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Real options for adaptive decisions in primary industries

Final Report

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REAL OPTIONS FOR ADAPTIVE DECISIONS IN PRIMARY INDUSTRIES

Will Primary Producers Continue to Adjust Practices and Technologies, Change Production Systems or Transform Their Industry – An Application of Real Options

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The role of NCCARF is to lead the research community in a national interdisciplinary effort to generate the information needed by decision-makers in government, business and in vulnerable sectors and communities to manage the risk of climate change impacts.

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ABSTRACT

The long term sustainability of Australian crop and livestock farms is threatened with climate change and climate variability. In response, farmers may decide to (1) adjust practices and technologies, (2) change production systems, or (3) transform their industries, for example, by relocating to new geographical areas. Adjustments to existing practices are easy to make relative to changes to production systems or transformations of an industry. Switching between production regimes requires new investments and infrastructure and can leave assets stranded. These changes can be partially or wholly irreversible but hysteresis effects can make switching difficult and mistakes costly to reverse.

'Real options' is a framework to structure thinking and analysis of these difficult choices. Previous work has demonstrated how real options can be applied to adaptation, and extends traditional economic analyses of agricultural investment decisions based on net present values to better represent the uncertainty and risks of climate change.

This project uses transects across space as analogues for future climate scenarios. We simulate yields from climate data and draw on data from actual farms to estimate a real options model referred to as 'Real Options for Adaptive Decisions' (ROADs). We present results for the transformation of wheat dominant cropping systems in South Australia, New South Wales, and Western Australia. We find that farmers' decisions, as much as a changing climate, determine how agriculture will be transformed.

EXECUTIVE SUMMARY

Agricultural production systems depend upon weather and climate. Current agricultural practices are adaptations to specific characteristics of the prevailing climate (Gornall *et al.* 2010). Accordingly, Australian agricultural systems have evolved to suit a highly variable environment. Over time, Australian producers improved their understanding of the climate regimes and responded by making appropriate decisions.

Climate change presents a challenge to current understanding and practices. We can think about a prevailing climate as a stochastic system in which decisions have been informed by historical experiences (Antle 1996). Over time, decisions are calibrated to the current regime. Yet climate change, by its very nature, implies that we can no longer assume that the climate we are familiar with will be the climate of the future.

This research project applies recent developments in the mathematics of uncertainty to investigate the optimal choice of production regimes under climate change. In this environment, we need tools such as mathematical real options analysis, which can take the dynamic nature of risks into account. '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 scenario testing approaches generally seek to simply understand the impacts of change, whereas the real options approach specifically seeks to show how decision-makers can manage risk. This approach examines 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.

In this study, we apply the Real Options for Adaptive Decisions (ROADs) framework (Hertzler 2012b) to assess whether farmers in wheat dominant agriculture will continue to adjust practices and technologies, change production systems or transform their industry (Howden *et al.* 2010; Rickards and Howden 2012). We use transects across space as an analogue for climate change. Producers in one region may look to a drier and hotter region to see what their climate and production systems may look like in the future. Wheat is the major winter crop in southern Australia (Figure 1), and we focus on wheat producing regions of New South Wales, South Australia and Western Australia.

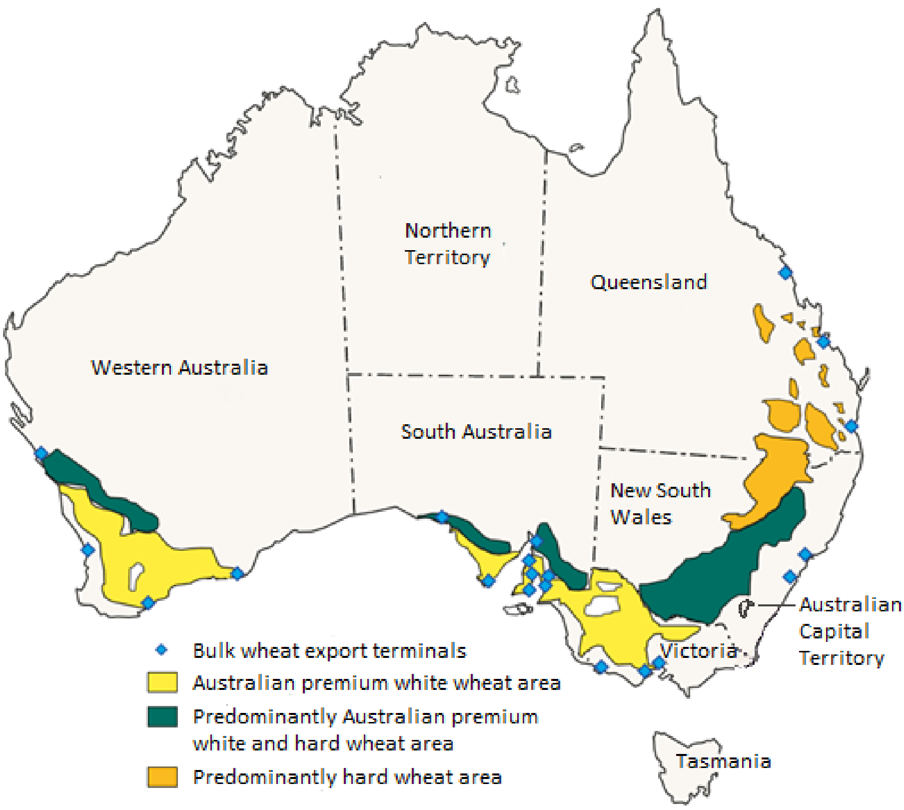

Figure 1: Australian wheat production regions (ABARES 2011b)

We chose transects in South Australia and New South Wales for their sensitivity to climate change. Because Western Australia is forecast to become hotter and drier throughout the state, we analysed its nine major agro-ecological zones. For South Australia and New South Wales we used APSIM simulations (McCown *et al*. 1996), with representative returns and costs. For Western Australia we obtained summarised results from actual data on 155 farms in the 9 agro-ecological zones.

We estimated the stochastic dynamics of climate change along the chosen transects and within the agro-ecological zones and entered these estimations into the calculation of option values, thresholds, the expected times of switching and the probabilities of crossing the thresholds. The option values are the amount farmers are willing to pay to keep their options open and before committing to an inflexible decision which may turn out to be costly. The thresholds are the points at which farmers choose to switch cropping or livestock regimes and transform their production systems. The expected time corresponds to how long farmers may wait to resolve the uncertainties about climate change and the probabilities of crossing the thresholds show the likelihood of crossing the threshold in the near or distant future.

The chosen transect in South Australia straddles Goyder's line, with Clare below the line, Orroroo on the line and Hawker above the line. Currently at Clare, farmers are almost certain to adopt wheat, less likely to adopt merino grazing, with no chance of abandoning agriculture. At Orroroo, farmers are less likely to be in wheat and somewhat more likely to adopt merino grazing, but probably will never abandon

agriculture. At Hawker, there is a small chance of adopting wheat, a larger chance of adopting merino grazing and a reasonable chance of abandoning agriculture altogether. As climate becomes hotter and drier in South Australia and Goyder's line moves south, Clare will become more like Orroroo and Orroroo will become more like Hawker. The landscape will change as wheat becomes less dominant, merinos are adopted on more farms and some farms leave agriculture.

Compare this with wheat dominant agriculture in Western Australia. Even though the impacts of climate change are expected to be severe and make the state much hotter and drier, wheat will continue to dominate agriculture in all agro-ecological zones, including high, medium and low rainfall zones. Sheep do not compete with wheat in any zone. There is virtually no chance that wheat dominant agriculture will disappear from any of the zones. Farmers will continue to choose wheat and will not transform agriculture in Western Australia in response to climate change.

The chosen transect in New South Wales may be less affected by climate but more sensitive to climate change. Cootamundra is in reliable country, Temora is intermediate in reliability and Narrandera is the riskiest region in the entire study. As climate changes, Cootamundra will switch to become more like Temora and manage the risks with a mixed cropping system. Temora may become more like Narrandera with the adoption of sheep. Narrandera is likely to adopt sheep only enterprises or abandon farming altogether.

Of course, these results are not forecasts. They are predicated on the assumption that space is a good analogue for climate change and that climate will change significantly. If climate change is moderate, different regions may take on characteristic of other regions, but will never become exactly like its analogue on the climate transect.

The results show, however, that climate change does not translate directly into transformations of agriculture. Farmers' decisions are just as important in determining the impacts of climate change. For example, Western Australia will become hotter and drier, but is very unlikely to adapt its agriculture away from wheat, let alone transform into other production systems. The Mediterranean climate and limited options for growing crops and livestock will ensure that farmers choose wheat. South Australia is more likely to adapt away from wheat as Goyder's Line moves south, mostly because sheep are a more viable option and wheat can become unprofitable and very risky. As a counter example, New South Wales may be less subject to climate change, but farmers are more likely to transform their production systems into mixed farming. The favourable climate and good soils give farmers many options to choose among.

Finally, wheat dominant agriculture is important in Australia and has lessons for agriculture in general, but wheat is a highly resilient crop, perhaps the most resilient crop in agriculture. Wheat is bred to grow where other crops won't but we can't survive on bread alone. Agriculture is a very diverse industry with many sectors, all dependent on the climate in complex ways. Future research should investigate which agriculture sectors will be most impacted by climate change, taking into account that farmers will decide what those impacts will be.

1. OBJECTIVES OF THE RESEARCH

In order to understand the impacts of climate change on wheat dominated agriculture in Australia, let alone the options available for adaptation and transformation, we need to match existing scientific knowledge of the biophysical consequences of climate change with research into the likely responses of social and economic systems to these changes. The majority of previous research has focused on the biological and agricultural science dimensions of climate change and treated the decisions made by farmers and communities as exogenous factors. Quite the opposite is true.

The decisions made by farmers determine the impact of climate change on agricultural productivity. For example, the impact of climate change on agricultural productivity and the risk of crop failure will affect decisions such as producers' willingness to invest in new production technologies or diversification. These kinds of decisions can be viewed as responses to uncertainties that arise from the prevailing climatic, social and market systems. These uncertainties will ultimately determine the nature of agricultural production and the resilience of surrounding rural communities.

Understanding the consequences of uncertainties for decisions is necessary to evaluate the resilience of Australia's systems of agricultural production to climate change and for assessing the options available for climate adaptation. Past research provides some understanding of the range of possible climate scenarios, but without linking this research to an analysis of farmers' decisions we cannot understand the potential transformation of agricultural systems as the climate changes.

The actions of farmers and rural communities can take various forms, such as (1) adjusting practices and technologies, (2) changing production systems, and (3) re-locating production (Howden *et al.* 2010). These actions represent choices between alternative production regimes within the agricultural systems that will be affected by climate change. A switch from one regime to another can be irreversible or only partially reversible. Switching production regimes may require investments into production techniques (*e.g.* seeds, equipment, or knowledge), as well as processing and infrastructure. Old technology may have a salvage value. Conversely, assets may become stranded with no possibility of recovering the investment. These complications throw up barriers to adaptation, with broader implications for rural communities and regional economies.

The overall objective of this research project is to determine the thresholds for transformational change across Australia in wheat dominated agriculture, subject to climate change. This objective is achieved by decomposing it into the following sub objectives:

1. Build capacity and skills in the economic analysis of adaptive and transformational responses to climate change

2. Use transects across space to identify future scenarios for more favourable areas as they become less favourable with climate change

3. Use data from previous research and collect additional data to model the transformations from wheat dominant systems

4. Use climate data to assess the trends and increasing variability of crop and pasture production

5. Use a real options framework to find the thresholds for switching from wheat to mixed cropping to livestock to extensive grazing

6. Calculate the option values that growers will pay to avoid making a mistake and switching inappropriately, the transactions costs of reversing a mistake, the expected time until growers will switch and the probabilities of switching from one regime to the next.

2. RESEARCH ACTIVITIES AND METHODS

2.1 Introduction:

This research project employs recent developments in mathematics and economics to bridge the gap between the science of climate change impacts on agriculture and the socio-economic realities of agricultural adaptation and transformation. Previous research in the Australian context developed and demonstrated the appropriateness of real options as a framework to bridge this gap (Hertzler 2007).

'Real options' is the name given to the modern analytical method for modelling the value of flexibility and the timing of action in decision-making under uncertainty. Simulation and scenario 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.

Real options extends traditional economic analyses of agricultural investment decisions based on cost-benefit analysis and net present values to better represent incomplete knowledge and uncertainty. Taking option values into account is especially important since some adaptation decisions can be costly to reverse or can even have irreversible consequences for farmers and rural communities. For instance, real options can be used to understand why farmers may fail to adopt new varieties of crops or technologies. This hesitation to adopt can exist because there are uncertainties about the impact of adoption on production outcomes. For some farmers the risks may outweigh the apparent benefits predicted by the science.

Real Options for Adaptive Decisions (ROADs) is an extension of real options which allows us to understand the timing of adaptation decisions, modelled as switches from one production regime to another (Hertzler 2012b). A production regime is defined by the activities undertaken within it and Figure 2 presents a sequence of four possible production regimes available to a farmer currently engaged in wheat cropping.

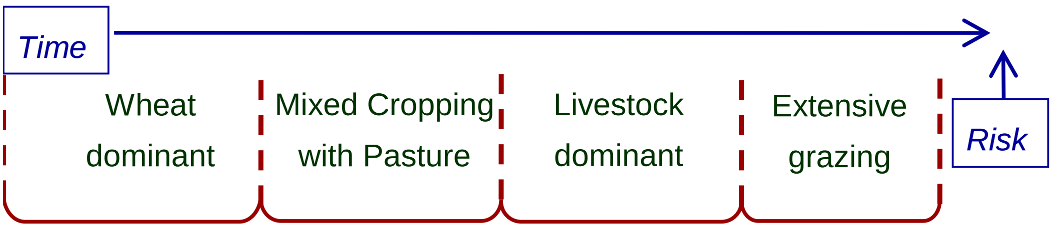

Figure 2: One of many possible sequences of regime transitions with climate change

When considering a sequence of production regimes, we need to calculate the value of remaining in a current regime whilst retaining the option to switch later if need be. When 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. ROADs provides an analytical framework to analyse this type of decision problem, by applying a real options analysis that decomposes complex decisions over time into choices between alternative regimes.

For example, Figure 2 represents a farmer[1] currently involved in an agricultural production regime which is primarily with wheat cropping. As the climate changes, wheat production may decline and the farmer may switch to a regime in which wheat is grown in some years with pasture in others. With extreme adverse climate change, this farmer might even switch to a regime of extensive grazing. Within each of these broader regimes there is the possibility to adapt by making smaller changes to farming practices, such as adopting improved techniques or adoption of genetically modified crop varieties. However, these adaptations may be both costly and risky, and farmers may be hesitant to adapt immediately.

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, from cropping to extensive grazing, for example, 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 changing and the variability associated with that change. The ROADs framework allows us to model the timing of decisions by maximising the option values of retaining flexibility and minimising the costs of switching back after a mistaken decision. This allows us to determine the resilience of alternative agricultural production regimes to climate change.

Two related problems are how to quantify the ROADs model and how to assess the probabilities of switching from one regime to another. Two components added to the ROADs framework solve these problems. The first added component, Gauging the Parameter Set (GPS), estimates the parameters of the stochastic dynamic system and the second added component, Transformations in Probability Space (TRIPS), calculates the probabilities of crossing thresholds between regimes (Hertzler 2012a, Hertzler 2012c).

2.2 Research Approach:

2.2.1 Identify transects for analysis in the case study regions

We study the implications of climate change by employing the spatial-temporal analogues approach (Hayman *et al.* 2010). Nidumolu *et al.* (2012) describe the pattern of rainfall isohyets in Australia as approximately concentric, with a steady decrease in average rainfall with distance from the coast. As we move inland from the coast, high

[1] Please note that the use of the term "farmer" in this report is used only for the purposes of exposition, rather than in any specific sense. This report focuses upon changes in agricultural production on a representative hectare of land at a given location, within which the farmer is considered to act as a representative decision maker.

rainfall agricultural cropping systems give way to wheat dominant marginal cropping, and finally, to extensive grazing systems. The transition between cropping and grazing on this margin has changed over time with technology and commodity prices, but it is also sensitive to climatic factors (Nidumolu *et al.* 2012).

We have identified case study transects for present-day wheat cropping regions and beyond in South Australia, New South Wales and Western Australia. Each of these transects transcend rainfall isohyets and meteorological isopleths (Hayman *et al.* 2010; Nidumolu *et al.* 2012) to capture a cross section of wheat dominant systems. This approach recognises that the position of farms is a good predictor of the prevailing farming activity. For instance, the transect in South Australia ranges from intensive cropping with a high proportion of relatively high risk and high return crops, through to an increasing proportion of cereals with lower inputs, and then finally to grazing enterprises with opportunistic cropping (Hayman *et al.* 2010).

