Climate change and adaptation in Australian wheat dominant agriculture: a real options analysis

Greg Hertzler[1], Todd Sanderson[1], Tim Capon[2], Peter Hayman[3] and Ross Kingwell[4]

[1]The University of Sydney, [2]CSIRO, [3]SARDI, [4]DAFWA/University of Western Australia

Selected paper presented at the
57th AARES Annual Conference at The Sydney
Convention and Exhibition Centre in Darling Harbour,
Sydney, New South Wales, 5th-8th February, 2013
http://www.aares.org.au/AARES/Events/2013_Conference_Homepage/AARES/Meetings_and_Conferences/Annual_Conferences/2013_AC_Website/Home_Page.aspx?hkey=46c806bd-ca83-4e4f-a89d-7c355ffa6ae0

Australian crop and livestock farmers face uncertain climate change and variability and a challenge for adaptation decisions. These decisions can be (1) adjustments to practices and technologies, (2) changes to production systems, or (3) transformation of industries, for example, by relocation to new geographical areas. Adjustments to existing practices are easy to make, relative to changes to production systems or transformations at the industry level. Transformations require new investments and infrastructure and can leave assets stranded. These transformations can be partially or wholly irreversible and hysteresis effects can make switching difficult and mistakes costly to reverse. Real Options offers a framework to structure thinking and analysis of these difficult choices. This paper generalises and extends the principles of real options to capture the expected time until transformative thresholds are crossed. An application to South Australian wheat dominant agriculture is explored.

Keywords: Australian agriculture, climate change, real options.

1. Introduction

Agricultural production systems are heavily influenced by climate, where observed agricultural practices may be considered as adaptations to specific characteristics of the prevailing climate (Gornall *et al.* 2010). In Australia, these systems have evolved to suit a production environment which is more variable and operates in more marginal conditions than most of our international competitors. Among production systems, risks differ markedly, in line with the ability of those systems to buffer against weather variability. For instance, in some environments the flexibility implied in broadacre grazing results in less volatile revenue than cropping activities.

Over time and with a growing understanding of the nature of the climate regime in which they operate, Australian primary producers have responded by making decisions over production systems and associated investments. We can think about the prevailing climate regime as a stationary stochastic process (Antle 1996), in which those decisions have been informed by the history of experience with the climate. The belief that a prevailing climate regime is stationary allows decisions to be made within standard risk analysis frameworks, as the range of possible outcomes and their attendant probabilities are known, and become increasingly so with time.

However, climate change presents a challenge to the established pattern of risks and the nature of optimal decisions in those systems. Climate change, by nature, implies the stationarity of the climate process may no longer be assumed and risk analysis frameworks are no longer suitable. The main reason for this is the inconstancy of the underlying probabilities of the system, in other words, the range of outcomes and attendant probabilities are no longer constant.

In this environment, there exists a need for tools which are capable of taking into account the non-stationary nature of risks to support decision making, one such tool is mathematical real options. 'Real options' is the name of the modern analytical method for modelling the value of flexibility and the timing of action in decision-making under uncertainty (Dixit and Pindyck, 1994; Copeland and Antikarov, 2001). Simulation and scenarios testing approaches generally seek to simply understand the effects of risk – the real options approach specifically seeks to show how decision-makers can manage risk. It does this by examining the trade-offs between acting sooner versus retaining the option to act later, by taking into account the value of flexibility and the value of new information that can help to resolve uncertainty.

This paper applies recent developments in the mathematics of uncertainty so that the decisions of primary producers can be translated into mathematical models and then solved for the optimal choice of regimes under conditions of climate change. Section 2, introduces a generalised mathematical exposition of a real options model which overcomes several issues in the 'Dixit and Pindyck' real options approach (Dixit and Pyndyck 1994). In section 3, an application is outlined for the adaptation and transformation of Australian wheat dominant agricultural systems subject to climate change. Finally, section 4 reports the results and section 5 exmines the implications for wheat dominant agriculture in Australia.

2. Real options for adaptive decisions

Australian agriculture is dominated by rain-fed broadacre production systems. Broadacre systems are characterised by the employment of land which has relatively low agricultural productivity per unit due to prevailing climatic conditions. Although, the low inputs of labour and capital imply high total factor productivity per unit. In Australia, the relatively low average per hectare yields for broadacre crops imply that land is employed more intensively than in other countries that utilise broadacre systems. In addition to which the nature of inputs in rain-fed broadacre farming systems implies that yields, unlike intensive input farming systems, are closely tied to the vagaries of the prevailing climate. As a consequence, in Australia rain-fed broadacre agriculture is considered particularly vulnerable to potential climate change, given the pre-existing high degree of climate variability.

The framework developed below seeks to understand the timing of adaptation decisions, modelled as changes from one regime to another. It will be used to calculate the value of remaining in a current regime, whilst retaining the option to switch regime later if need be. When production conditions are uncertain and changing, there is a trade-off between responding immediately with less information versus retaining the option to respond later when new information might be available that reduces the uncertainty. This framework seeks to analyse this type of decision problem, by applying a real options analysis that separates complex decisions over time into changes between alternative regimes.

For example, as the climate changes, a wheat producer who initially only engages in cropping activities might want to change to a new production mix with say, grazing and opportunistic cropping. With extreme climate change, this same producer might even switch to a regime of extensive grazing and abandon cropping altogether. Within each of these broader regimes there is the possibility to adapt by making smaller changes to farming practices, such as tillage technology or adoption of new crop varieties. Transformational changes between broader regimes may be viewed as crossing a threshold from one regime to another – to cross a threshold the farming system is transformed and sometimes crossing back can be very costly. However, the timing of these switches depends on the risks and uncertainties associated with the alternative regimes. A producer might choose to switch immediately or never, depending on how the climate is expected to change and the variability associated with that change.

If rainfall decreases and temperature increases with a high degree of certainty growers will switch regime as soon as the current regime becomes less profitable than the next best regime in the sequence. In contrast, suppose there is a high degree of uncertainty associated with climate change. Under conditions of high uncertainty it becomes difficult to ascertain just how the climate is actually changing. Producers would therefore be wise to delay switching to avoid the high costs of switching unnecessarily and in order to learn more about the changes that actually occur. By delaying their decision to switch, producers retain the option to switch and also benefit by learning more about the true nature of climate change.

We start with a model of a *Regime* which begins at time 0 and ends at time *T*

$$(1) \qquad U\big(x(0)\big) = \int_0^T e^{-\int_0^\tau r d\vartheta} f\big(x(t)\big)dt + e^{-\int_0^T r d\vartheta} V\big(x(T)\big)$$

Subject to

$$(2) \qquad dx = g(x)dt + h(x)dz$$

For instance, *Regime 0* begins at time 0 and ends at time *T* when the system switches to *Regime 1*. Regime 0 may have continuous benefits and costs, which we will call profit. This is the function *f* which is integrated over time. By Bellman's Principle of Optimality, the only thing Regime 0 needs to know about Regime 1 is the terminal value *V*. Discounting and summing gives *U*, the stochastic net present value. All this is subject to a stochastic differential equation for the system dynamics, with *g* as the expected change and *h* as the standard deviation. Of course Regime 1 has a similar model, with its own continuous profits, stochastic differential equation and terminal value. Discounting and summing would give *V*, the stochastic net present value of Regime 1 which, in turn, becomes the terminal value of Regime 0.

Before the model can be solved, we must take expectations and derive an option pricing equation. To derive the option pricing equation, we start from arbitrary time *t*, not just time 0.

