usually associated with further investments in large machinery and associated labour-saving technologies. In this study the upper and lower limits on the sizes of cropping programmes at each location are fixed under each climate scenario. Yet economies of size benefits may complement or offset partially or wholly the adverse impacts of climate change and thereby affect a farmer's investment in work rate.

Fourth, the climate change scenario considered in this article is conservative with an underlying CO<sub>2</sub> level of 440 p.p.m. whereas recent trends in CO<sub>2</sub> concentrations (IPCC 2007) suggest even higher concentrations are very likely in the period 2035 to 2064. Much higher CO<sub>2</sub> concentrations and commensurate higher mean temperatures could worsen the impacts on the rainfed production of wheat in south-western Australia. Finally, this study is based on profit-maximising behaviour by a farmer and so risk aversion is over-looked. Australian farmers are mostly acknowledged to be slightly risk averse (Bond and Wonder 1980; Bar-Shira 1991; Abadi 2000) and thus their attitude to risk will affect their investment decisions regarding work rate. Results in Tables 3 and 5 regarding coefficients of variation in key aspects of cropping programs point to these programs at many locations being subject to slightly more variability in the face of the projected climate change.

Notwithstanding these important caveats, this study does suggest that in a major wheat growing region of Australia, climatic challenges to traditional wheat production are likely to emerge in coming decades. Wheat production, especially in currently low rainfall parts of this grainbelt will face environmental conditions less conducive to wheat production. Hence, maintaining the profitability of wheat production in this region through innovation and productivity gain will be a major technical challenge. If there is no off-setting movement in wheat prices or marked technological advances then a leftwards shift in the distribution of profits from wheat production is very likely at many locations in the low rainfall marginal parts of this grainbelt.

## 6. Conclusions

This study examines projected climate change at several locations in the grainbelt of south-western Australia. Of particular interest in this study is how might farmers respond to the projected climate change at these locations, in terms of their investment in work rates for crop sowing? Farmers' investment in crop sowing machinery is a major component of their business expenses for grain production so it is important to understand how climate change may affect these costs.

Climate change at almost all study locations is likely to be associated with slightly later sowing on average and yield responses across times of sowing are altered. Accordingly, the interesting empirical issue addressed in this study is whether or not farmers may increase or decrease their investment in work rate in the presence of climate change; and is there a consistent response across the grainbelt?

Although subject to some caveats, the findings in this study suggest that at most locations in the study region fairly modest changes in work rate, often less than 8 per cent, are likely to form part of the grain producer's profit-maximising response to climate change. The main finding is that there is a likely divergence in investment response between high versus low rainfall locations, with increases and decreases in work rates, respectively, being forecast. However, as illustrated for a few locations, the investment response within a region of broadly similar rainfall, is not uniform. Hence to forecast the possible impacts of climate change on investments in work rate at a particular location requires understanding how climate change affects the pattern of yield response to time of sowing at that location for its range of weather-year types.

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