Identifying transects allows us to model the adaptation and transformational processes that might occur in the future by examining the nature of optimal decisions at another site where those possible future conditions are already observed. For example, we can compare conditions at Clare and Orroroo in South Australia. Clare currently enjoys a growing season rainfall (GSR) of 485.91mm, with a standard deviation of 126.87mm. Due north at Orroroo, GSR is 224.86mm with a standard deviation of 72.28mm, approximately half the GSR of Clare.

If we anticipate that climate change will lower GSR, then the future at Clare may be modelled along a transect from Clare to Orroroo and comparing the optimal farming decisions at these two sites. Indeed, if we expect Clare to experience a 50% decline in GSR, then we may look directly at Orroroo to foretell the future of wheat dominant agriculture at Clare. We don't pretend to forecast the date when Clare may become like Orroroo, however. Instead, farmers will monitor the climate and switch accordingly.

2.2.2 Develop an understanding the agronomic systems of interest

To develop an understanding of the agronomic systems available to farmers in each of the States, we applied recent developments by the research team into the use of stochastic differential equations. We are able to estimate the dynamic and stochastic nature of production within the available regimes. For data, we use the outputs of biophysical models in New South Wales and South Australia and actual data collected by farm advisors in Western Australia.

In this research we are interested in understanding the implications of climate change on wheat dominant agricultural systems and the thresholds for transformations to other agricultural systems. As a consequence, we must understand both the wheat dominant agricultural system and alternative systems such as extensive grazing. As mentioned, we can use simulated or observed data to estimate these systems. For example, Figure 3 presents a time-series of simulated wheat yields in tonnes per hectare (t/ha), and Figure 4 presents a time-series of livestock carrying capacity in "dry sheep equivalents" (DSE), both at Clare in South Australia.

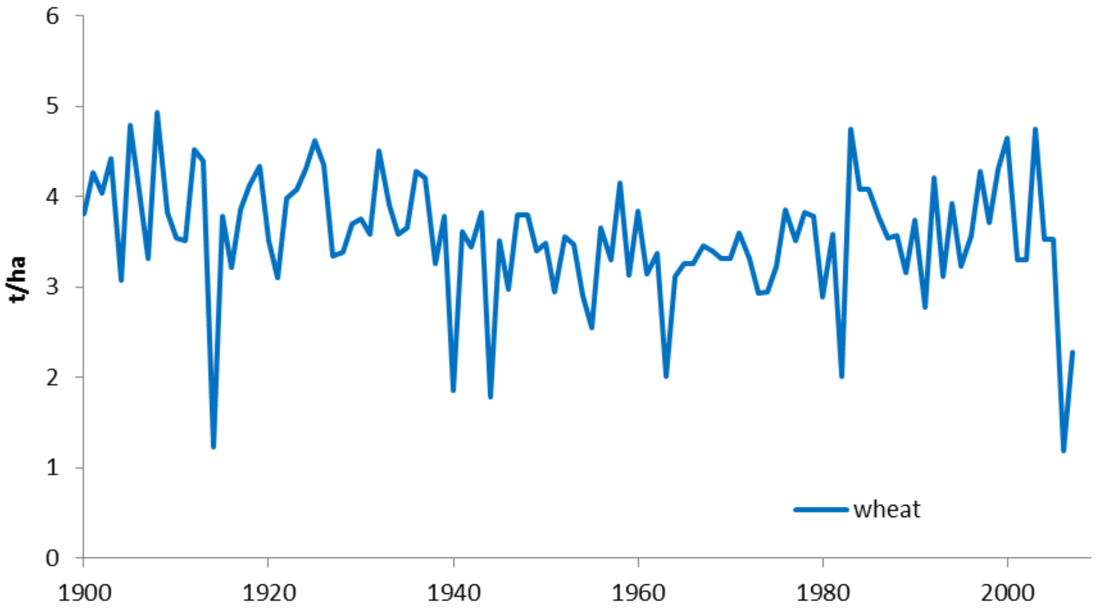

Figure 3: Wheat yields at Clare (t/ha)

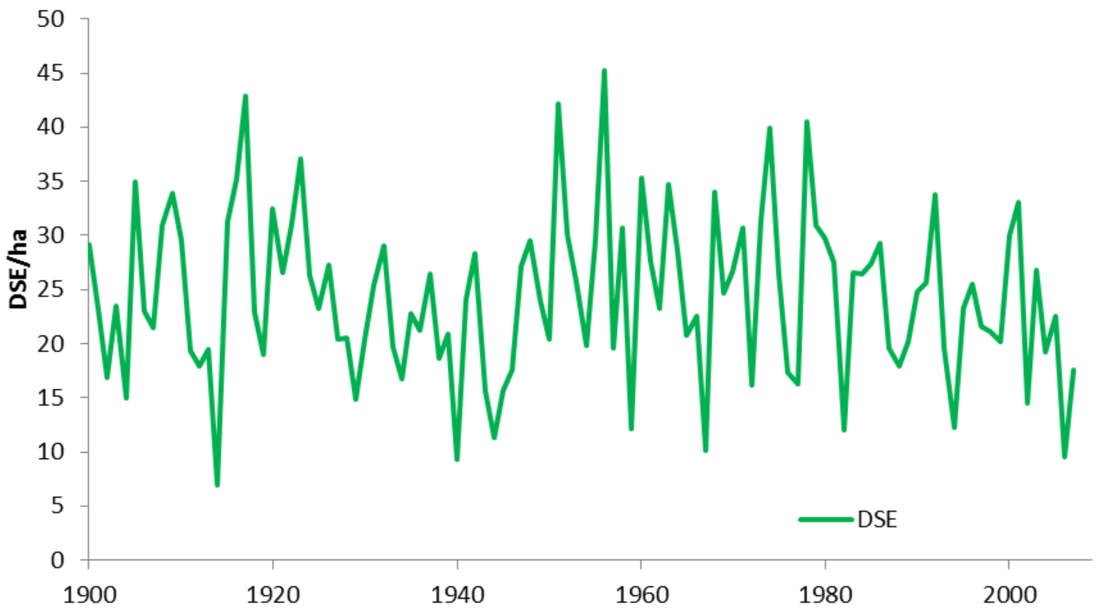

Figure 4: Stock carrying capacity in DSE at Clare (DSE/ha)

For the purposes of exposition we can think of wheat cropping and livestock grazing, in this case merino sheep production, as the two alternative regimes available to a farmer at Clare. Of course, there are many more options available.

Once we have identified at least two agronomic systems of interest, we need to convert these systems into a common unit of measurement to facilitate comparison. In this case, we will convert these systems into dollars, by taking into account the prices of outputs and the costs of inputs. Figures 5 and 6 present the time-series of gross margins per hectare ($/ha) that correspond to wheat cropping and merino sheep

production. The assumptions employed to generate these time-series are outlined fully in the South Australian case study below.

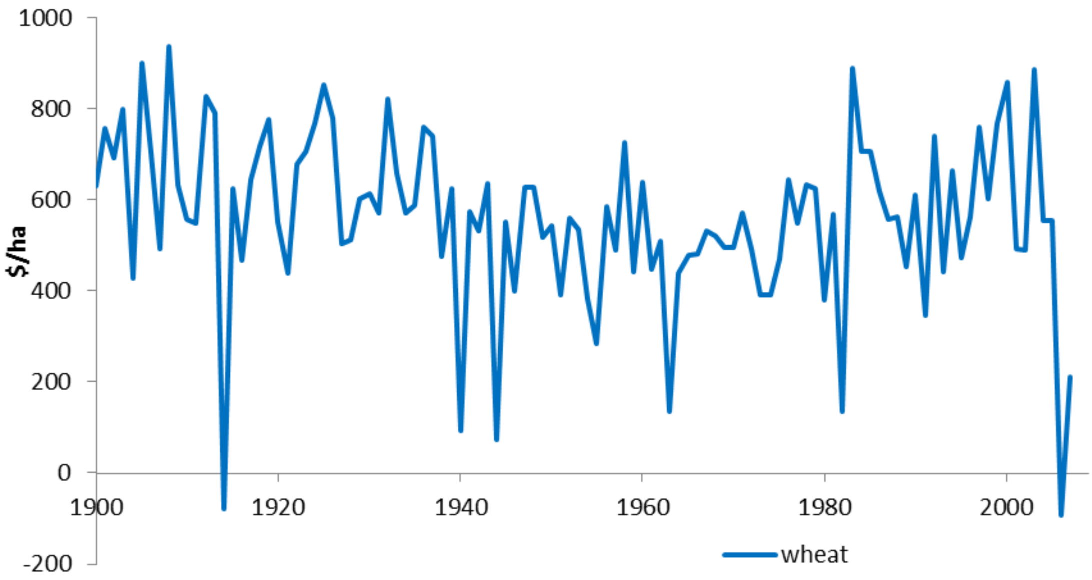

Figure 5: Wheat gross margins at Clare ($/ha)

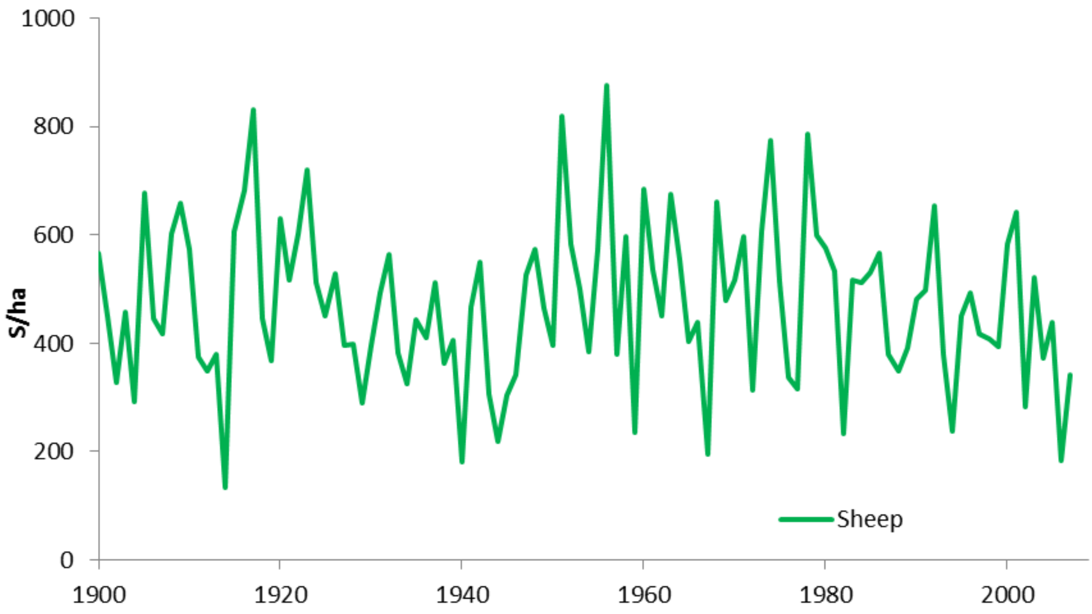

Figure 6: Sheep gross margins at Clare ($/ha)

Having defined the agronomic systems of interest in a common unit of measurement we can proceed to define these systems mathematically. For this analysis, we characterise these systems as stochastic processes modelled by stochastic differential equations.

The first step is to represent the time-series of gross margins for each system as a phase diagram. This involves plotting the year-to-year variations in gross margins, dx, on the y-axis against the current gross margin, x, on the x-axis. A phase diagram tells

us for a given point what the gross margin is for that year as well as the change in the gross margin that results in the observation for the following year. Important characteristics of any system are the rate at which the system can change year to year and whether or not there is a tendency toward equilibrium.

To illustrate, Figure 7 presents a phase diagram for wheat gross margins, and Figure 8 presents a phase diagram for sheep gross margins, each at Clare.

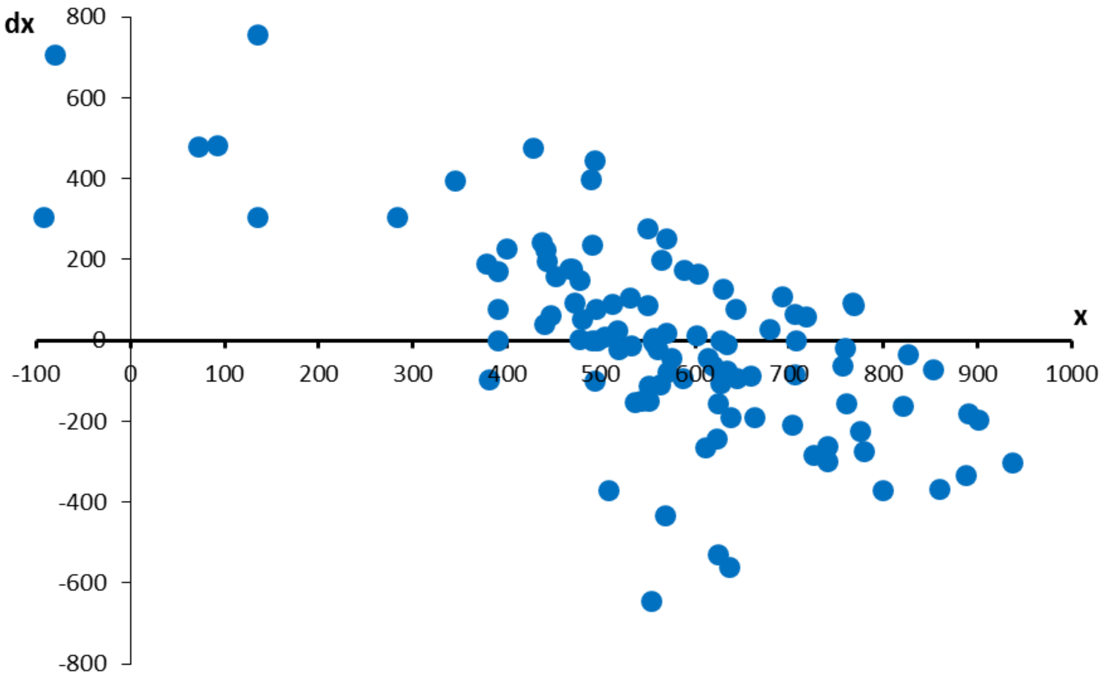

Figure 7: Wheat gross margin phase diagram at Clare ($/ha)

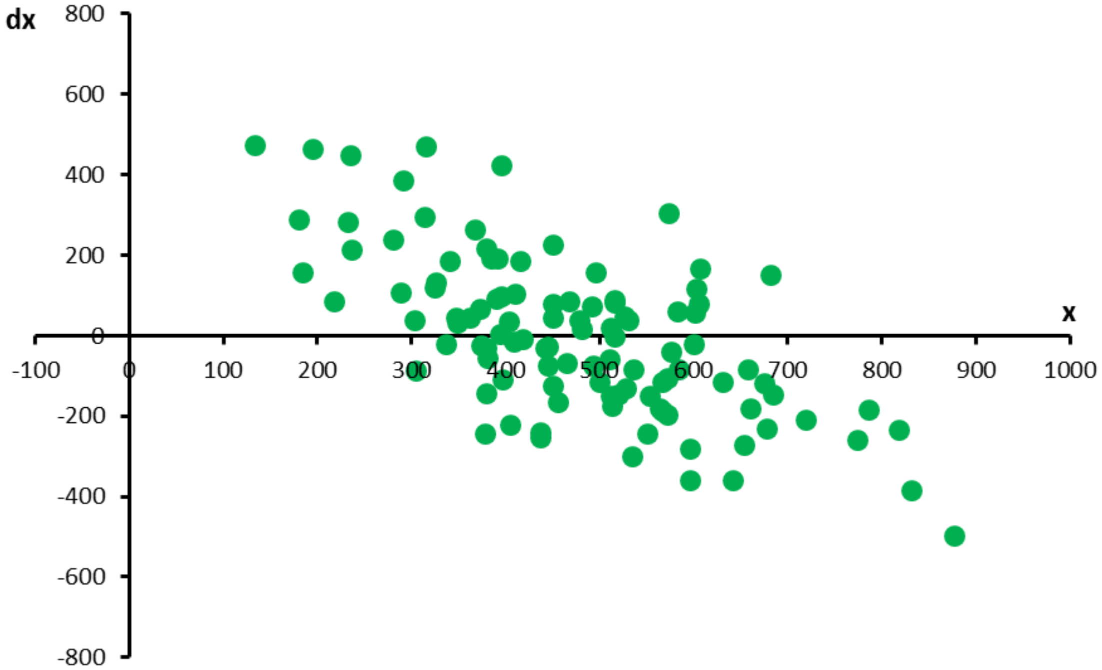

Figure 8: Sheep gross margin phase diagram at Clare ($/ha)

There are a number of stochastic processes which may be used as models of the data series. In real options analyses, a stochastic process known as Geometric Brownian Motion (GBM) is almost always used, due to the existence of the well-known analytical solution for option pricing called the Black-Scholes Formula. Another well known stochastic process is the Ornstein-Uhlenbeck (OU) process, although an analytical solution for option pricing is not known. These two processes have very different properties and their application needs to be carefully considered.