(3) $$U\big(t, x(t)\big) = \int_t^T e^{-\int_t^\tau r d\vartheta} f\big(x(\tau)\big) d\tau + e^{-\int_t^T r d\vartheta} V\big(x(T)\big)$$

Subject to

(4) $$dx = g(x)dt + h(x)dz$$

Next, we take expectations which are conditional upon the state of the system at time *t*

(5) $$W\big(t, x(t)\big) = E\big\{U\big(t, x(t)\big)\big\}$$

The expected net present value is the option price, W. It depends upon time *t* and state *x*. Taking the stochastic differential of both sides of this equation gives the option pricing equation. The left hand side is easy to differentiate using Itô's Lemma, but the right hand side is difficult to differentiate and requires the martingale representation theorem. Amazingly, the martingales on both sides cancel with the following well known result

(6) $$\frac{\partial W}{\partial t} - rW + f(x) + \frac{\partial W}{\partial x} g(x) + \frac{1}{2}\frac{d^2 W}{dx^2} h^2(x) = 0$$

(7) $$W\big(T, x(T)\big) = V\big(x(T)\big)$$

This is a partial differential equation called the Hamilton-Jacobi-Bellman equation. It could also be called a risk-adjusted dynamic profit function. As we know, time is money. The first term in the option pricing equation is the shadow price of time. It may be positive or negative. The second term is the opportunity cost of investing instead of leaving the money in the bank. The opportunity cost is always negative. The third term is the current profit. Usually it will be positive. The fourth term is the total user costs or benefits, in which the shadow price of the state multiplies the expected change in the state. The term can be a negative as a cost or positive as a benefit. The fifth term is the risk premium, in which the shadow price of risk multiplies the variance. The risk premium will usually be positive, but can be negative.

2.1 Stochastic benefits

Exit and entry decisions are determined by the streams of benefits and costs associated with each regime, as well as, any salvage value *S* and fixed costs *F*. These benefits could be thought of as revenues, and costs as the variable costs associated with an activity. These could be combined, as in gross margins or profits and we could think about streams of stochastic net benefits.

If the gross margin in a given regime were not stochastic, farmers would exit if revenue above variable costs plus the salvage value were negative. Farmers would enter if revenue above variable costs plus fixed costs were positive. However, gross margins are stochastic and farmers will not exit or enter immediately. There may be some good years and some bad years and farmers must learn over time whether the industry is going to yield positive gross margins in the long run. To find out how long they will wait, we must derive a stochastic gross margin function. This may be a function of climate and price risk. Climate risk may be summarised for the purposes of this exposition as the year to year variation in crop yields or livestock produced. The gross margin G is a function of the price P, yield ψ and variable cost C of the regime i

(8) $$G_i(P, \psi) = R_i(P, \psi) - C_i$$

Gross margins are stochastic because yields and prices are stochastic. For option pricing, we need the expected change in the gross margin and its variance. To derive these, we apply stochastic calculus to the gross margin function.

(9) $$dG = \frac{\partial G}{\partial P} dP + \frac{\partial Y}{\partial \psi} d\psi + \frac{1}{2}\frac{\partial^2 Y}{\partial P^2} dP^2 + \frac{1}{2}\frac{\partial^2 Y}{\partial \psi^2} d\psi^2 + \frac{\partial^2 Y}{\partial P \partial \psi} dP d\psi$$

Each of dP and $d\psi$ can be represented by an Itô stochastic differential equation

(10) $$dP = \mu_P(P)dt + \sigma_P(P)dz_P$$

(11) $$d\psi = \mu_\psi(\psi)dt + \sigma_\psi(\psi)dz_\psi$$

In this context the drift of the equation μ can be a take on any functional form appropriate to characterise the system dynamics, such as linear or quadratic. Likewise, the diffusion σ of the equation can take as simple or as complex functional forms as appropriate. For each, the functional form may be estimated from observed or simulated data for price and yields.

In addition to these we will also need the variances

(12) $$dP^2 = \{\sigma_P(P)\}^2 dt$$

(13) $$d\psi^2 = \{\sigma_\psi(\psi)\}^2 dt$$

There may also be some correlation between price and yield that will need to be taken into consideration

(14) $dPd\psi = \{\sigma_P(P)\}\{\sigma_\psi(\psi)\}\omega_{P\psi}dt$

Where $\omega_{P\psi}$ is a correlation coefficient.

Now we work backward to get the stochastic change in gross margins. We may substitute equations (10), (11), (12), (13) and (14) into equation (9)

(15) $$dG = \frac{\partial G}{\partial P}\{\mu_P(P)dt + \sigma_P(P)dz_P\} + \frac{\partial Y}{\partial \psi}\{\mu_\psi(\psi)dt + \sigma_\psi(\psi)dz_\psi\} + \frac{1}{2}\frac{\partial^2 Y}{\partial P^2}\{\{\sigma_P(P)\}^2 dt\} + \frac{1}{2}\frac{\partial^2 Y}{\partial \psi^2}\left\{\{\sigma_\psi(\psi)\}^2\right\} + \frac{\partial^2 Y}{\partial P \partial \psi}\left\{\{\sigma_P(P)\}\{\sigma_\psi(\psi)\}\omega_{P\psi}dt\right\}$$

This can be rewritten

(16) $$dG = \left[\frac{\partial G}{\partial P}\mu_P(P) + \frac{\partial Y}{\partial \psi}\mu_\psi(\psi) + \frac{1}{2}\frac{\partial^2 Y}{\partial P^2}\{\sigma_P(P)\}^2 + \frac{1}{2}\frac{\partial^2 Y}{\partial \psi^2}\{\sigma_\psi(\psi)\}^2 + \frac{\partial^2 Y}{\partial P \partial \psi}\{\sigma_P(P)\}\{\sigma_\psi(\psi)\}\omega_{P\psi}\right]dt + \sigma_P(P)dz_P + \sigma_\psi(\psi)dz_\psi$$

Finally, the change in the gross margin for a regime has a variance

(17) $dG^2 = 2\sigma_P(P)\sigma_\psi(\psi)\omega_{P\psi}dt$

2.2 Option pricing equations

We can now specify the option pricing equations, including terminal values, for regime exit and entry decisions. Let us define α and β, which arise from equations (16) and (17)

(18) $$\alpha = \frac{\partial G}{\partial P}\mu_P(P) + \frac{\partial Y}{\partial \psi}\mu_\psi(\psi) + \frac{1}{2}\frac{\partial^2 Y}{\partial P^2}\{\sigma_P(P)\}^2 + \frac{1}{2}\frac{\partial^2 Y}{\partial \psi^2}\{\sigma_\psi(\psi)\}^2 + \frac{\partial^2 Y}{\partial P \partial \psi}\{\sigma_P(P)\}\{\sigma_\psi(\psi)\}\omega_{P\psi}$$

(19) $\beta = 2\sigma_P(P)\sigma_\psi(\psi)\omega_{P\psi}$

Instead of using the long formulas from the stochastic gross margins derived above, we can write the option pricing equations more simply. For the exit decision, the option pricing equation is

(20) $$\frac{\partial W}{\partial t} - rW + \frac{\partial W}{\partial G}\alpha + \frac{1}{2}\frac{\partial^2 W}{\partial G^2}\beta = 0$$

(21) $W\{T, G(T)\} = max[S - G; 0]$

The terminal value equals either the losses foregone by exiting or zero, whichever is larger. The option price, W, is the amount farmers are willing to pay in loses to remain in business while they learn about whether wheat production is profitable in the long run. If they exit the industry prematurely, it will require a larger investment to enter again.

For the entry decision, the option pricing equation is

$$\frac{\partial W}{\partial t} - rW + \frac{\partial W}{\partial G}\alpha + \frac{1}{2}\frac{\partial^2 W}{\partial G^2}\beta = 0 \tag{22}$$

$$W\{T, G(T)\} = max[0; G - F] \tag{23}$$

The differential equation is the same as before, although, in this case the terminal value equals either zero or the profits from wheat production, whichever is larger. The option price is the amount farmers are willing to pay in foregone profits while they learn about whether wheat production will be profitable in the long run. If the enter prematurely, some of their investment will be lost if they exit again.