If we define an OU process over gross margins, the corresponding stochastic differential equation would be:

(1) $$dx_t = b\{\mu - x_t\}dt + \sigma dz_t$$

We can estimate the unknown parameters *b,* μ and σ for the data in Figures 5 and 6 using GPS. The OU process tends toward long run equilibrium at μ (Doob, 1942). The application of the OU process is indicated where we believe (a) there is a tendency for the data series to revert to some mean, and (b) the convergence is linear.

GBM, unlike an OU process, does not tend toward a mean and is undefined for negative values of *x*. The standard representation of a GBM process is:

(2) $$dx_t = \alpha x_t dt + \sigma x_t dz_t$$

Again, we can estimate the unknown parameters α and σ using GPS.

Figures 9 and 10 show the GBM and OU processes estimated using the gross margin data for wheat at Clare. Standard error bars of the estimation appear as red dotted lines around the fitted process which appears as a solid red line.

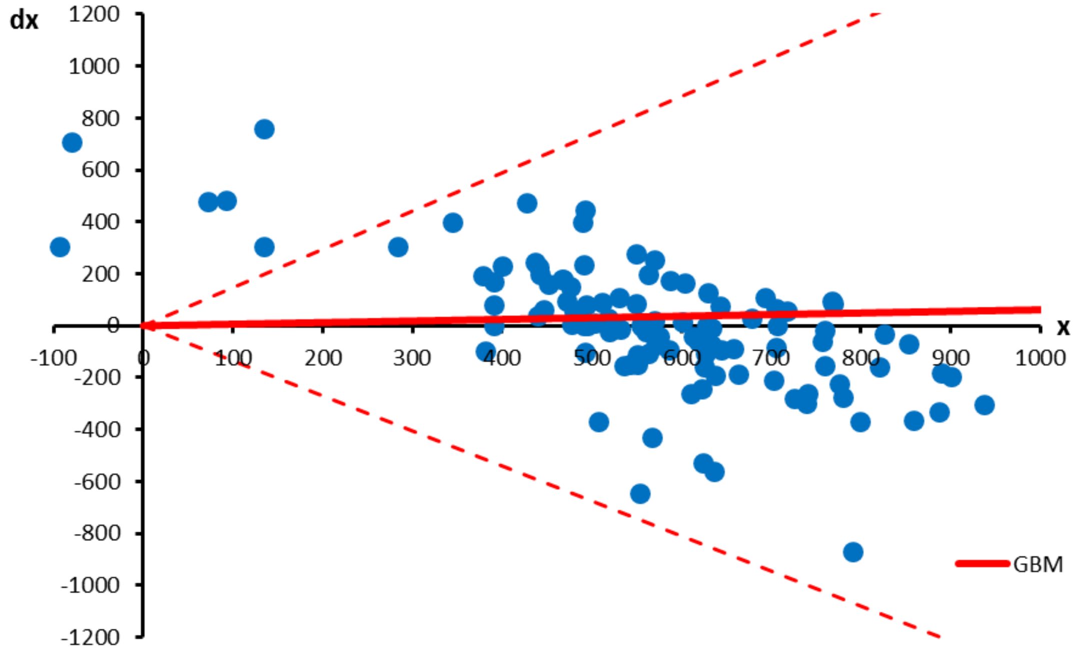

Figure 9: Estimation of wheat gross margins with GBM stochastic differential process

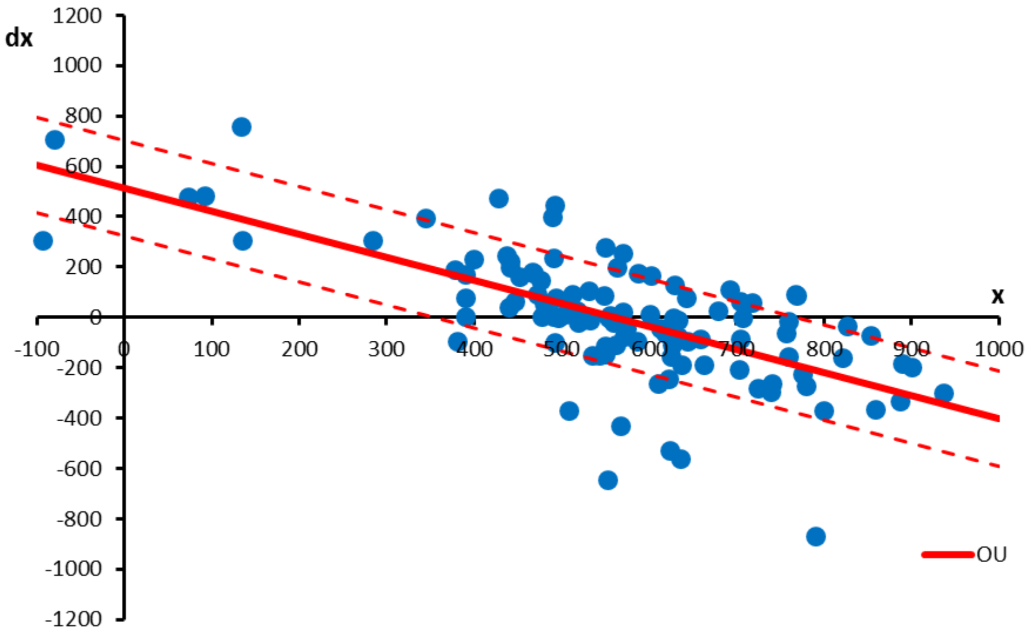

Figure 10: Estimation of wheat gross margins with OU stochastic differential process

Whether the GBM or OU process provides a more appropriate characterisation of the system can be seen immediately in Figures 9 and 10. The OU process fitted to the wheat gross margins data is more appropriate. We observe that agricultural systems tend to revert to equilibrium and do not grow exponentially.

We can also estimate the sheep gross margins at Clare, as presented in Figures 11 and 12. Again, the OU process appears to better characterise the dynamics of the system.

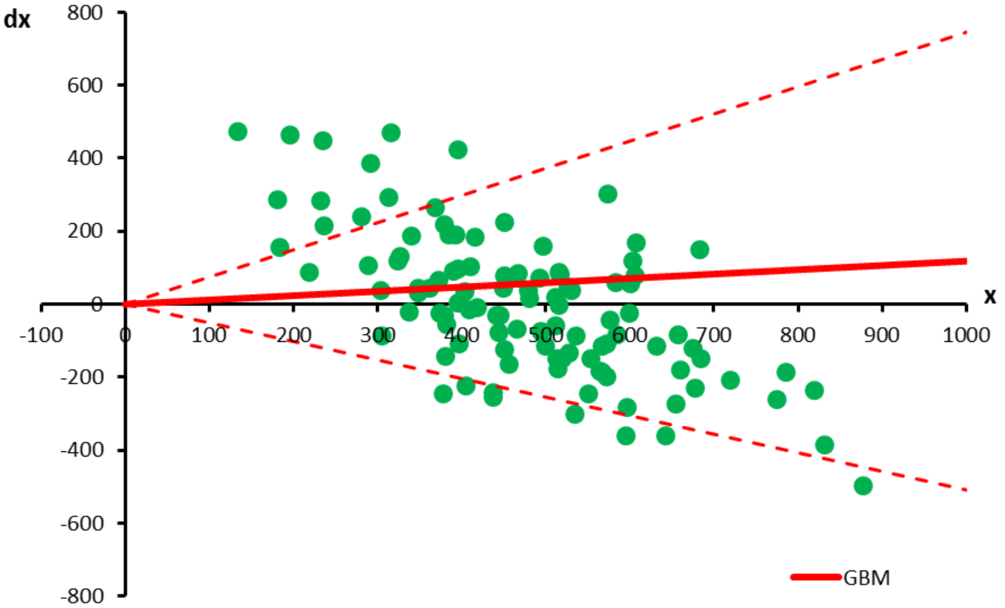

Figure 11: Estimation of sheep gross margins with GBM stochastic differential process

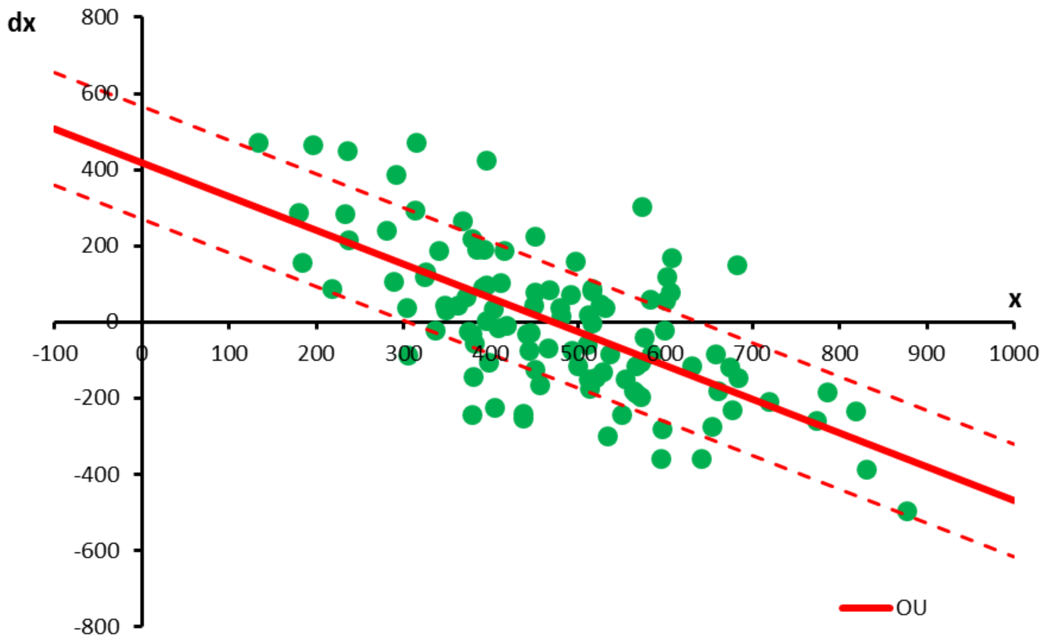

Figure 12: Estimation of sheep gross margins with OU stochastic differential process

2.2.3 Generating option values, identifying thresholds and estimating probabilities for transformations between regimes

After estimating the stochastic dynamic systems using GPS, we solve for the stochastic optimal choice of regimes using Itô stochastic control procedures (Hertzler 1991), as implemented in ROADs (Hertzler 2012b). We calculate the thresholds, option values and expected times until the optimal switches among regimes. Finally, using TRIPS, we calculate the probabilities of transformation of wheat dominant agriculture in Australia.

An option value is the price a farmer is willing to pay for flexibility. This can be explained with the following graphs of gross margins (Figure 13).

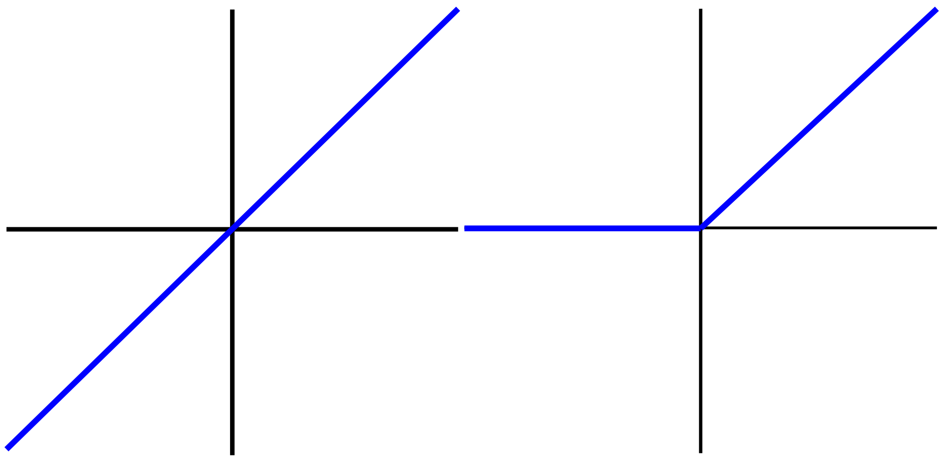

Figure 13: Gross margins with the obligation to continue and the option to exit

In the left panel, the gross margins are represented by the 45° line. In this case, the farmer is obligated to continue farming and can have both positive and negative gross margins, with no flexibility to avoid the negative gross margins. In the right panel, gross margins are represented by the 45° line for positive gross margins and zero otherwise. In this case, the farmer has the option to exit and avoid the negative gross margins. The payoff to the farmer of the option to exit is simply the gross margins in right panel minus the gross margins in left panel, or the losses avoided by exiting, as shown below (Figure 14).

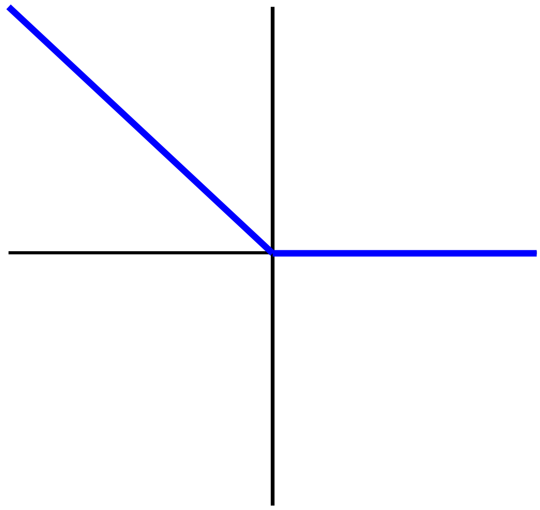

Figure 14: A farmer's payoff from the option to exit

Conversely, if a farmer is not yet committed, negative gross margins are automatically avoided, but positive gross margins can only be gained by entering into farming. This gives a payoff to the farmer from the option to enter as shown below (Figure 15).

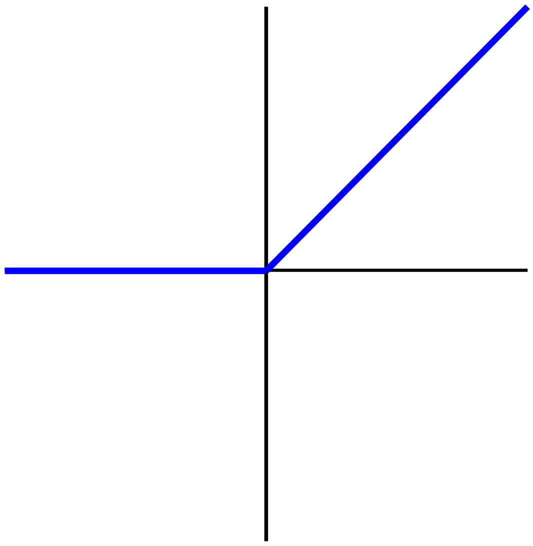

Figure 15: A farmer's payoff from the option to enter

Of course there is more to the decision than whether or not the gross margins are positive. To enter, a farmer must commit to investing in plant and equipment. Upon exit, some, but not all of this plant and equipment can be salvaged. Accounting for the plant and equipment per hectare shifts the payoffs to the right, as shown below (Figure 16).

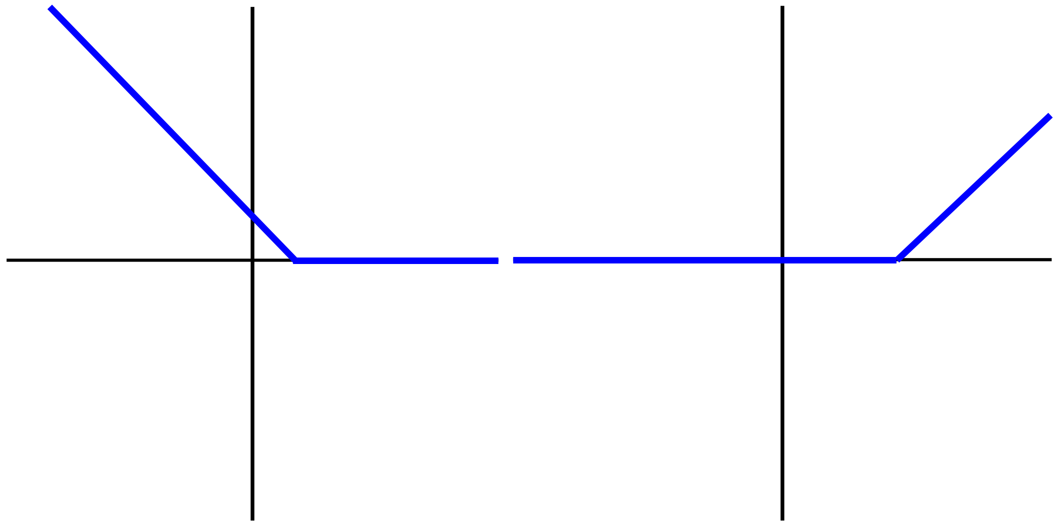

Figure 16: A farmer's payoffs with plant and equipment

Analogous to financial options, the option to exit in the left panel is a put option and the option to enter in the right panel is a call option. Also analogous to financial options, we have the following option pricing equations

(3) $$\frac{\partial w}{\partial t} - rw + \frac{\partial w}{\partial x} b\{\mu - x\} + \frac{1}{2}\frac{\partial^2 w}{\partial x^2}\sigma^2 = 0$$

(4) $$w\big(T, x(T)\big) = V\big(x(T)\big)$$

In equation (3), *w* is the option price, *x* is the gross margin, *r* is the interest rate and parameters b, μ and σ are from the Ornstein-Uhlenbeck process in equation (1). The first term in equation (3) is the shadow price of time. The second term is the opportunity cost of retaining the option instead selling it and putting the money in the bank. The third term is the value of an expected change in the gross margin. In this term, a shadow price multiplies the expected change to give a negative cost or a positive benefit. The fourth term is the risk premium. In this term, a shadow price for risk multiplies the variance. Together, the last two terms are the risk-adjusted capital gains from retaining the option. If the capital gains exceed the opportunity cost, the option price will increase. Otherwise it will decrease.