In practical applications, entry and exit decisions are rarely considered in insolation, and a farmer may be considering exiting one regime (denoted as 1) and entering another (denoted as 2). In this instance, the option pricing equations would be

$$\frac{\partial W_1}{\partial t} - rW_1 + \frac{\partial W_1}{\partial R_1}R_1\alpha_1 + \frac{1}{2}\frac{\partial^2 W_1}{\partial R_1^2}R_1^2\sigma_1^2 = 0 \tag{24}$$

$$\frac{\partial W_2}{\partial t} - rW_2 + \frac{\partial W_2}{\partial R_2}R_2\alpha_2 + \frac{1}{2}\frac{\partial^2 W_2}{\partial R_2^2}R_2^2\sigma_2^2 = 0 \tag{25}$$

$$W\{T, R(T)\}_2 = max[W\{T, R(T)\}_1; G - F] \tag{26}$$

Here, there are two differential equations representing the two production regimes, 1 and 2. Each regime has its own underlying continuous profits and stochastic differential equation. There is a salvage benefit from exiting the initial regime, which is summarised in the option value W_1 to exit from that regime, and a fixed investment cost associated with entry into another. This illustrates the notion that where sequential options exist, then the option value of a regime is functionally related to alternative regimes.

3. An application to wheat dominant agriculture in South Australia

South Australia presents a theoretically interesting case study to examine adaptation and transformation in wheat dominant agriculture in Australia. The primary reason for this is the South Australian grain belt defined by the Goyder's Line[1], has traditionally been viewed as a transect from relatively reliable high to medium rainfall cropping land near the coast to low rainfall with extensive grazing and desert as we move away from the coast to the north (Hayman *et al.* 2010, Nidumolu *et al.* 2012). This means that we can employ the temporal-spatial analogues approach (Hayman *et al.* 2010) to model transitions in farming regimes driven by climate changes. This approach recognises that current broadacre production zones transcend rainfall isohyets and the position of farms within the pattern of isohyets is a good predictor of the prevailing farming activity. For instance, the medium rainfall to low rainfall zone in SA covers a spectrum from intensive cropping with a high frequency of relatively high risk and high return crops to an increasing proportion of cereals with lower inputs and then grazing enterprises with opportunistic cropping (Hayman *et al.* 2010).

The partial map of SA reproduced in Figure 1 identifies the three sites on the study transect in relation to the red Goyder's line. These are Hawker, Orroroo and Clare. The map is the normalised difference vegetation index (NDVI) for September where the darker green is more vegetative growth. Most of the green to the north of Orroroo is native vegetation on the southern Flinders' ranges. The Hawker site has the lowest annual and growing season rainfall and these figures steadily increase as we move in a southerly direction towards Clare. The different marks on the map show where Goyder's Line would shift to with a 10%, 20%, 30% and 50% decline in rainfall. Table 1 provides a summary of the characteristics of the three study sites positioned along the transect.

The transect approach allows us to model the adaptation and transformation processes at a given site by examining the nature of current optimal decisions at another site. For instance, if we anticipate that climate change will lower GSR, then the experience at say Clare on our transect may be modelled by examining the current optimal decisions at Orroroo, where Orroroo currently enjoys rainfall which Clare is predicted to receive as the climate changes. Generally, it is predicted that with climate change, declining GSR will eliminate the option of cropping on

[1] Goyder's Line has traditionally been viewed as a demarcation for the suitability of land for cropping. The south of the line is reasonable cropping land, and to the north is generally grazing. However, some cropping does occur to the north of the line when seasons permit.

Figure 1. shows a Normalised Vegetation Index (NDVI) a transect of rainfall from Clare to Orroroo with an indication of points that are 10%, 20%, 30% and 50% wetter than Orroroo.

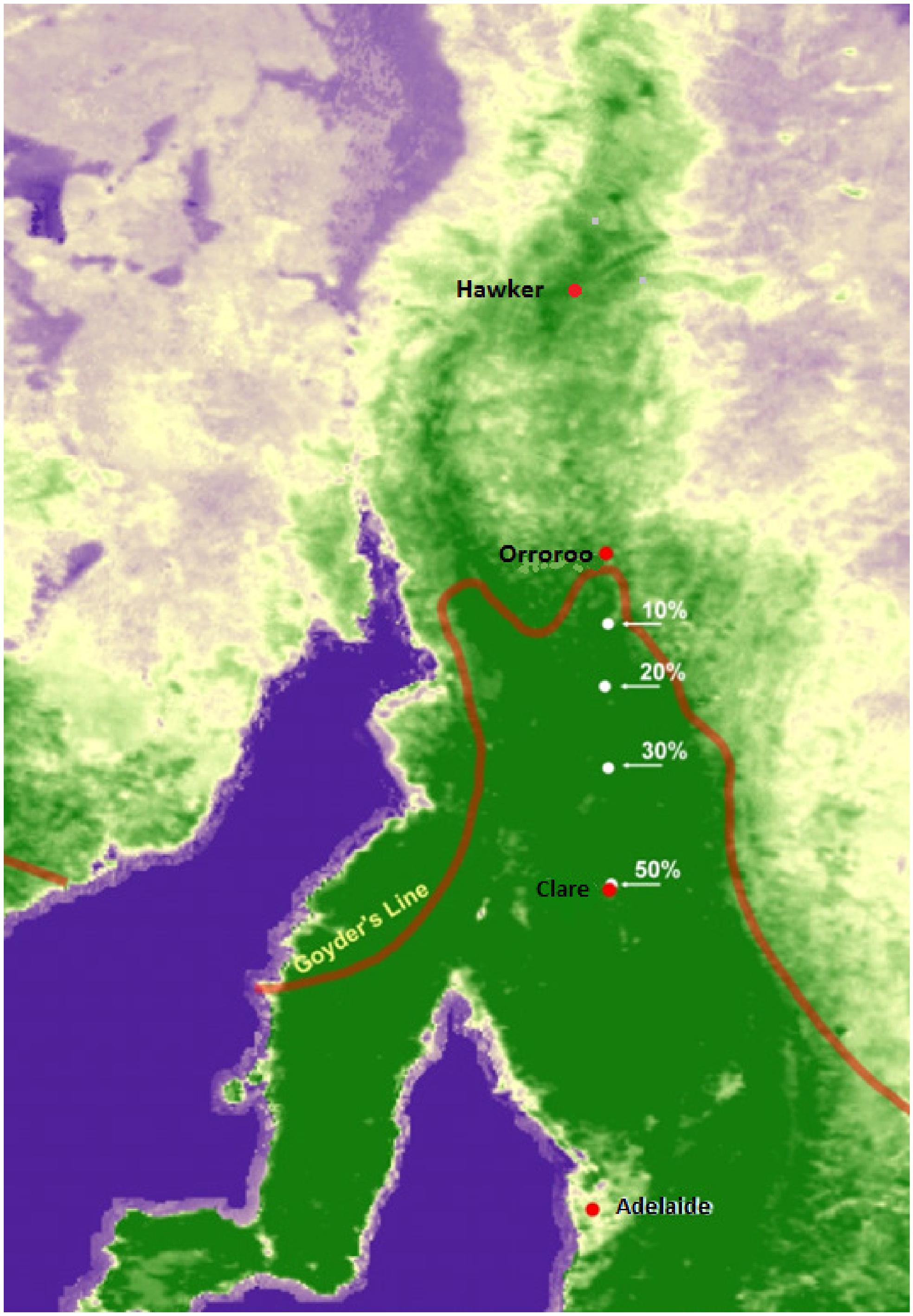


Table 1. Summary of key characteristics on the study transect[a].

Site	Clare	Orroroo	Hawker
Growing Season Rainfall mm (Apr-Oct)	485.91 (126.87)	224.86 (72.28)	200.97 (88.49)
Annual Rainfall mm	622.62 (141.80)	338.38 (100.48)	310.10 (118.40)
Average wheat yield[b] (T/Ha)	3.56 (0.69)	1.95 (1.22)	1.42 (1.09)

[a]Standard deviations reported in brackets.
[b]Wheat yield averages are derived from APSIM simulations.

already marginal lands in the north of the transect and push these activities south. The challenge is to identify when the future farming regime of a given site becomes sufficiently alike that of the current regime of another site to model the adaptation and transformational processes.

For the purposes of illustrating the applicability of ROADs, we will assume that farmers have two options to use their land – grow wheat or graze livestock. There are many variations within each of these options and to simplify we have assumed that wheat cropping is that for Australian prime white (APW) wheat and the grazing activity are merino wethers primarily for wool production. The gross margins for these activities are reported in the *Farm Gross Margin Guide 2012* (Rural Solutions South Australia, 2012). For this illustration, output prices will be kept constant, with wheat at $300/t and wool at …c/kg. Combining the gross margin information with the simulated data series for wheat and grazing, a gross margin data series may be generated for each of the activities in each of the study site locations.

3.1 Characteristics of wheat cropping along the study transect

Preliminary simulations for wheat cropping have been performed using the daily time step model APSIM (McCown *et al*. 1996) over the three sites along the transect for consistent soil[2]. Simulation modelling results for wheat yields are generated using daily data from 1900 to

[2] For consistency, soil is assumed to be calcareous sandy loam over clay, with a plant available water capacity (PAWC) of 70mm.

2007 across the three sites of the study transect. In this instance the yields are limited by nitrogen rates, that is, with unlimited nitrogen the yields at Clare would be higher. The graph presented in Figure 2 presents wheat yield results of APSIM simulation at Clare. Because APSIM holds constant all other inputs and technologies the pattern of variability is driven exclusively by the timing and magnitude of weather events. Figure 3 and 4 present the APSIM simulations for Orroroo and Hawker.

Figure 2. Simulated wheat yields at Clare (t/ha)

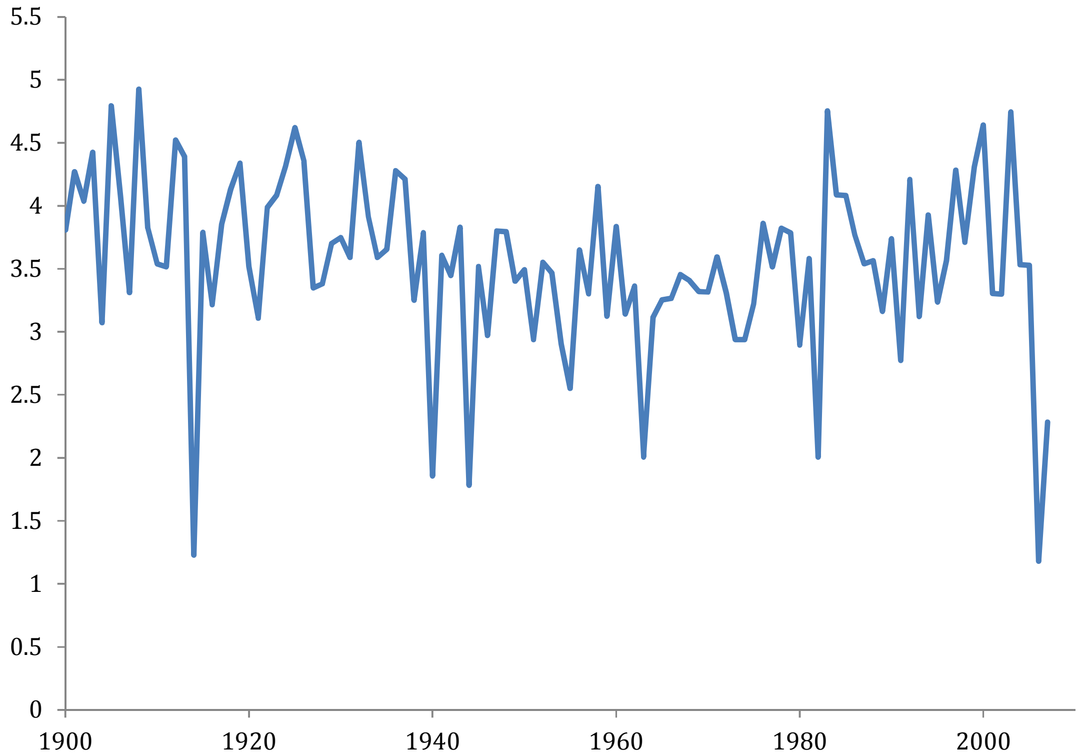


Figure 3. Simulated wheat yields at Orroroo (t/ha)

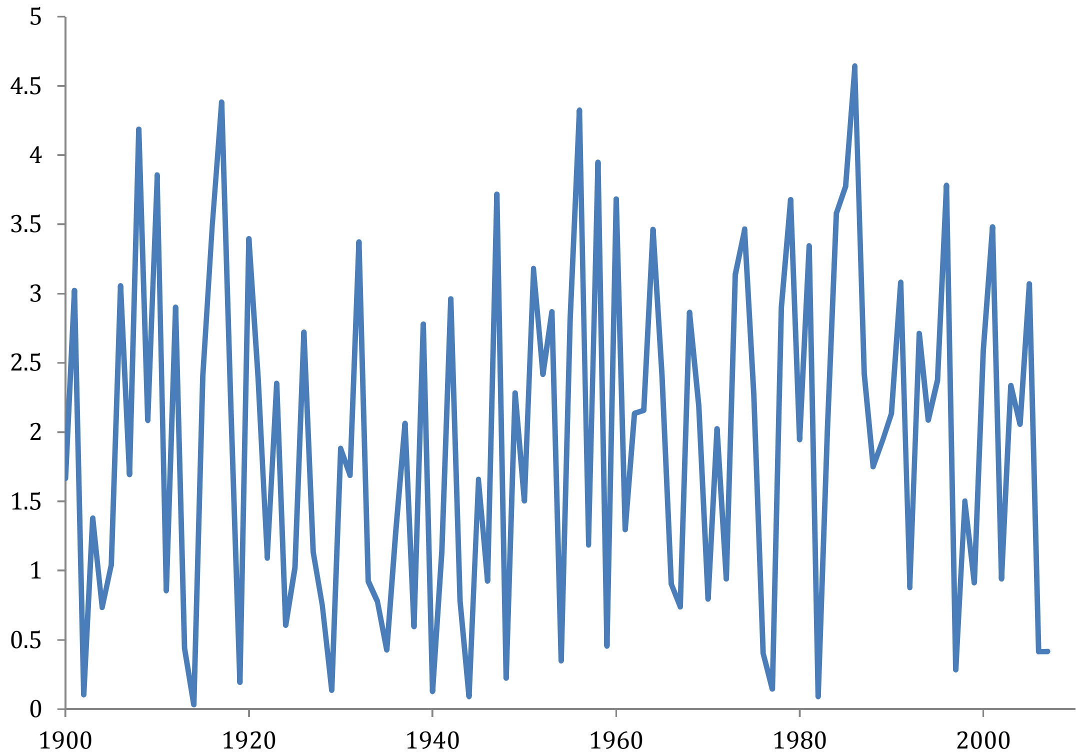
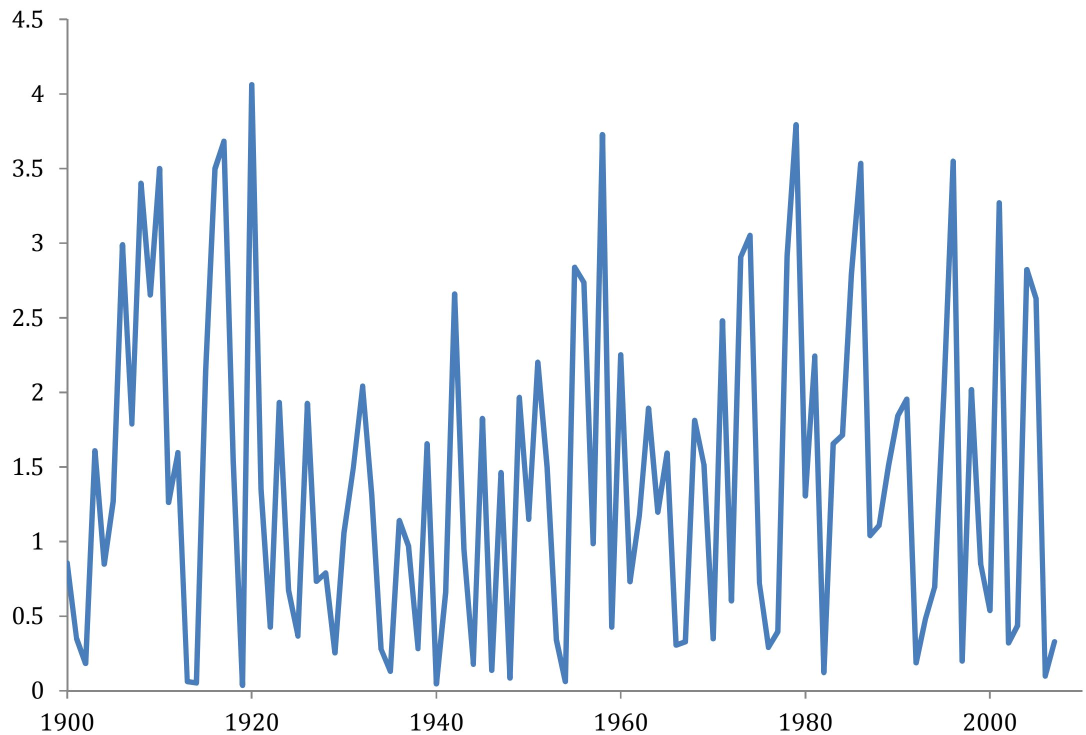