In equation (4), *V* is the payoff function. Unlike financial options, the options to exit and enter are perpetual options and can be held indefinitely or exercised at any time. The exercise time chosen by the farmer is *T*. If the option price exceeds the payoff function, the farmer will retain the option. If the payoff function exceeds the option price, the

farmer should exercise the option. The optimal exercise time occurs when the option price falls to just equal the payoff function.

As shown in the figures above, the payoff function is highly nonlinear with a kink. It is specified as

(5) $$V = \begin{cases} \chi[x(T) - k]; & \chi[x(T) - k] > 0 \\ 0 & \chi[x(T) - k] \leq 0 \end{cases}$$

In equation (5), χ is equal to +1 for the option to enter and -1 for the option to exit. The parameter k is either the annual cost of plant and equipment or the annual salvage value per hectare.

Of course, the entry and exit decisions are even more complicated than this. When a farmer enters a regime, the option to enter is destroyed but a new option is created—the option to exit. A farmer anticipates this will happen before deciding to enter. In other words, the payoff function for the option to enter also includes the value of the option to exit. To go further, upon exiting, the option to exit is destroyed and the option to enter another regime is created. The option value of the next regime must be included in the option value to exit from this regime, and so on in a sequence of regimes. In summary, we must find an optimal sequence of perpetual options.

We have to assume, however, that there is a last regime and a complete exit from farming with the money put in the bank. We solve for the exit from this last regime using the payoff function in equation (5). Of course we hope the answer to the question "When do I exit the last regime?" is "Never." For the entry into the last regime, we use a more complicated payoff function

(6) $$V = w_f\left(x_f(T_f)\right) + \begin{cases} \chi[x(T) - k]; & \chi[x(T) - k] > 0 \\ 0 & \chi[x(T) - k] \leq 0 \end{cases}$$

In equation (6), w_f is used to denote the value of future options. For the entry into the last regime, this is just the option value of exiting. For earlier regimes, w_f is the value of all future options. In this way, a sequence of regimes is modelled.

The farmer may switch between regimes at any time *T*. In other words, we must find the optimal stopping time for each regime. Unfortunately, the option prices are poorly behaved. The discount rate reduces the option prices. Uncertainty and the nonlinear payoffs increase the option prices. At the optimal time, the conflict is most intense, creating waves in the option prices. There are many local maximums and minimums and the usual methods of optimising will not work. Instead, finding the optimal stopping time 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 gross margins.

Step 2: Assume the gross margin is fixed and search for the largest option price for that particular gross margin. Make note of the expected time before the switch.

Step 3: Repeat step 2 for all possible gross margins and identify the gross margin where the largest option price is no longer greater than the payoff function.

Step 1 requires the most work, sometimes considerable work. The option pricing equation is solved using finite difference methods because there are no analytical solutions for the sequence of entry and exit options as farmers switch from one regime to another. Step 1 creates a large table which is searched in Step 2. Repeating Step 2 creates a small table of all expected times. The small table is searched in Step 3 to find the threshold at which the farmer will choose to switch.

Finally, TRIPS calculates the probabilities of transformation from one regime to another. In our example, these probabilities are determined by the Ornstein-Uhlenbeck process in equation (1). Its transition density function is:

$$(7) \qquad f(s,x,t,y) = \left\{\frac{b^{0.5}}{\pi^{0.5}\sigma(1-e^{-2b(t-s)})^{0.5}}\right\} e^{-b\left\{\frac{\left[(y-\mu)-(x-\mu)e^{-b(t-s)}\right]^2}{\sigma^2(1-e^{-2b(t-s)})}\right\}}$$

In this equation, *f* is the probability density function, *s* is the present time, *x* is the present gross margin, *t* is some time in the future, and *y* is a random gross margin which can occur at time *t*. The parameters *b*, μ and σ are determined by the estimation of the stochastic differential equation using GPS.

As time *t* gets large, the transition density converges to the invariant density.

$$(8) \qquad f(y) = \left\{\frac{b^{0.5}}{\pi^{0.5}\sigma}\right\} e^{-b\left\{\frac{(y-\mu)^2}{\sigma^2}\right\}}$$

If parameter *b* was set to 0.5, this would be the more familiar normal density. The cumulative transition probability distribution is the integral of the density.

$$(9) \qquad F(s,x,t,y) = \int_{-\infty}^{y} f(s,x,t,v)dv$$

If *y* in equation (9) is set equal to the threshold for switching, then *F* is the probability of being below the threshold and 1-*F* is the probability of being above the threshold. We call these the transformation probabilities. If we are exiting a regime, *F* is the probability of crossing the threshold. Conversely, if we are entering a regime, 1-*F* is the probability of crossing the threshold.

As time *t* gets large, the transition probability distribution also converges to an invariant probability distribution.

$$(10) \qquad F(y) = \int_{-\infty}^{y} f(v)dv$$

In equilibrium, *F* is the equilibrium probability of being below the threshold and 1-*F* is the equilibrium probability of being above the threshold.

Geometric Brownian Motion in equation (2) also has a known transition density.

$$(11) \qquad f(s,x,t,y) = \left\{\frac{1}{2^{.5}\pi^{0.5}\sigma(t-s)^{0.5}}\right\} e^{-0.5\left\{\frac{\left[ln(y/x)-\left(\alpha-0.5\sigma^{0.5}\right)(t-s)\right]^2}{\sigma^2(t-s)}\right\}}$$

It has a transition probability distribution, as in equation (9), but it is non-stationary, does not converge toward equilibrium and has neither an invariant density nor an invariant probability distribution.

We can illustrate the application of ROADs and TRIPS by following on with our example of Clare and considering two situations. First, let us consider the situation where we currently hold land in Clare with an option to enter wheat production, but also have the option to exit again. We can employ the parameters we estimated from the Ornstein-Uhlenbeck process fitted to the wheat gross margins data in Figure 10. Inputting these parameters into ROADs we can calculate an option value for entry and the threshold which must be crossed in order to enter wheat production. These values are summarised in Figure 17. The option value *w* for entry with the possibility to exit is \$240/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 future gross margins, they will have to exit again. At the corresponding entry threshold the gross margin is \$550/ha. The first time the farmer observes gross margins greater than \$550/ha they will commit to wheat production.

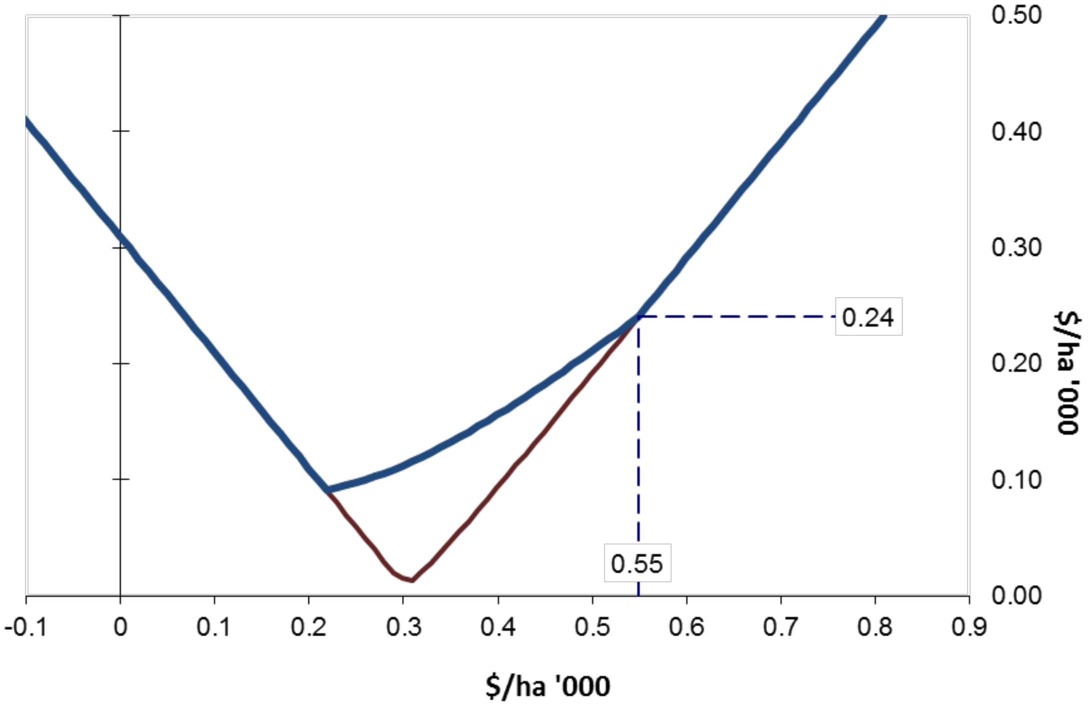

Figure 17: Option value and threshold - Clare entry into wheat with possibility to exit

Associated with the threshold of $550/ha are the transformation probabilities, shown in Figure 18. For illustration, suppose the current gross margin is zero. This is shown by the vertical line. Because the current gross margin is far below the threshold, there is no chance of crossing the threshold immediately and little chance of crossing the threshold in the next one or two years. After about 5 years, the transition probabilities converge to the invariant distribution. For the invariant distribution, the probability of being below the threshold in any year is 47%, giving a probability of being above the threshold in any year of 53%. With such high odds, the farmer will surely enter into wheat, if not this year, then soon.

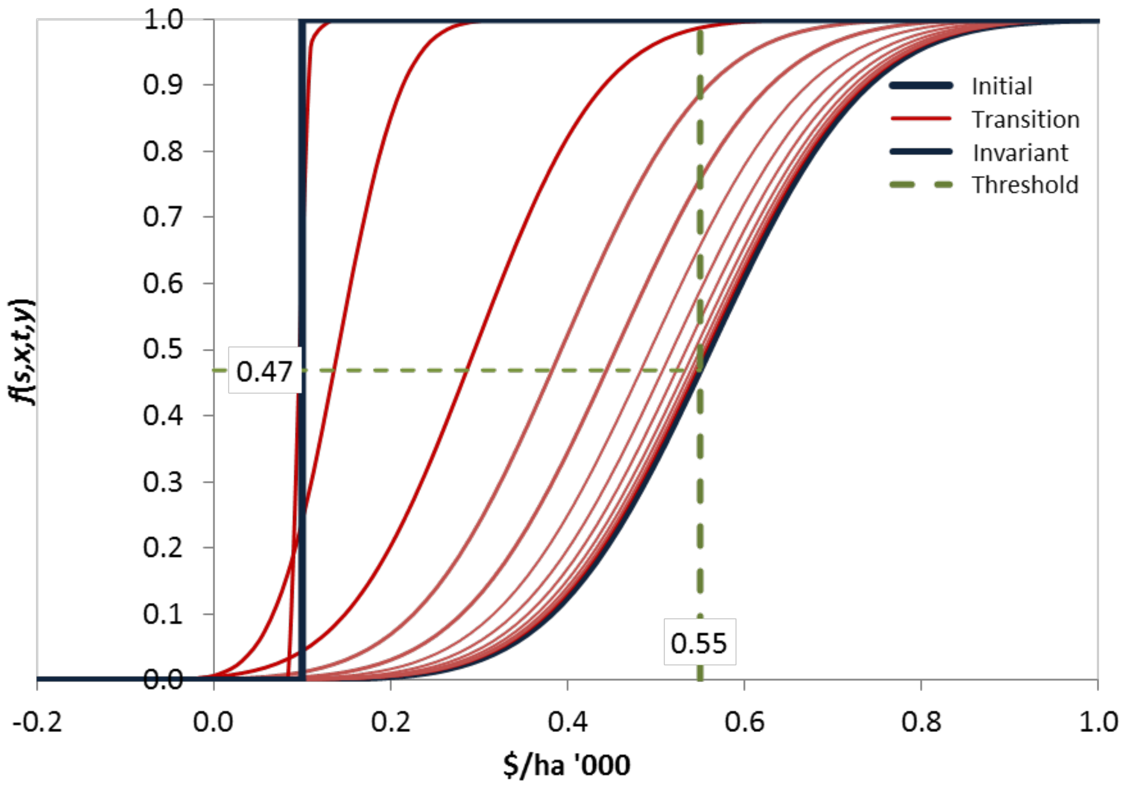

Figure 18: Transformation probability – Clare entry into wheat with possibility to exit

A second situation may be where the farmer is currently in wheat dominant agriculture, and is considering the option to exit and enter into sheep grazing. Performing the same procedure in ROADs, although this time adding the option values for sheep to the payoff for wheat, we get the result summarised in Figure 19. The option value to exit wheat cropping and enter into sheep grazing is $200/ha. We interpret this as the farmer's willingness to lose money on wheat cropping before finally committing to enter sheep grazing. At the corresponding exit threshold of $180/ha the farmer will finally commit to exit. The transformation probabilities for the threshold of $180/ha are shown in Figure 20. For illustration, the initial gross margin is set to zero. This is below the threshold and the farmer would exit wheat and enter merinos. But this is a highly unlikely situation. Looking at the invariant distribution, over the medium term of 5 years, there is virtually no chance of being below the threshold. The probability is 0.0033 or 0.33%. This gives us an indication that the wheat regime at Clare is very resilient and seeing merinos on the landscape would be an extremely rare event.