Figure 4. Simulated wheat yields at Hawker (t/ha)



From each of these series we can calculate a gross margin and estimate a stochastic differential equation for use in the option pricing equations outlined above. This process is done in two steps. The first, involves plotting the year-to-year variations in gross margins dG (y-axis) against the gross margin G which precedes the variation (x-axis). This produces a representation which could be called a phase graph. This tells us for a given data point the gross margin this year and the change in gross margin the following year. Figures 5, 6 and 7 present these phase diagrams for Clare, Orroroo and Hawker respectively. The second step, is to estimate a function which adequately describes the relationship between G and dG – this is our stochastic differential equation.

Figure 5. Gross margin phase graph wheat cropping at Clare.

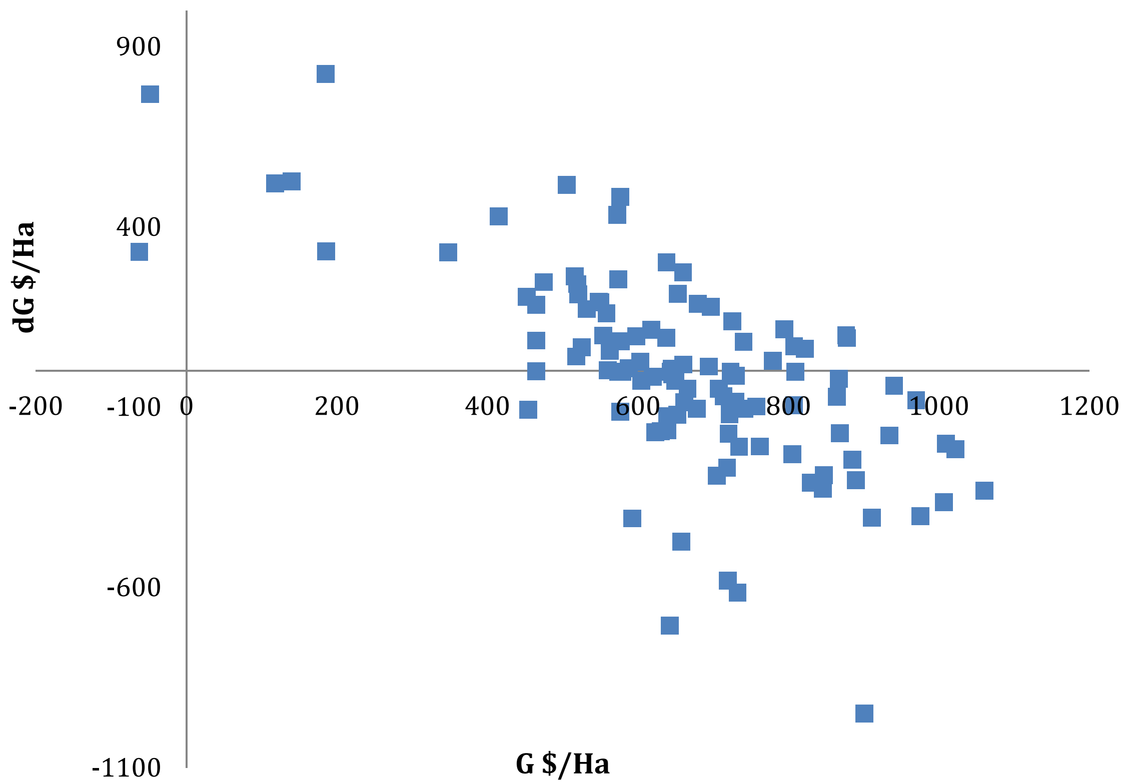


Figure 6. Gross margin phase graph wheat cropping at Orroroo.

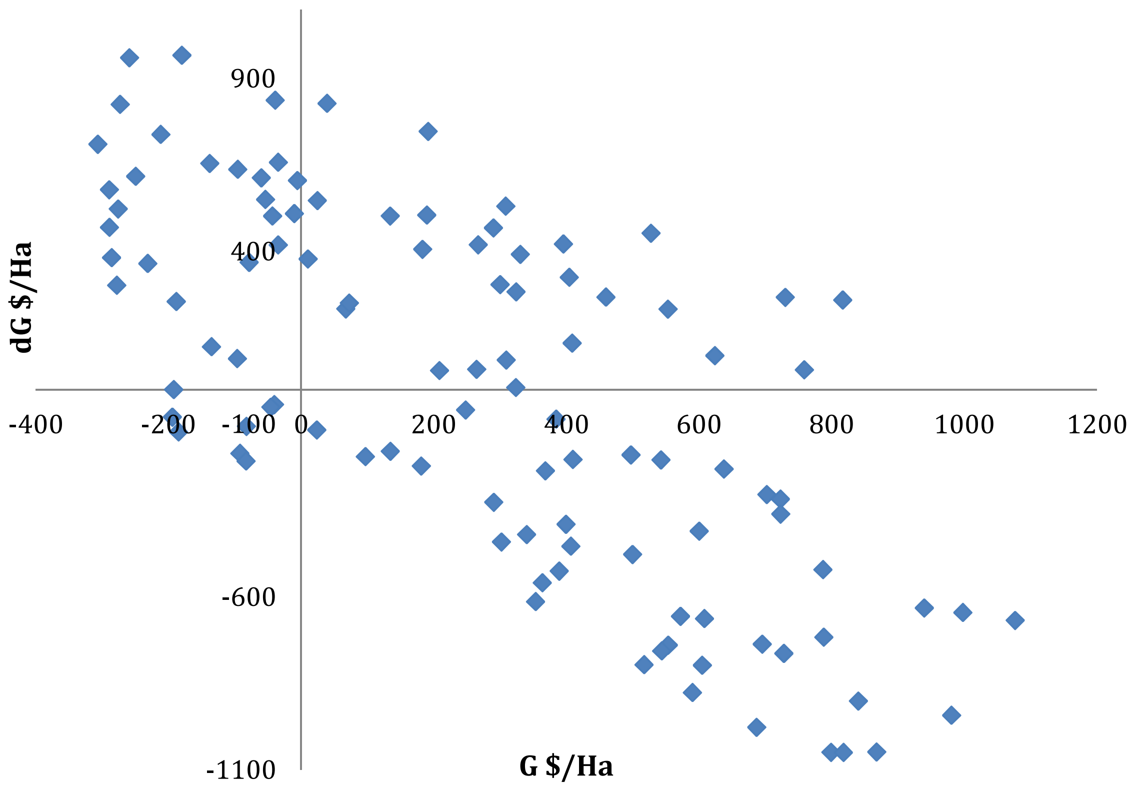
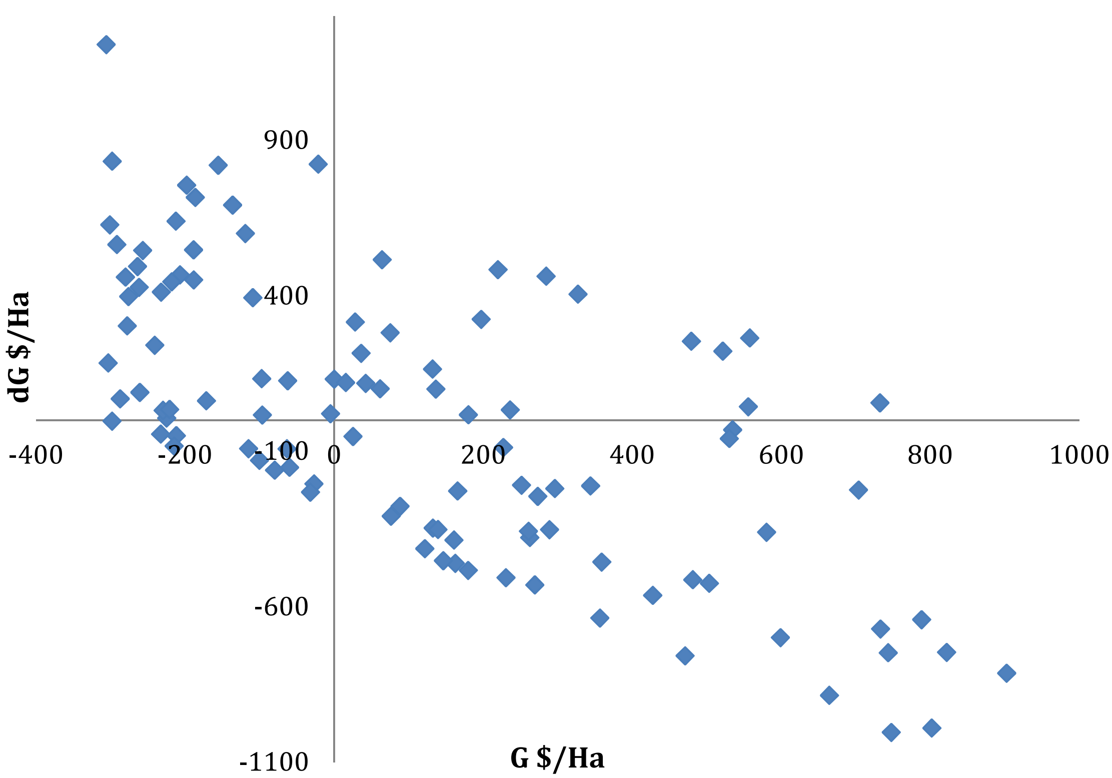


Figure 7. Gross margin phase graph wheat cropping at Hawker.



3.2 Characteristics of grazing systems along the study transect

The productivity dynamics of grazing systems along the transect are assumed to be driven by annual rainfall. In rainfall limited grazing environments, this turns out to be a surprisingly reasonable assumption. Invoking this assumption, allows us to characterise the dynamics of grazing gross margins at each of the study sites along the lines outlined above. These are presented in Figure 8, 9 and 10 for Clare, Orroroo and Hawker respectively.

Figure 8. Gross margin phase graph merino wether grazing at Clare.

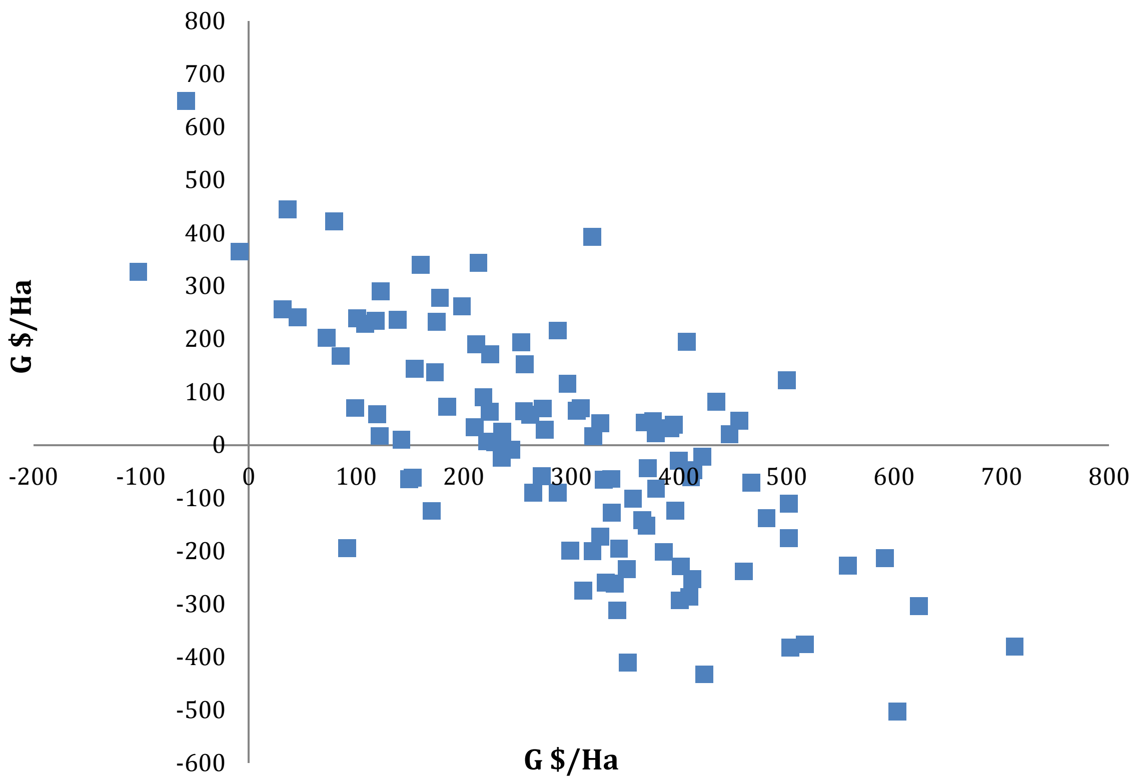


Figure 15. Gross margin phase graph merino wether grazing at Orroroo.