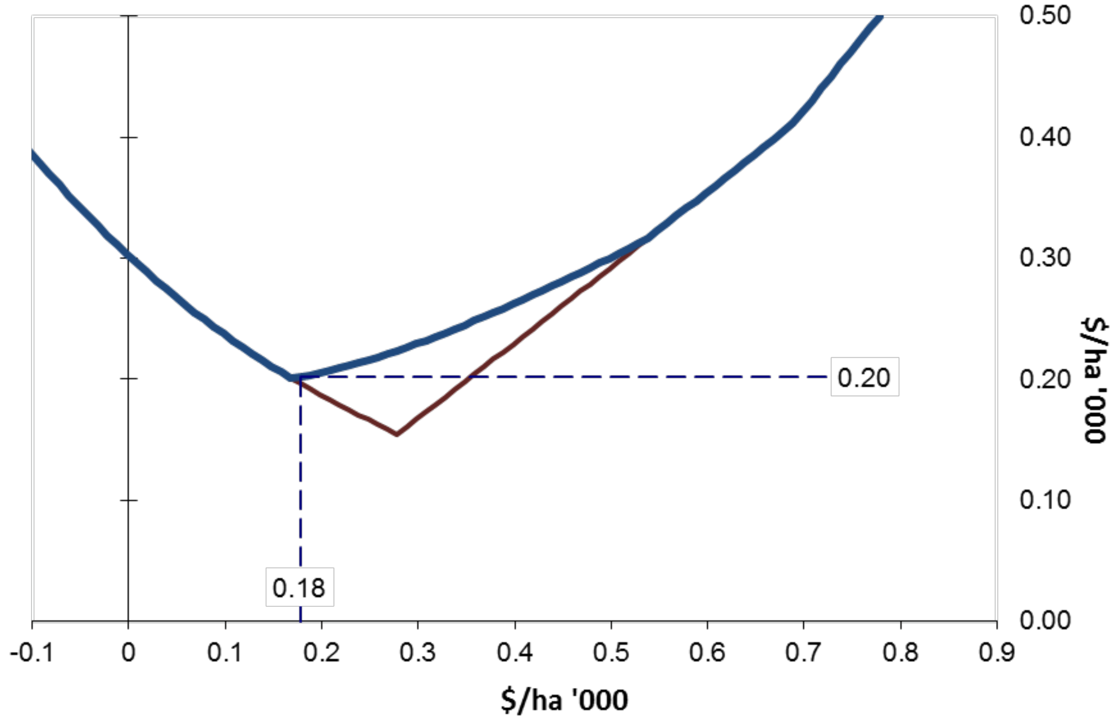

Figure 19: Option value and threshold - Clare exit from wheat and enter into merinos

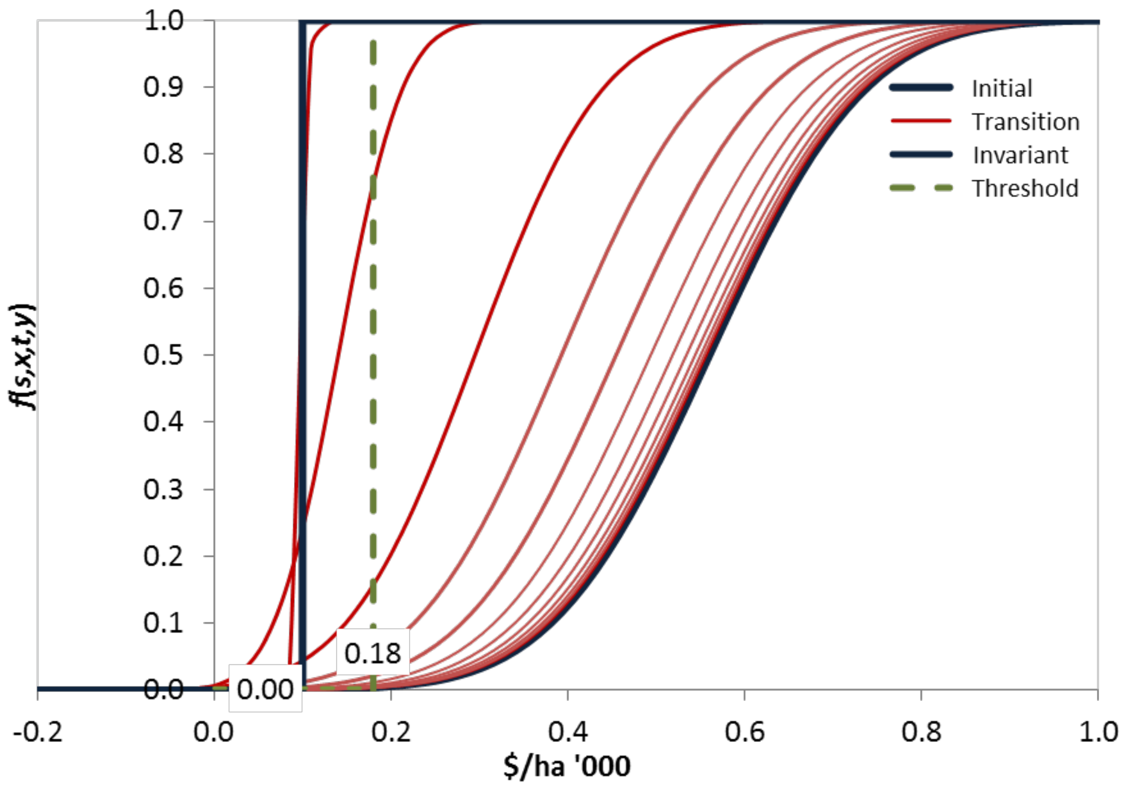

Figure 20: Transformation probability – Clare exit from wheat and enter into merinos

We now use GPS, ROADs and TRIPS to evaluate the transformation of agricultural systems in response to climate change for case studies in South Australia, New South Wales and Western Australia.

3. RESULTS AND OUTPUTS

3.1 South Australia

The edge of the Australian grain belt, where wheat cropping gives way to extensive grazing, is an interesting economic and ecological margin. While margins exist in the majority of growing regions around the world, there are few that rival the well documented identification of the South Australian margin, known as Goyder's Line. Mapped in the 1860s this line has traditionally been viewed as a demarcation for the suitability of land for cropping or extensive grazing. The general pattern is to move from relatively reliable high to medium rainfall cropping land near the coast to low rainfall with extensive grazing and desert as we cross Goyder's Line in the north (French 1993; Reyenga *et al.* 2001; Hayman *et al.* 2010; Nidumolu *et al.* 2012). However, in some regions cropping has extended north of the line and in other regions cropping south of the line is only practiced when seasons permit.

The farming systems employed in South Australia vary greatly due to social and practical influences. Hayman *et al.* (2010) note that higher rainfall in the south is characterised by a predominance of relatively high risk and high return crops such as canola and pulses, with an increasing proportion of cereal with lower inputs and then grazing enterprises with opportunity cropping in the north. The wheat cropping season in South Australia runs from May to October in a Mediterranean climate with a high concentration of annual rainfall in the winter seasons and dry summers. The two main factors for rainfall in the region are distance from the western coast and topography, especially in the central region (Hayman *et al.* 2010).

Duplex soils make up most of the wheat growing areas of South Australia and are typically used for cereals and grazing on improved pastures in the upper South-East and Eyre Peninsula. Hard red duplex soils are among the most important agricultural soils; the expanse of which approximately defined the limits of the wheat belt in the nineteenth century (Government of South Australia 2012). Hard red duplex soils dominate the Eastern and Lower Eyre Peninsula as well as the Upper North, Mid North and Lower North, Upper South East and Lower South East zones (Northcote *et al.* 1968). The remainder of the wheat growing areas have a combination of sandy soils and calcareous earths which have low to moderate fertility but are easy to cultivate and their productivity for cereals in the agricultural regions has been greatly enhanced through the application of fertilisers and the use of medic pasture rotations (Government of South Australia 2012).

In our analysis of South Australia we employ the temporal-spatial analogues approach (Hayman *et al.* 2010) to model transitions in farming regimes driven by climate changes. This approach recognises that currentbroad acre production zones transcend rainfall isohyets and the position of farms within the pattern of isohyets is a good predictor of the prevailing farming activity. The partial map of South Australia reproduced in Figure 21 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, with a steady increase moving in a southerly direction towards Clare. The different marks on the map show where Goyder's Line would shift 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 this 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 growing season rainfall (GSR), then the experience at, say, Clare on our transect may be modelled by examining the current optimal decisions at Orroroo, where Orroroo currently has 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 already marginal lands in the north and push these activities south. The challenge is to identify when the future of Clare becomes sufficiently like the present at Orroroo and the future at Orroroo becomes sufficiently like the present at Hawker for farmers to transform agriculture in these locations.

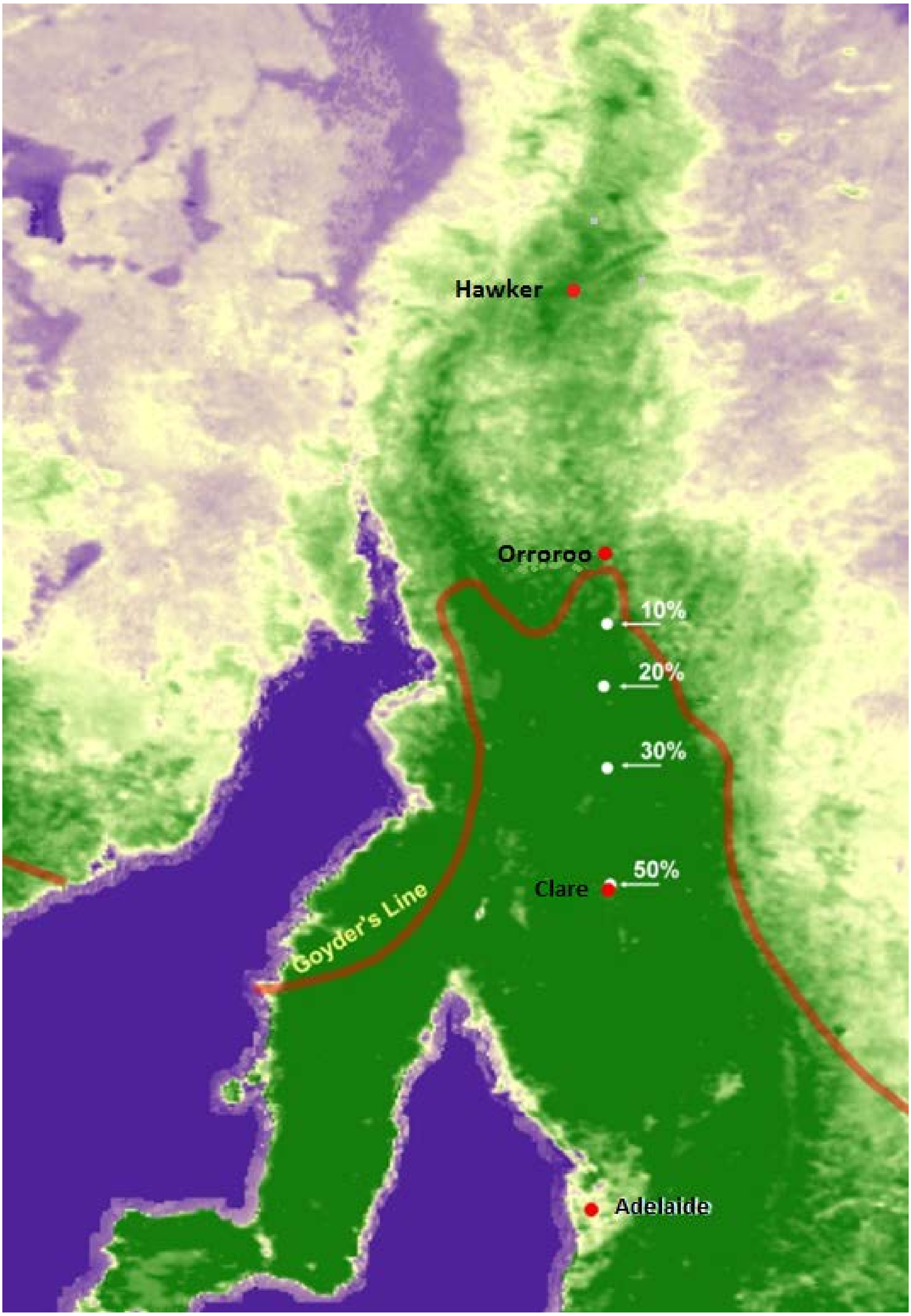

Figure 21: Normalised Vegetation Index of a transect of rainfall from Clare to Orroroo with an indication of points that are 10%, 20%, 30% and 50% wetter than Orroroo (diagram provided by Uday Nidumolu SARDI/CSIRO)

Table 1: Summary of key characteristics along 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.

To focus on transformations of agriculture north and south of Goyder's Line, 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 assume that wheat cropping is Australian prime white (APW) wheat and the grazing activity is merino wethers primarily for wool production.

3.1.1 Characteristics of wheat cropping along the study transect

To simulate wheat cropping we use APSIM (McCown *et al.* 1996). Simulated wheat yields are generated using daily climate data from 1900 to 2007 across the three sites of the study transect, assuming consistent soil of calcareous sandy loam over clay, with a plant available water capacity (PAWC) of 70mm. In these simulations, the yields are limited by nitrogen rates. With unlimited nitrogen the yields at Clare would be higher in favourable years. Figures 22, 23 and 24 present the APSIM results for Clare, Orroroo and Hawker. Because APSIM holds constant all other inputs and technologies, the pattern of variability is driven exclusively by the timing and magnitude of weather events, primarily rainfall.

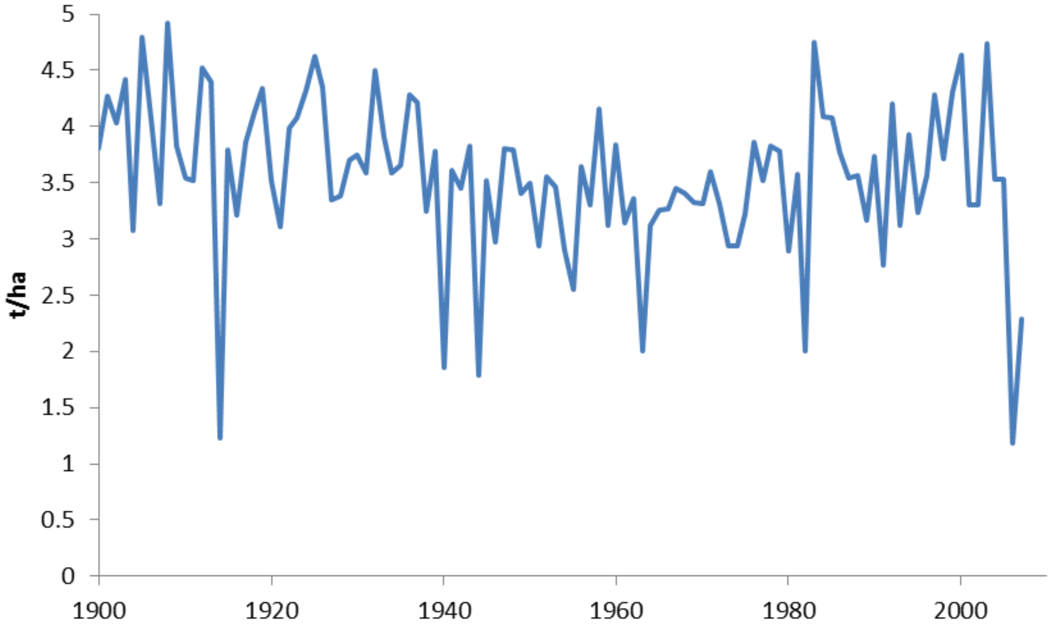

Figure 22: Simulated wheat yields at Clare (t/ha)

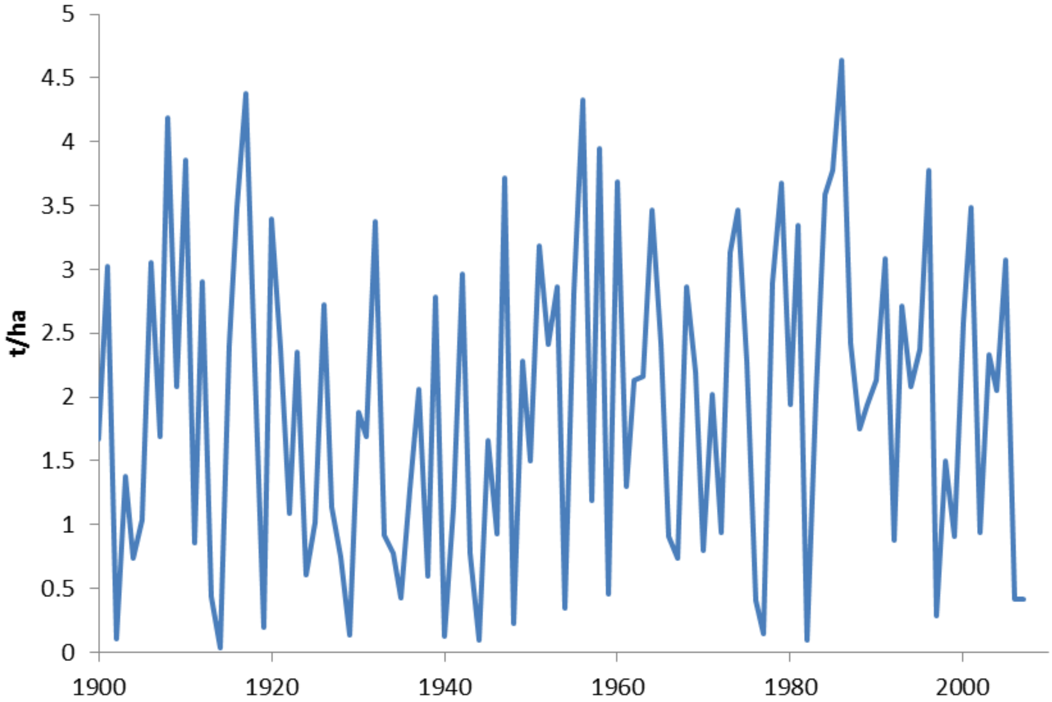

Figure 23: Simulated wheat yields at Orroroo (t/ha)

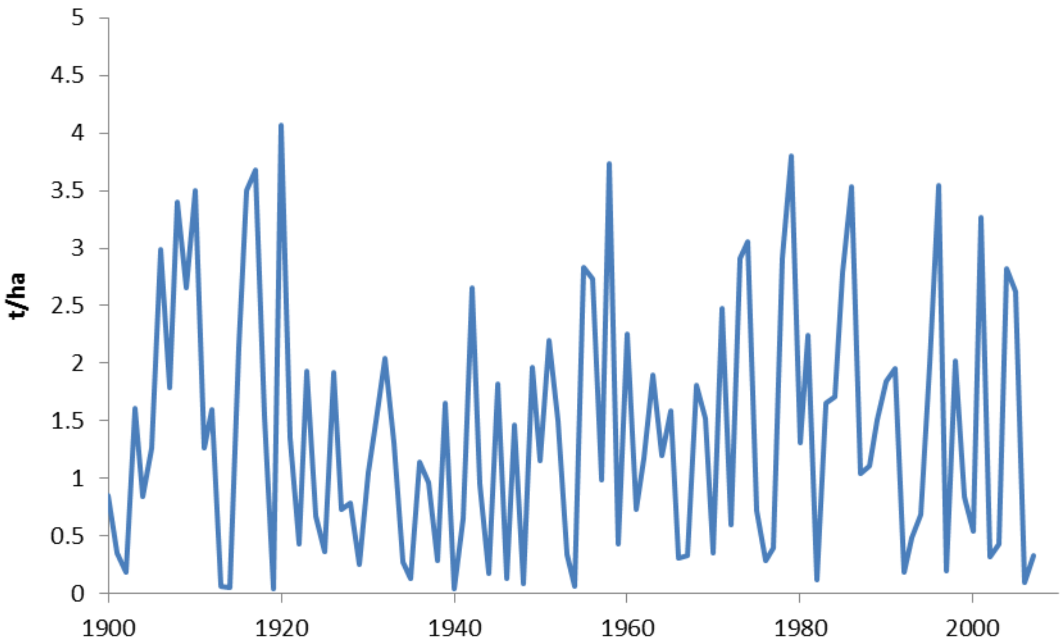

Figure 24: Simulated wheat yields at Hawker (t/ha)

From each of these series, we can calculate a corresponding series of gross margins by employing the assumptions outlined in Table 2. Table 2 reports input cost assumptions which vary depending upon the nature of the season. This recognises that there are some costs which may be avoided (*e.g.*, harvest costs) if the wheat crop should fail to reach a minimum tonnage per hectare. The price of wheat in Australian dollars is assumed to be $275/t (Rural Solutions 2012), reflecting an average of the preceding five years of prices excluding freight and other post production costs.