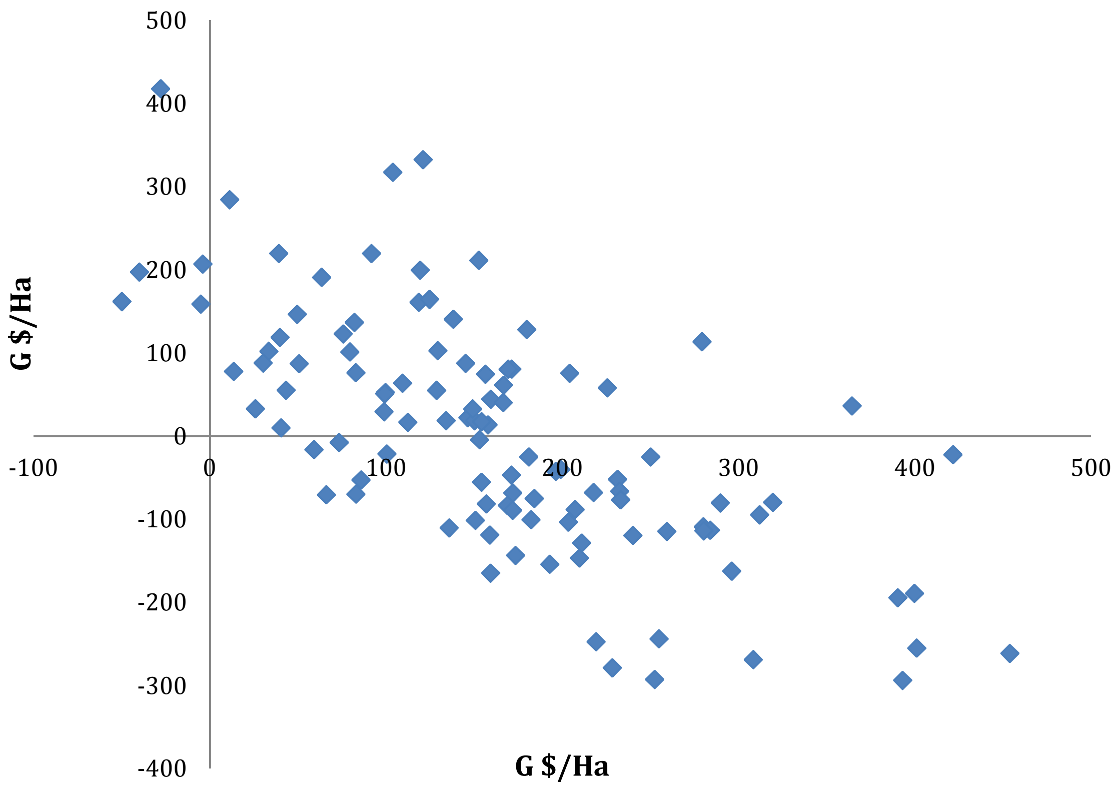
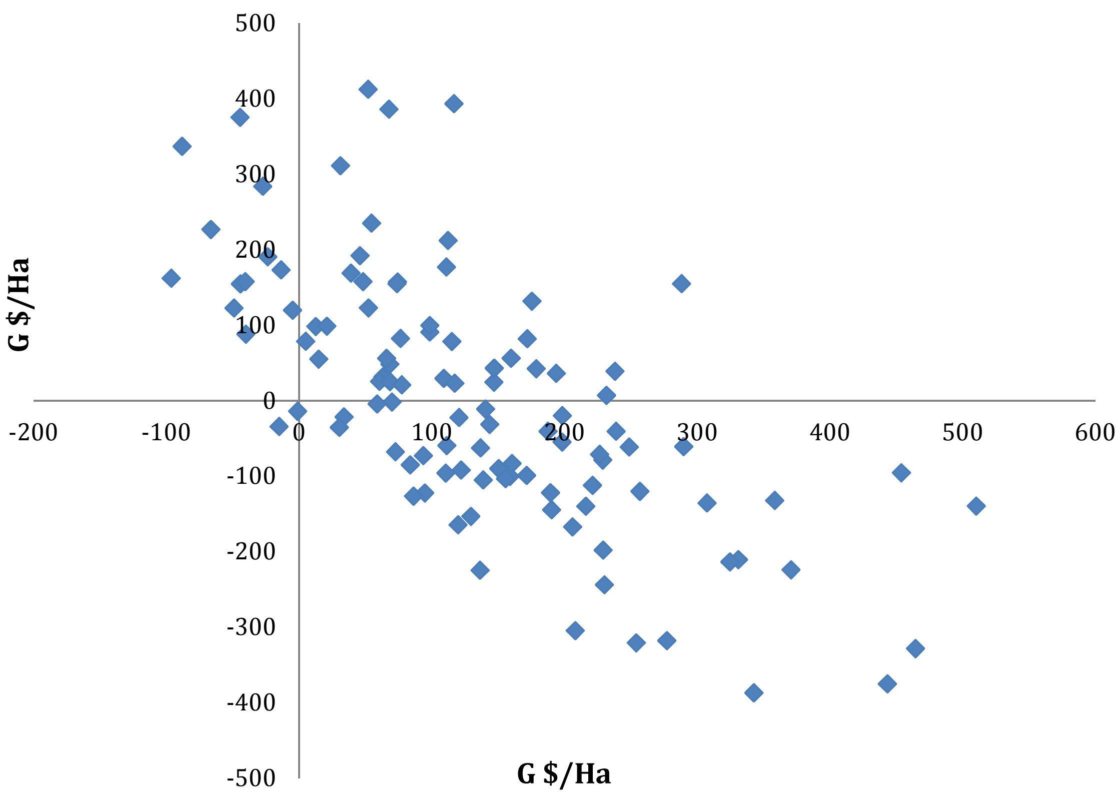


Figure 16. Gross margin phase graph merino wether grazing at Hawker.



3.3 Estimating stochastic differential equations

There are a number of stochastic processes which may be employed to approximate the data series necessary to inform the *ROADs* model. In real options models, two common stochastic processes are Ornstien-Uhlenbeck and Geometric Brownian motion, each of which has very different properties. If we defined an Ornstein-Uhlenbeck process G_t the corresponding stochastic differential equation would be

(27) $$dG_t = b\{\mu - G_t\}dt + \sigma dz_t$$

The important property of Ornstein-Uhlenbeck processes is that they tend to drift towards a long-term mean μ (Doob, 1942). The application of such a process is acceptable where we believe (a) there is a tendency for the data series to revert to some mean, and (b) this process of reversion is linear. Geometric Brownian motion, unlike an Ornstien-Uhlenbeck process, does not possess the property of a stable equilibrium, so that there is no tendency to revert to a mean. The standard representation of which is

(28) $$dG_t = \alpha G_t dt + \sigma G_t dz_t$$

In this instance we will employ a functional form which displays the equilibrium attraction property of an Ornstien-Uhlenbeck, although in a non-linear form. This is

(29) $$dG_t = b\{\mu_1 - G_t\}\{\mu_2 - G_t\}dt + \sigma dz_t$$

The appropriateness of this functional form is reflected in the observation that (a) the agricultural systems we are observing have a tendency to revert to some equilibrium state, and (b) the reversion from a "poor" state is different to the reversion from a "good" state. The difference is reflected in the different periods of persistence of good or bad states. Table 2 presents the parameter estimates for each of the study sites and regimes, approximated using OLS regression procedures.

Table 2. Estimated SDE parameters for regime gross margins in ('000s).

Activity	Parameter	Clare	Orroroo	Hawker
Wheat	b	0.1146	0.2343	0.2032
	μ_1	8.4569	4.1351	4.9716
	μ_2	0.6445	0.2978	0.0897
	σ	0.2074	0.3693	0.3305
Merino Grazing	b	0.4429	1.0516	0.8895
	μ_1	2.5717	1.1185	1.2737
	μ_2	0.2824	0.1532	0.1222
	σ	0.1514	0.1027	0.1211

In Table 2, the parameter values give some key insights into the nature of the production systems at each of the study sites. At each of the sites we have estimated two values for attractor points, that is where $dG_t = 0$. The systems are attracted to these points and if we have a linear SDE, we would be describing these attractor points as averages. In each estimation, one of these attractors is outside the reasonable domain of consideration. For instance, at Clare, we have $\mu_1 = 8.4569$ and $\mu_2 = 0.6445$ as the gross margins are denoted as fractions of a thousand, these attractor points amount to \$8456.9/ha and \$644.50/ha respectively. Examination of Figure 5, the phase graph of wheat cropping gross margins for Clare, reveals that the upper value of \$8456.9/ha is well outside of the domain of consideration. As such, the only reasonable attractor for this system is at the gross margin value of \$644.50/ha. The same thought process may be applied to each of the study sites and regimes, and in all cases the smaller of the two attractor values is reasonable estimate. It is also worth noting that wheat cropping is substantially more variable and larger in the gross margin attractor value than that generated in merino grazing.

4. Results

The farming system at a given site may switch between regimes at any time *T*. In other words, we must find the optimal stopping time. Finding the optimal stopping time is difficult and requires a global search algorithm. The search algorithm employed in *ROADs* has three steps.

> *Step 1*: Solve the option pricing equation for all possible times and states.
>
> *Step 2:* Assume the state is fixed and search for the largest option price for that state. Note the expected time before the switch, given that state.
>
> *Step 3:* Repeat step 2 for all possible states and identify the state where the largest option price is no longer greater than the terminal value.

Step 1 requires the most work, sometimes considerable work, and creates a large table which is searched in Step 2. Repeating Step 2 creates a small table of all expected times before the switch. The small table is searched in Step 3 to find the state where the system will optimally exit one activity. The problem is solved by the optimal stopping algorithm, using the Black-Scholes formula or finite difference methods to calculate all possible option prices in Step 1, finding the largest option price for each state in Step 2 and finding the exit state and time in Step 3. If this was an exercise in finance, Step 1 would calculate the prices of European options, Step 2 would calculate the prices of American options and Step 3 would calculate the trigger for exercising the American option. In the real world, we can observe the current state of the system and, from the table created in Step 2, look up the expected time before crossing the threshold. We find the threshold, itself, in Step 3.

We have applied ROADs to each of the study sites, and examined four decision problems between the two regimes of wheat cropping and merino grazing. These decision problems are (1) entry into wheat cropping with the possibility to exit, (2) exit from wheat cropping with the possibility to enter merino grazing, (3) entry into merino grazing with the possibility exit, and (4) exit from merino grazing. These option values are presented in Table 3.

Table 3. Estimated option values, state values and expected times until exercise

Decision		Clare	Orroroo	Hawker
Entry into wheat with possibility to exit	w	0.600	0.326	0.223
	x	0.600	0.300	0.170
	T-t	0.100	0.800	0.800
Exit from wheat with possibility to enter merinos	w	0.486	0.284	0.218
	x	-0.270	-0.170	-0.120
	T-t	3.700	2.600	1.200
Entry into merinos with possibility to exit	w	0.261	0.141	0.117
	x	0.260	0.140	0.110
	T-t	0.300	0.300	0.800
Exit from merinos	w	0.011	0.010	0.014
	x	-0.010	-0.010	-0.010
	T-t	0.100	0.100	0.200

Clare entry into wheat. The option value *w* for entry with the possibility to exit is \$600/ha, which is interpreted as the farmer's willingness to forego income from wheat cropping while they wait to see what happens. They are willing to forego income because entering is partially irreversible. If they enter and are wrong about the stream of gross margins, they will have to exit again. At the corresponding entry threshold gross margin *x* of \$600/ha the farmer will commit to wheat cropping. This value is modest when we consider that the equilibrium gross margin in Clare for wheat cropping is calculated (from Table 2) as \$644.5/ha. It explains in part why wheat is being produced in Clare at present on arable land that is not used for higher return options such as viticulture. Also, the expected timing *T-t* until the option is exercised is 0.1, which has no direct interpretation by itself. In the context of other decisions and other study sites, it may be interpreted as a relative measure of expected time.

That is, compared to Orroroo and Hawker which have expected times of 0.8 each, the commitment to enter wheat at Clare is expected to happen eight times faster. This is a direct function of the lower risk and higher return nature of wheat cropping at Clare compared to Orroroo and Hawker (Table 2).

Clare exit from wheat and entry into merinos. The option value for exit wheat cropping with the possibility to enter into merino grazing is $486/ha. In this instance, we interpret this as the farmer's willingness to lose money on wheat cropping before finally committing to enter merino grazing. At the corresponding exit threshold wheat cropping gross margin of -$270/ha the farmer will finally commit to exit. The expected time until exercise of this option is 3.7, which is thirty-seven times longer than the expected time the farmer took to choose to commit and enter wheat cropping. This expected time tells us that wheat cropping at Clare is in a relative sense, a very robust production regime. This is likely the consequence of the gross margin attractor for merino grazing being $282.4/ha as compared to wheat cropping which is $644.5/ha (Table 2). The decrease in the riskiness of the gross margins by switching from wheat cropping to merino grazing is not sufficient to compensate for the loss of income.

Clare entry and exit from merinos. The option value for entry with the possibility of exit is $261/ha, with a corresponding gross margin threshold of $260/ha. That is, the farmer will wait until production potential hits $260/ha before committing to enter merino grazing. Again, when compared to the estimated gross margin attractor value (Table 2) for the regime of $282.4/ha, this threshold value appears quite modest. The expected time until committing to enter is 0.3, which is three times longer than the expected time for the farmer to enter wheat cropping.

5. Conclusions

These preliminary results have introduced and explained the real options method of determining entry into and exit from two broadacre farming activities, wheat and merino wethers, in South Australia. Broadly, these preliminary results correspond to *a priori* suspicions about the nature of farming activities along the study transect. However, further research is required to resolve some remaining issues.

References

Andersen, E.B. (1980) *Discrete Statistical Models with Social Science Applications*. North Holland Publishing Company.

Dixit, A.K. and Pindyck, R.S. (1994) *Investment Under Uncertainty*. Princeton University Press, Princeton.

Doob, J.L. (1942) The Brownian Movement and Stochastic Equations. *The Annals of Mathematics, Second Series*, 43(2), 351-369.

Gunasekera D, Kim Y, Tulloh C, Ford M (2007) Climate Change, impacts on Australian Agriculture. ABARE project 1163. In *'Australian Commodities, December Quarter'*. (Ed. A Wright). (Australian Bureau of Agricultural and Resource Economics: Canberra).

Hayman, P., Alexander, B., Nidumolu, U. And Wilhelm, N. (2010) *Using spatial and temporal analogues to consider impacts and adaptation to climate change in the South Australian grain belt.* 15th Australian Agronomy Conference, Lincoln New Zealand, 15-18 November 2010.

Hennessy K, Fitzharris B, Bates BC, Harvey N, Howden S, Hughes L, Salinger J, Warrick R (2007) Australia and New Zealand. In *'Climate change 2007- Impacts, Adaptation and Vulnerability - Contribution of Working Group II to the Fourth Assessment Report of the International Panel on Climate Change*'. (Eds ML Parry, OF Canziani, PJ Palutikof, PJ van der Linden, CE Hansen) pp. 507-540. (Cambridge University Press: Cambridge).

Hertzler, G. (2012) *Real Options for Adaptive Decisions* (Software). University of Sydney, Sydney.

Howden SM, Gifford RG, Meinke H (2010) Grains. In 'Adapting Agriculture to Climate Change. Preparing Australian agriculture, forestry and fisheries for the future'. (Eds CJ Stokes, SM Howden) pp. 21-40. (CSIRO: Melbourne).

McCown, R.L., Hammer, G.L., Hargreaves, J.N.G., Holzworth, D.P., Freebairn, D.M. (1996) APSIM: a Novel Software System for Model Development, Model Testing, and Simulation in Agricultural Systems Research. *Agricultural Systems* 50, 255-271.

Nidumolu, U.B., Hayman, P.T., Howden, S.M. and Alexander, B.M. (2012) Re-evaluating the Margin of the South Australian Grain Belt in a Changing Climate. *Climate Research*, 51, 249-260.

Productivity Commission. (2012) *Barriers to Effective Climate Change Adaptation*. Draft Report, Canberra.

Rural Solutions South Australia. (2012) *Farm Gross Margin Guide*. Government of South Australia, Adelaide.