Table 2: Variable costs parameters for wheat cropping

Parameter	Value
Variable costs:	
Clare ($ per ha)	417.00 (all t/ha)
Orroroo, Hawker ($ per ha)	85.14 (0 – 0.2 t/ha)
	87.42 (0.2 – 0.6 t/ha)
	91.84 (0.6 – 1.2 t/ha)
	105.26 (1.2 – 1.8 t/ha)
	112.75 (>1.8 t/ha)
Wheat value ($ per tonne)	275

(Source: Rural Solutions 2012)

3.1.2 *Characteristics of sheep grazing systems along the study transect*

The productivity dynamics of sheep grazing systems along the transect are assumed to be driven by growing season rainfall (Assang *et al.* 2012). In rainfall limited grazing environments, this turns out to be a surprisingly reasonable assumption. Assang *et al*. (2012) explore the ability of seasonal forecasts to improve stocking rate decisions in the 'Mediterranean' farming systems of Western Australia. They use the relationship estimated by Bolger and Turner (1999) between growing season rainfall and pasture growth.

$$(12) \qquad P = 0.03\{GSR - 30\}$$

Where *P* is pasture grown in metric t/ha and *GSR* is growing season rainfall in mm (May-October). This equation predicts that 0.03 t/ha of pasture is grown for each mm of GSR above 30 mm. From Wooldridge *et al*. (2005) the potential stocking rate (SR) in dry sheep equivalents (DSE) is given by the relationship:

$$(13) \qquad SR = 2\{P - 1.5\}$$

A DSE is the feed requirement of a two year old merino sheep to maintain its weight. Different types of livestock will have a different DSE value, and so the capacity of the land to carry different types of livestock will vary. For merinos, *SR* is 2 for every t/ha of pasture grown above 1.5 t/ha. The similarity of the West Australian and South Australian agro-ecosystems lets us derive estimates of stocking rates for Clare, Orroroo and Hawker. Consequently, we can estimate the gross margins for merino wethers using the variable costs and production parameters presented in Table 3.

Table 3: Variable cost and production parameters for merino wether grazing

Parameter	Value
Breed	Merino wethers
Standard reference weight (kg)	55
Greasy fleece weight (kg)	7.5
Fibre diameter (micron)	21
Death rate – Adults (% per year)	3
Merino DSE	1.2
Variable cost ($ per sheep)	36
Wool value (cents per kg)	840
Wether value ($ per sheep)	95

(Source: Rural Solutions 2012)

Gross margin series are shown in Figures 25, 27 and 29, and associated phase diagrams in Figures 26, 28 and 30 for Hawker, Orroroo and Clare, respectively. Estimates from the phase diagrams will later become the stochastic differential equations required for calculating the options values.

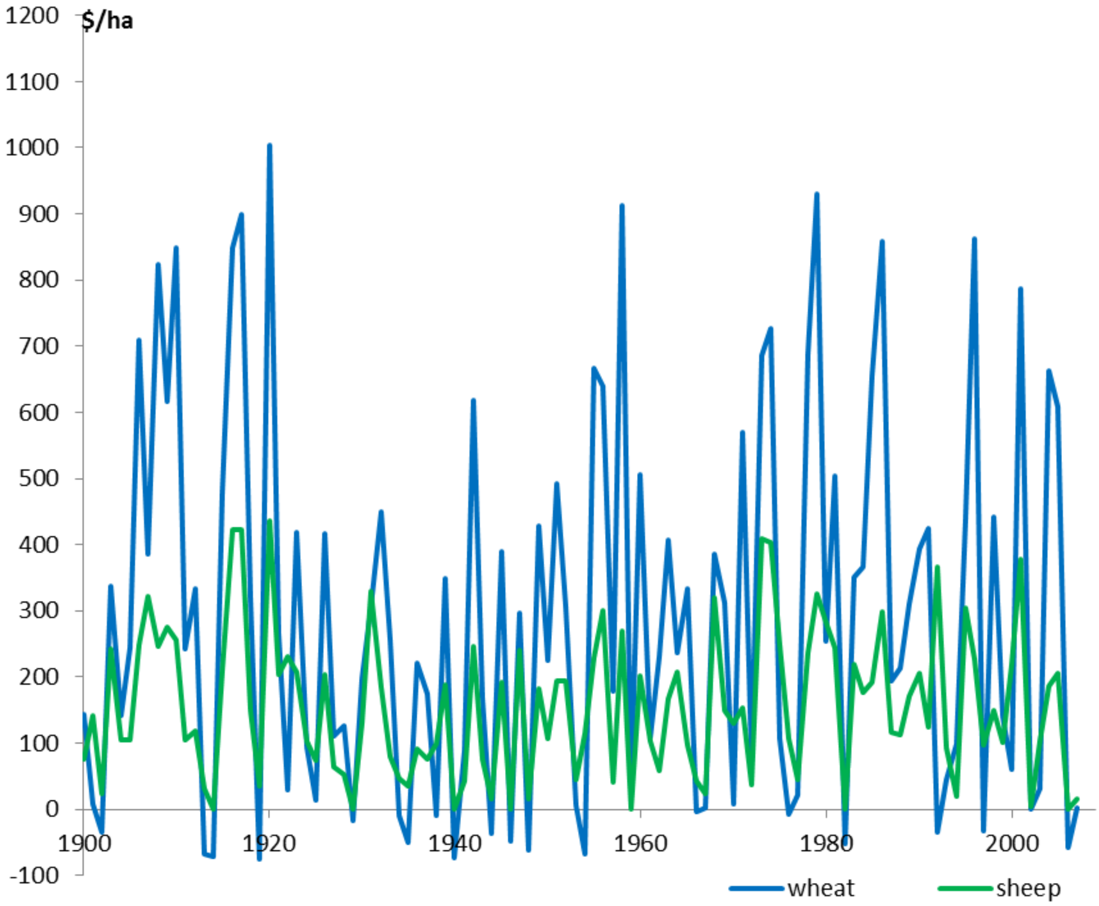

Figure 25: Hawker wheat and sheep gross margins ($/ha)

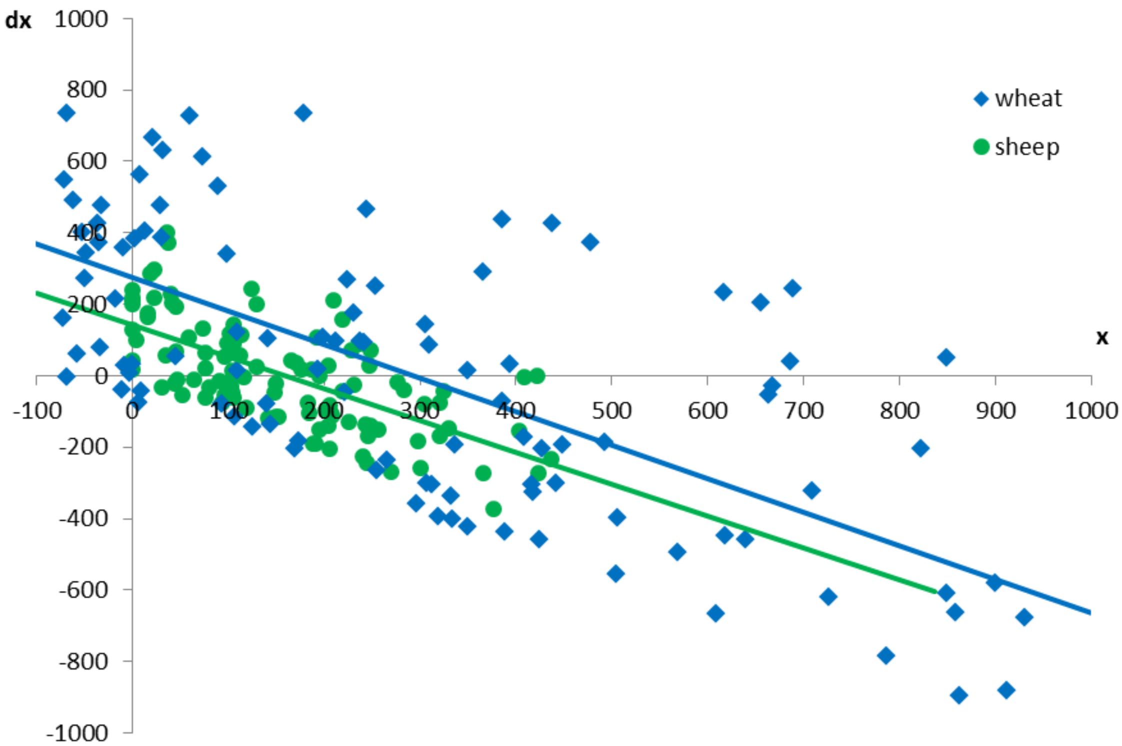

Figure 26: Hawker gross margin phase diagram ($/ha)

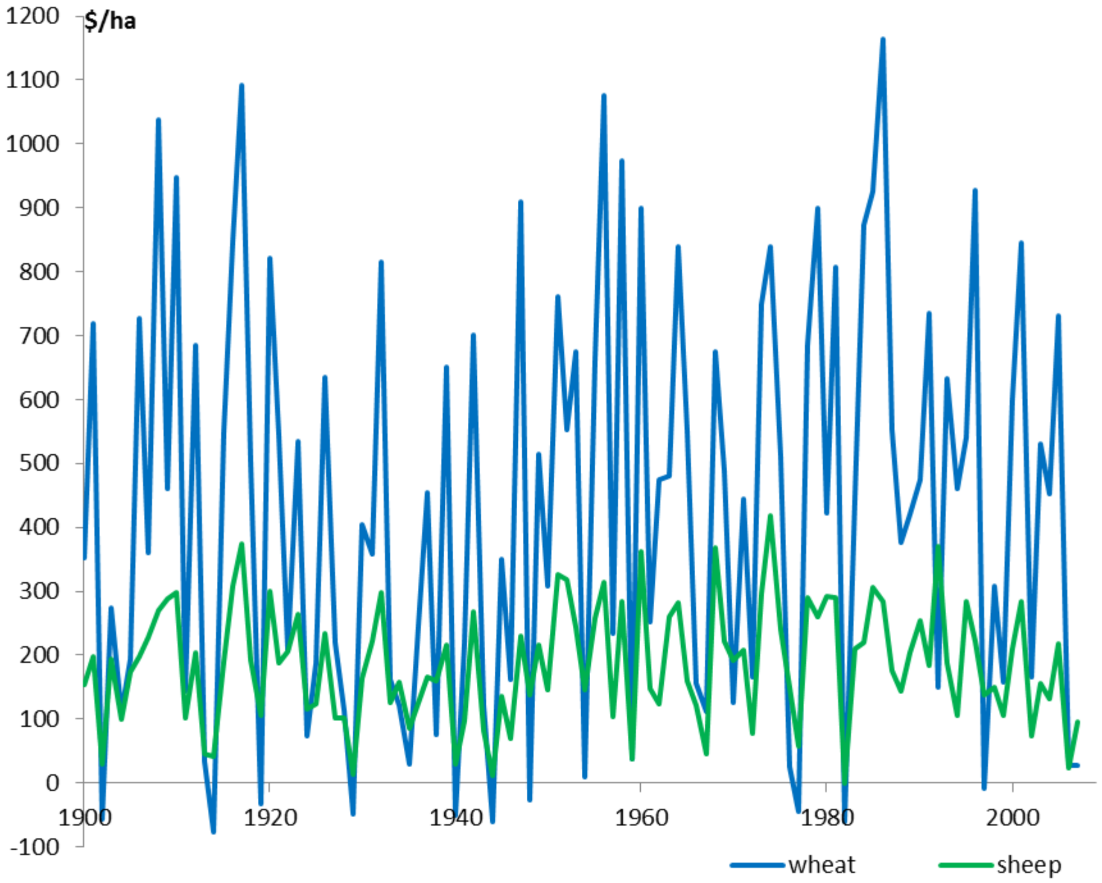

Figure 27: Orroroo wheat and sheep gross margins ($/ha)

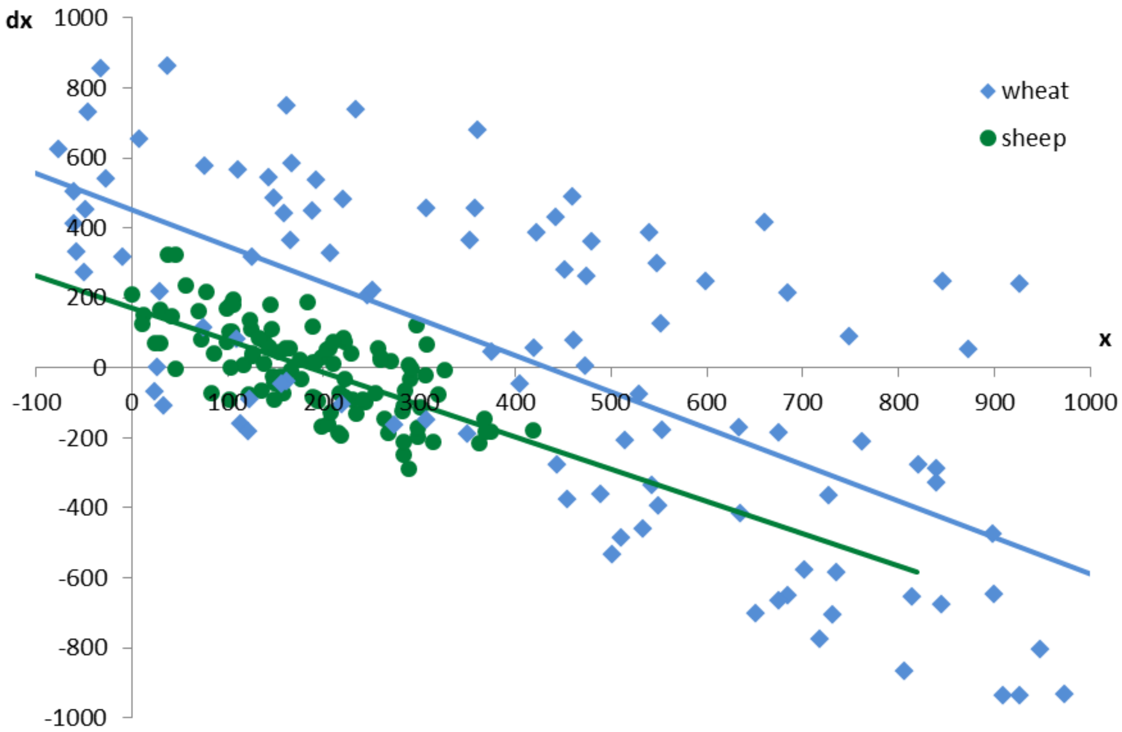

Figure 28: Orroroo gross margin phase diagram ($/ha)

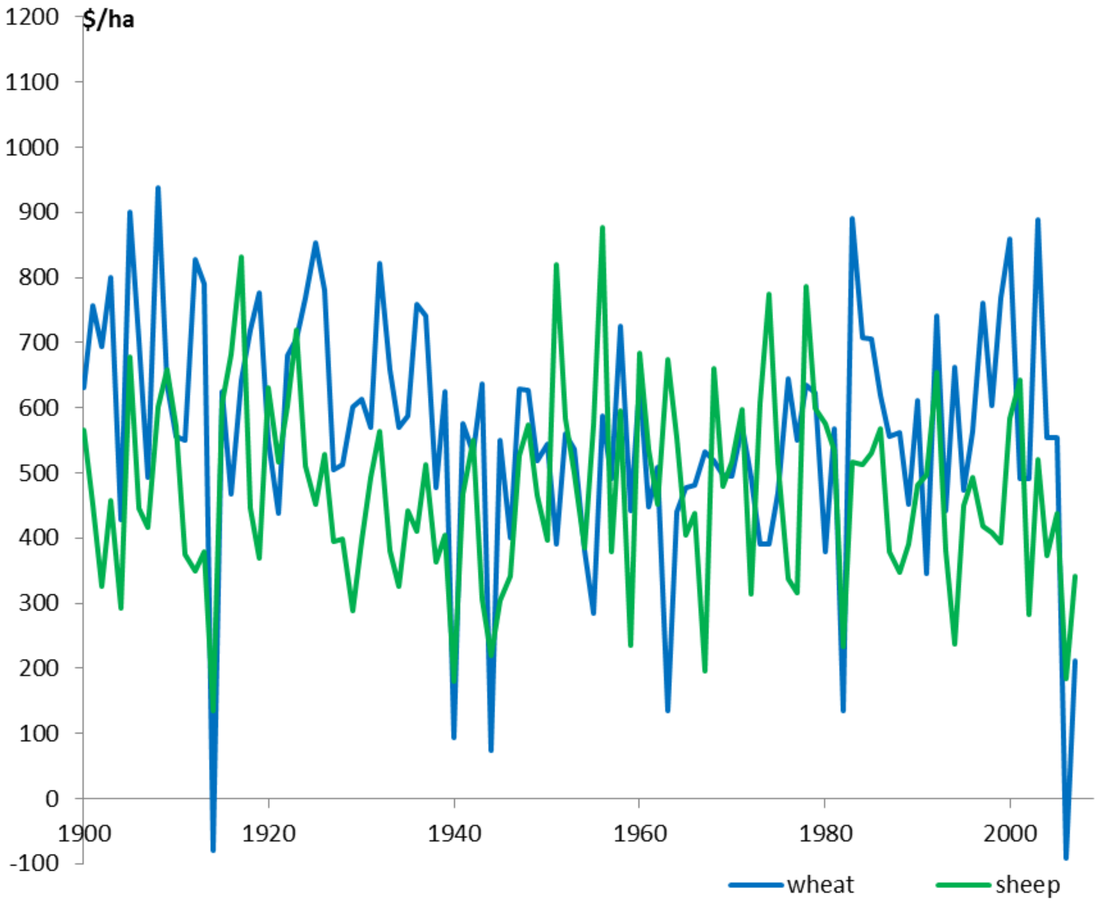

Figure 29: Clare wheat and sheep gross margins ($/ha)

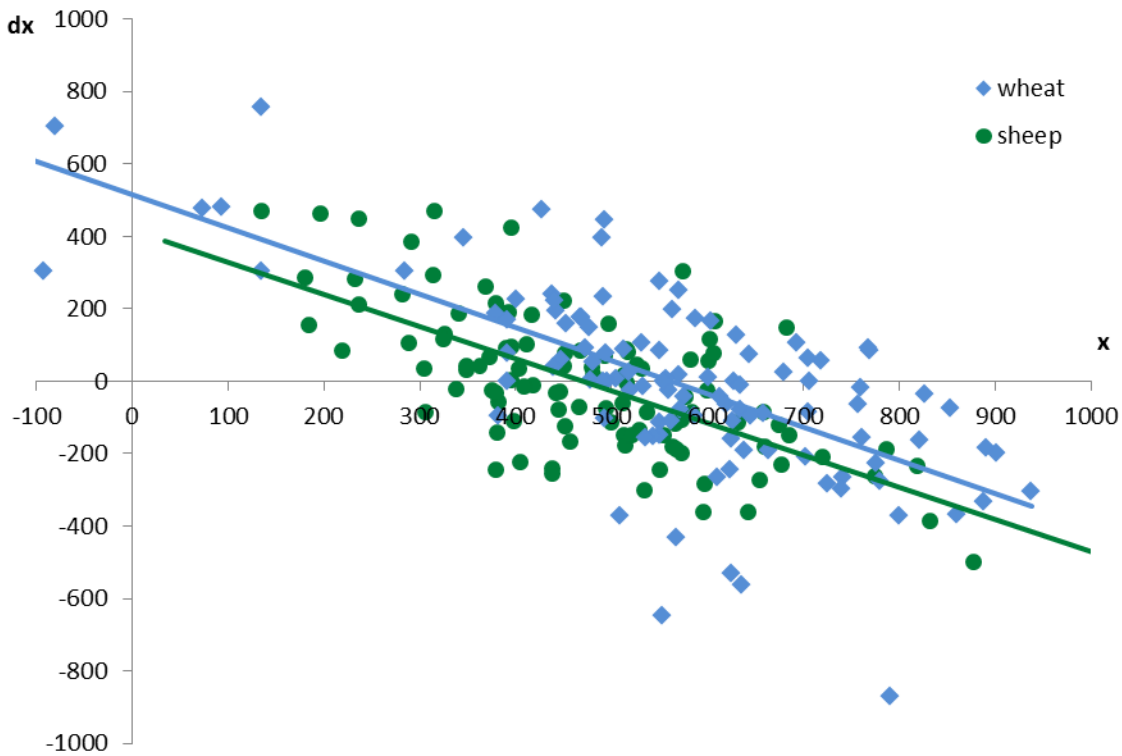

Figure 30: Clare gross margin phase diagram ($/ha)

Table 4 reports the estimated parameters of the Ornstein-Uhlenbeck process for Clare, Orroroo and Hawker.

Table 4: Estimated Ornstein-Uhlenbeck parameters for gross margins ($/ha)

Activity	Parameter	Clare	Orroroo	Hawker
Wheat	b	-0.916	-1.038	-0.940
	μ	560.90	432.60	293.00
	σ	189.30	328.20	291.70
	σ/μ	0.3375	0.7587	0.9956
Merino Grazing	b	-0.887	-0.923	-0.891
	μ	471.60	186.60	157.60
	σ	147.90	93.50	111.90
	σ/μ	0.3136	0.5011	0.71000

These estimated parameter give insights into the nature of the production systems at each of the sites along the transect. We may interpret μ as the mean attractor. For

instance, at Clare the value of μ is 560.90 and, for any given year, the expected gross margin is $560.90/ha. Moving along the transect towards less favourable growing conditions, Orroroo has an average gross margin of $432.60/ha and Hawker $293.00/ha. We can also calculate the ratio of the deviation in the gross margin to the average gross margin to find the relative riskiness of production. In Clare, σ/μ has a value of 0.3375, and at Orroroo and Hawker has values of 0.7587 and 0.9956 respectively. Clare is the least risky system followed by Orroroo and Hawker. Indeed, at Hawker a value close to 1 implies substantial risk. To compare these measures to the more familiar coefficient of variation from a normal distribution, they can be multiplied by approximately 0.7. Agricultural production at Hawker is extremely risky.

We may interpret the estimated parameters for merino grazing in a similar manner. At Clare merino grazing is less profitable than wheat and about as risky. At Orroroo and Hawker, merino grazing is less profitable than wheat, but also less risky.

3.1.3 Results

Applying ROADs and TRIPS to these estimated parameters, we examine four decision problems. 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 results are presented in Table 5, for the option value *w*, the regime threshold *x*, the expected waiting time at the threshold *T*-*t*, and the probability of transformation from one regime to another P_{trans}.

For example, the first decision in Table 5, ‘Entry into wheat with the possibility to exit’, is the switch from leaving money in the bank to investing in the growing of wheat. Growing wheat is more risky and the switch will not happen immediately. The results in Table 5 indicate that we will wait until we observe a threshold gross margin (*x*) of $549.0/ha before committing to produce wheat and we are willing to pay an option value (*w*) in forgone potential earnings of $240.3/ha while we wait to be sure the threshold gross margin will occur. The short expected waiting time at the threshold (*T*-*t*) of 0.041 years indicates that once we observe a gross margin of $549.0/ha we will get in as soon as feasibly possible. The probability of transformation (P_{trans}) is 0.5336, which indicates that within about a 5 year time frame there is a 53.36% chance of finding ourselves having crossed the threshold and switched to wheat production at Clare. This decision is also represented graphically in Figures 31 and 32. Figures 33 and 34 represent the decision to exit wheat and enter merino grazing.

Table 5: Estimated option values ($/ha), threshold values ($/ha), expected times until exercise (years) and transformation probabilities

Decision	Parameter	Clare	Orroroo	Hawker
Enter into wheat and possibly exit	w	240.3	211.2	169.6
	x	549.0	497.0	447.0
	T-t	0.0410	0.5000	0.5000
	P_{trans}	0.5336	0.3899	0.2368
Exit from wheat and enter merinos	w	201.9	161.3	161.6
	x	178.0	128.0	128.0
	T-t	0.5000	0.5000	0.5000
	P_{trans}	0.0033	0.0930	0.2213
Enter into merinos and possibly exit	w	410.7	142.1	121.7
	x	442.0	172.0	152.0
	T-t	0.2620	0.5000	0.5000
	P_{trans}	0.6041	0.5832	0.5264
Exit from merinos	w	5.3	5.5	12.6
	x	29.0	29.0	19.0
	T-t	0.0520	0.1310	0.1480
	P_{trans}	0.0000	0.0117	0.0507

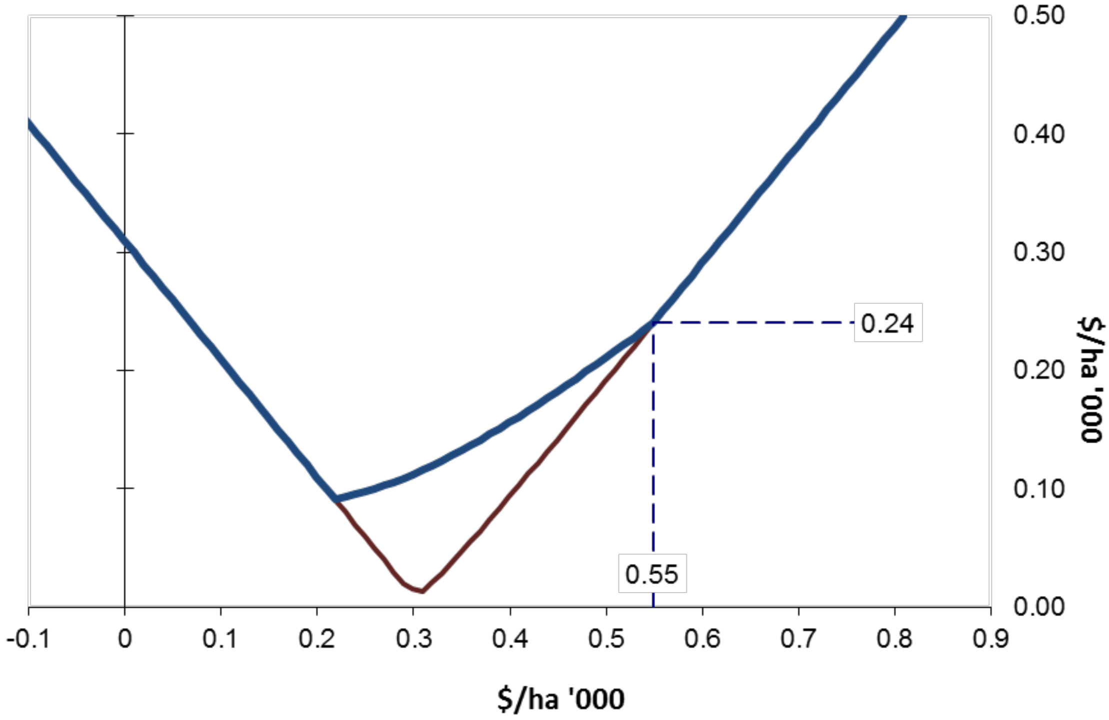

Figure 31: Option value and threshold - Clare enter into wheat and possibly exit

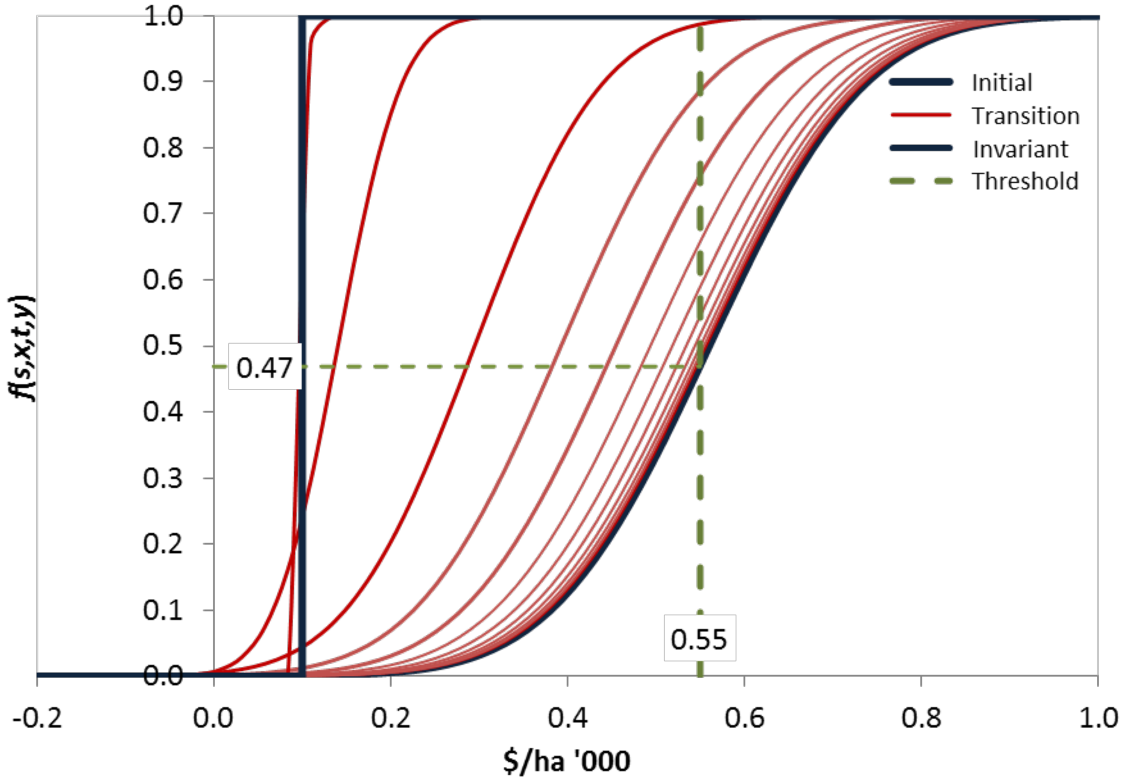

Figure 32: Transformation probability – Clare enter into wheat and possibly exit

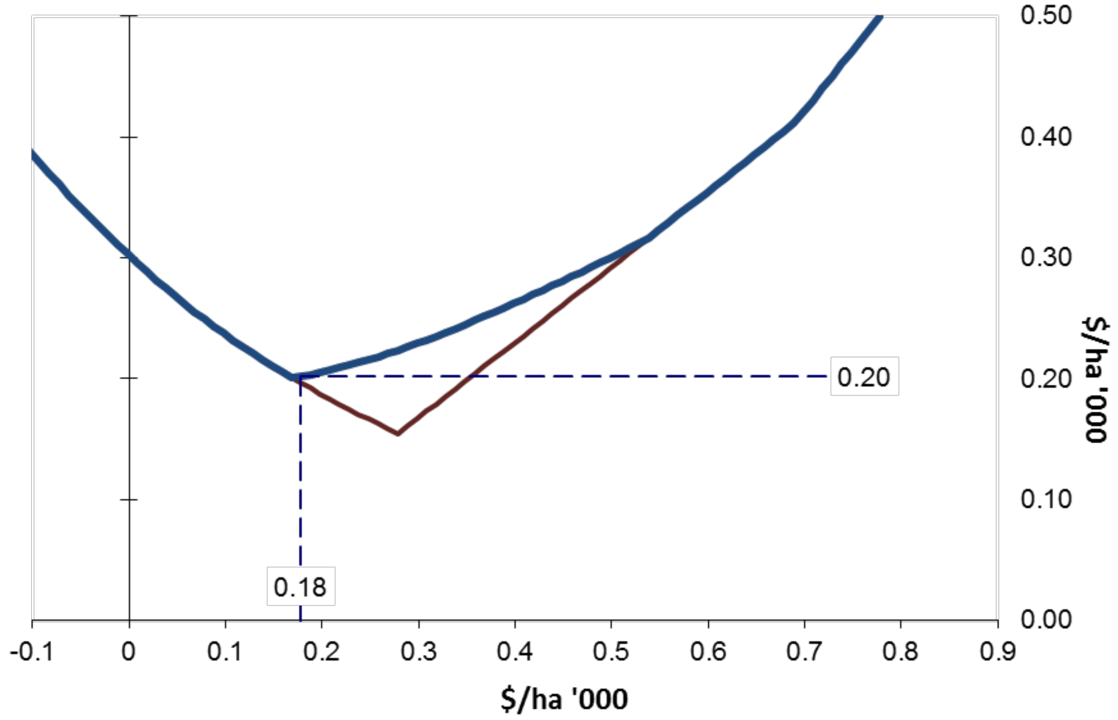

Figure 33: Option value and threshold - Clare exit from wheat and enter merinos

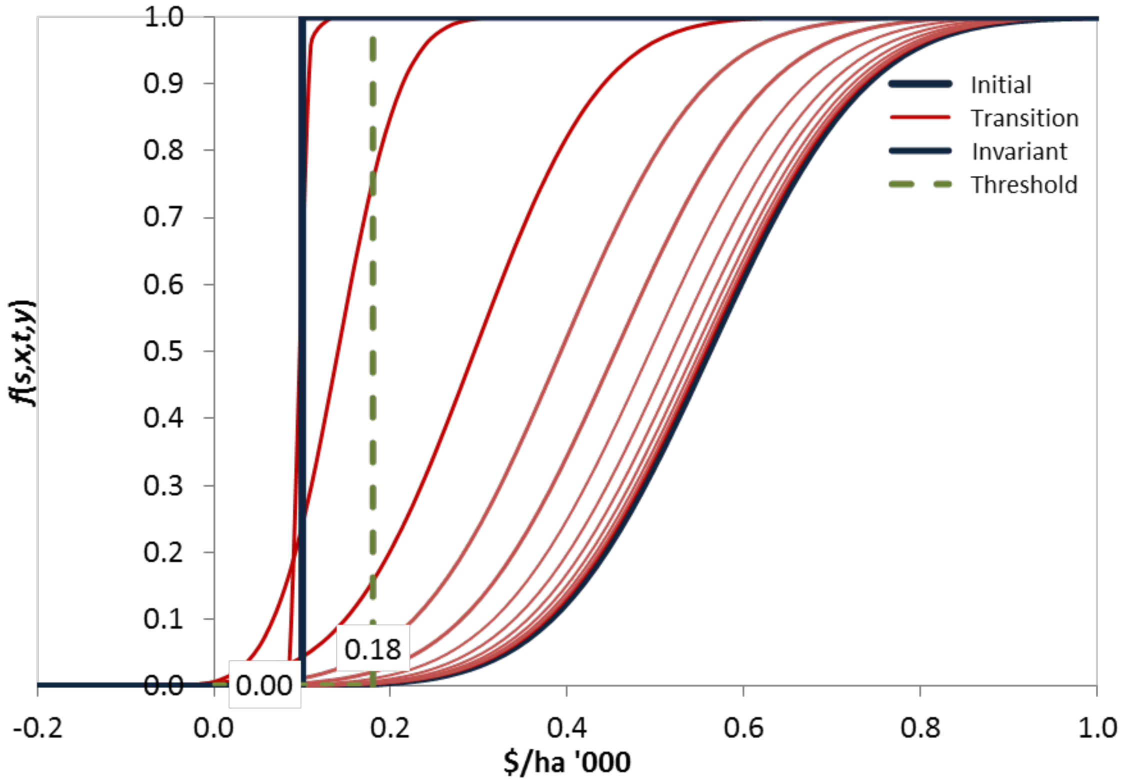

Figure 34: Transformation probability – Clare exit from wheat and enter merinos

3.1.4 Spatial analogues for climate change in South Australia

Decreases in average rainfall are predicted for most parts of South Australia with declines ranging from zero to thirty percent (PIRSA 2011). Figure 35 illustrates where the rainfall has decreased (cream shading) in the southern regions and increased in the northern regions (green shading). The projected declines, especially in spring will have negative implications for grain production.

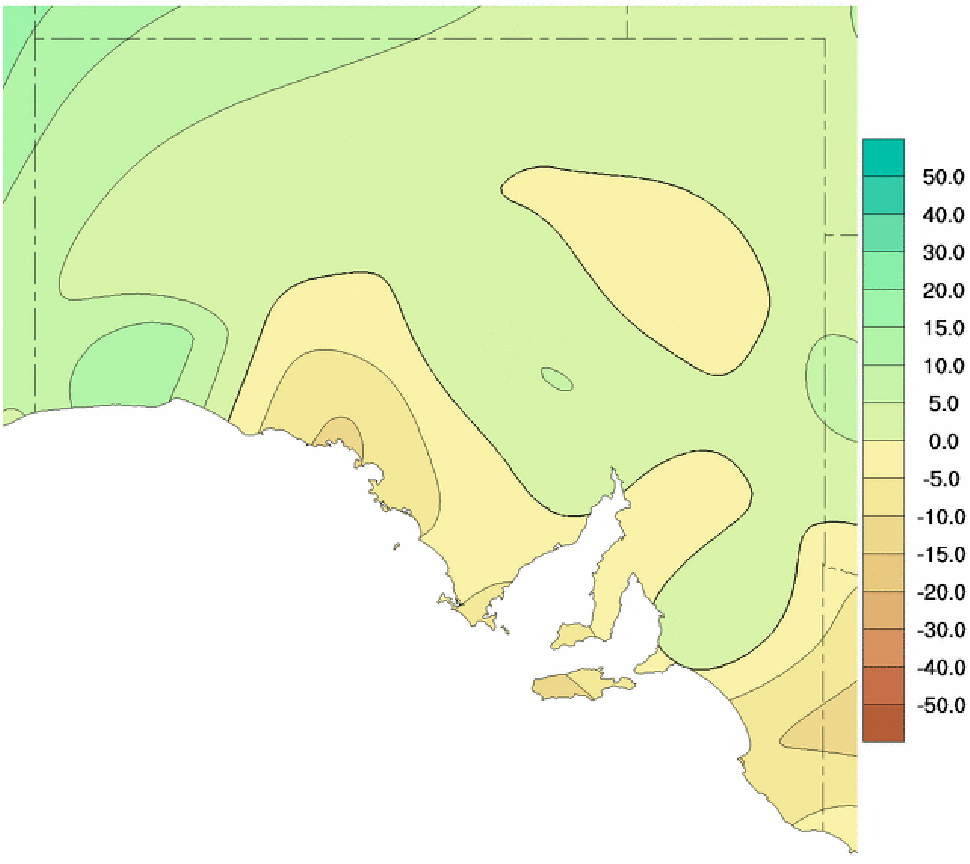

Figure 35: Trend in annual total rainfall for South Australia from 1950-2011 (mm/10yrs) (Source: www.bom.gov.au/climate/change)

In the grain growing regions of South Australian temperatures are expected to increase between 0.2 and 1.4 degrees Celsius by 2030 and between 0.6 and 4.4 degrees Celsius by 2070. Uniform changes are expected throughout each season with a slightly warmer outlook for spring (PIRSA 2011). Increased temperatures will reduce soil moisture, increase disease risk and have a direct effect on growth (van Gool and Vernon 2005). A number of climate change projections for South Australia indicate a general drying and warming trend for 2030 and beyond (Suppiah *et al.* 2006) and whilst a warming and drying trend is anticipated to bring drought it will also result in increased aridity (Nidumolu *et al.* 2012). Using a system of climate scenarios with various climate models and greenhouse gas emissions scenarios, Howden and Hayman (2005) examined the probability of shifts in Goyder's line, concluding there was a small probability of the line shifting north, but a larger probability of it shifting south, increasing pressure on marginal cropping zones along the wheat belt. In the presence

of a warming and drying trend, the expectation is a shift of the Goyder's Line to the south (Hayman *et al.* 2010)

We can use the spatial and temporal analogues approach (Hayman *et al.* 2010; Nidumolu *et al.* 2012) to provide some important clues as to how each of the study sites are likely to respond to adverse climate change. Examining the decision to 'Exit from wheat and enter merinos' in Table 5 we can see that Clare possesses a transformation probability (P_{trans}) of 0.0033. That is, in a given 5 year period the likelihood of exiting a wheat production regime and entering a merino production regime is 0.33%. At Orroroo this likelihood is 9.30%, and at Hawker it is 22.13%. This indicates that if meteorological conditions at Clare become more similar to those currently at Orroroo, then the probability of crossing the threshold also changes from a trivial to a non-trivial risk and worse still if conditions at Clare come to resemble those at Hawker.

We conclude that if Goyder's line does move south, Clare will become somewhat more like Orroroo, but is likely to remain a reliable cropping area. Orroroo and Hawker are much less likely to be cropping and more likely to be grazing country.

3.2 New South Wales

Farms in southern NSW are mixed enterprises based around winter cropping activities. Wheat and sheep are the dominant activities however the mix of winter cropping to livestock varies considerably between farms. The diversity of enterprise mix between farms reflects a range of financial and social influences as well as land suitability and rainfall reliability. Only a small proportion of farms concentrates solely on either crop or livestock production (Patton and Mullen 2001).

Information on crop areas for the Murrumbidgee ABS Statistical Division (which encompassed the case study sites of Cootamundra, Temora and Narrandera) highlight the dominance of wheat above other winter crops in southern farming systems. Wheat accounted for 60% of total crop area in 2009-10, while barley and canola were the next largest crops accounting for 15% and 7% of total crop area (ABS 2011).

Most farms will have at least some non-arable land, so livestock enterprises provide the scope to utilise these areas. Pasture has also played an important role in crop rotation to reduce the effects of disease and improve soil conditions. Since the 1990's, canola has been incorporated into the southern farming system as a key break crop and to improve soil nitrogen levels. With a canola based rotation, continuous cropping is an option for the higher rainfall areas.

Moving from east to west, rainfall becomes lower and less reliable. Mixed farms in the western areas are larger in area, utilising scale to offset the decline in productivity associated with lower, more variable rainfall. Livestock have played an important role in these areas, although in recent years with improvements in tillage technology and practices leading to better soil moisture conservation, cropping has become a more regular feature of the farming system in western areas. Reflecting the riskiness of cropping activities in lower rainfall areas, however, these cropping activities are often based upon low input cereal production and are mostly wheat. Farms in the lower

rainfall areas tend to have a longer pasture phase of 5 to 7 years and run lower stocking rates compared to those in higher rainfall areas.

Across southern NSW, summer cropping opportunities are limited due to high evaporation rates and irregular summer rainfall events and predominantly occur in irrigation areas.

3.2.1 Selection of NSW transects

Based on the expected change in rainfall for the southern region of NSW, a transect was chosen from within the Riverina Murray Region – Cootamundra, Temora and Narrandera. Mean and median rainfall data are provided for the three sites (Table 6). The percentage change in annual and growing season rainfall (GSR) between each site is also shown. For example, from Cootamundra to Temora there is an 18% decline in the mean GSR. From Temora to Narrandera there is a 20% decline in mean GSR.

Table 6: Summary of rainfall

	Cootamundra	Temora	Narrandera
Mean:			
Annual (mm)	652	539	437
GSR (mm Apr-Oct)	404	331	226
% change annual		-17%	-19%
% change GSR		-18%	-20%
Median:			
Annual (mm)	635	527	426
GSR (mm Apr-Oct)	355	281	223
% change annual		-17%	-19%
% change GSR		-21%	-21%

3.2.2 Production system assumptions and data

Enterprise gross margins for Canola and Wheat are based on current practice for Cootamundra. The base variable costs are provided in Table 7. The cost of levies, insurance, windrowing and harvest were linked to estimated annual crop yields and as such vary year by year. APSIM (McCown *et al*. 1996) was used to generate the time series of crop yields for wheat and canola based on historical rainfall for Cootamundra, Temora and Narrandera.

Table 7: Base variable production costs ($/ha)

	Wheat	Canola
Variable costs (excluding levies, insurance, windrowing and harvest costs):		
70kg applied N	$310	$298
90kg applied N	$348	$344
Levies	1.02% gross income	1.015% gross income $1.50 per tonne
Insurance	2.22% gross income	3.8% gross income
Windrowing	-	$25
Harvest	$37	$50

The assumptions for the APSIM runs are provided in Table 8. ASPIM takes account of crop stress factors such as water availability and nitrogen but disease, heat or frost stress, water logging and weeds are not taken into account (McCown *et al*. 1996).

Table 8: APSIM parameter settings

	Wheat	Canola	Source
Sowing date	14 May	25 April	Estimates from Winter Cereal Crop Sowing Guide (2012)
Sowing rate (kg/ha)	60	3	P.Bowden (Pers. Comm., 2012)
Applied N (kg/ha)	70, 90	70, 90	P.Bowden (Pers. Comm., 2012)
Soil	Red Kandosol	Red Kandosol	
Biomass (t DM/ha)	Sept 15th	-	

Using the APSIM data for grain yield (t/ha) and crop biomass production (t DM per ha at Sept 15th), a comparison was made between grazing value and grain value. The

trade-off between grazing and grain values was included to represent the grazing of crops in low yield potential years. Grazing value was selected as the best option as opposed to hay making. With hay making costs typically around $120 per tonne of dry matter, grazing is the cheapest way to utilise biomass. In years when grazing value exceeded grain value, harvest costs and levies were avoided and the feed value of the crop was used to calculate revenue. Grazing and grain values for wheat were calculated as follows:

Grazing value ($/ha) = Biomass (DM t/ha)
x Utilisation (%)
x Feed Conversion Rate (kg live weight per kg of DM forage consumed)
x Live Weight Price (c/kg)

Grain value ($ per ha) = Grain Yield (t/ha) x Price ($/t) - Harvest costs ($/ha)

Utilisation rates were estimated to be 50% up to 3 tonnes of DM per ha, from which point a sliding scale was used for yields up to 6 tonnes DM per ha and 40% utilisation. A feed conversion rate of 0.08 was assumed (P. Graham, pers. comm., 2012).

Figures 36, 37 and 38 show the years between 1960 and 2009 for 70kg/ha nitrogen application rates at Cootamundra, Temora and Narrandera, respectively. Given historical rainfall patterns and the commodity prices used, low yield potential crops would be sacrificed to grazing in 8% of years for Cootamundra, 22% for Temora and 36% in Narrandera. Higher livestock prices will change the point of trade-off between grazing and grain. For example, using Cootamundra conditions, a 10% increase in the price of wethers would increase the frequency of crop sacrifice from 8 to 12%.

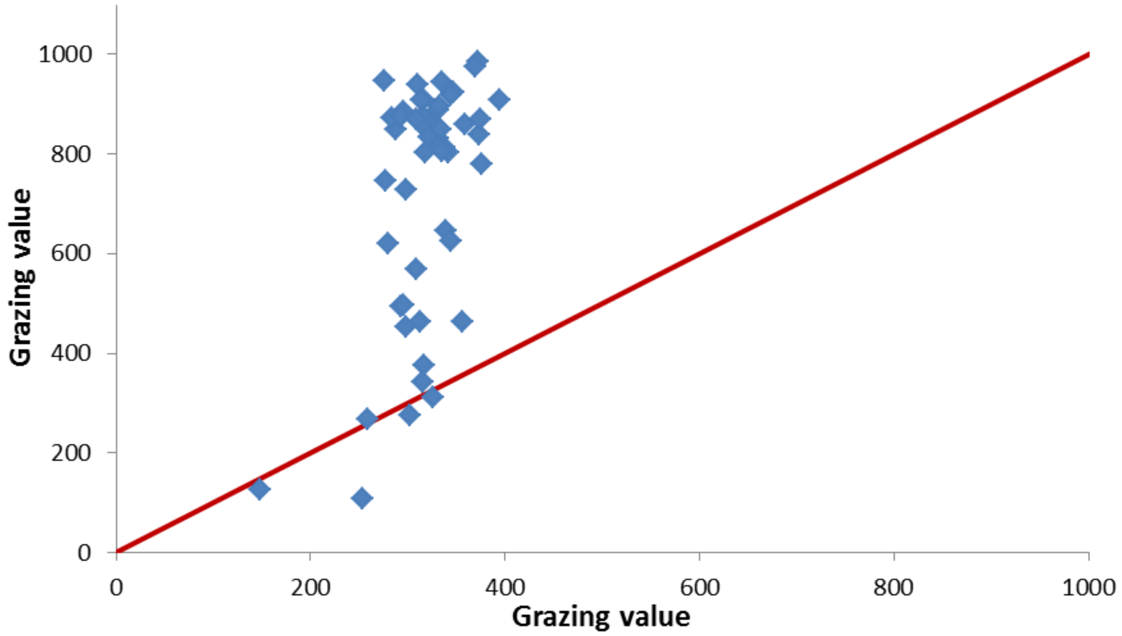

Figure 36: Grazing versus grain value Cootamundra ($/ha)

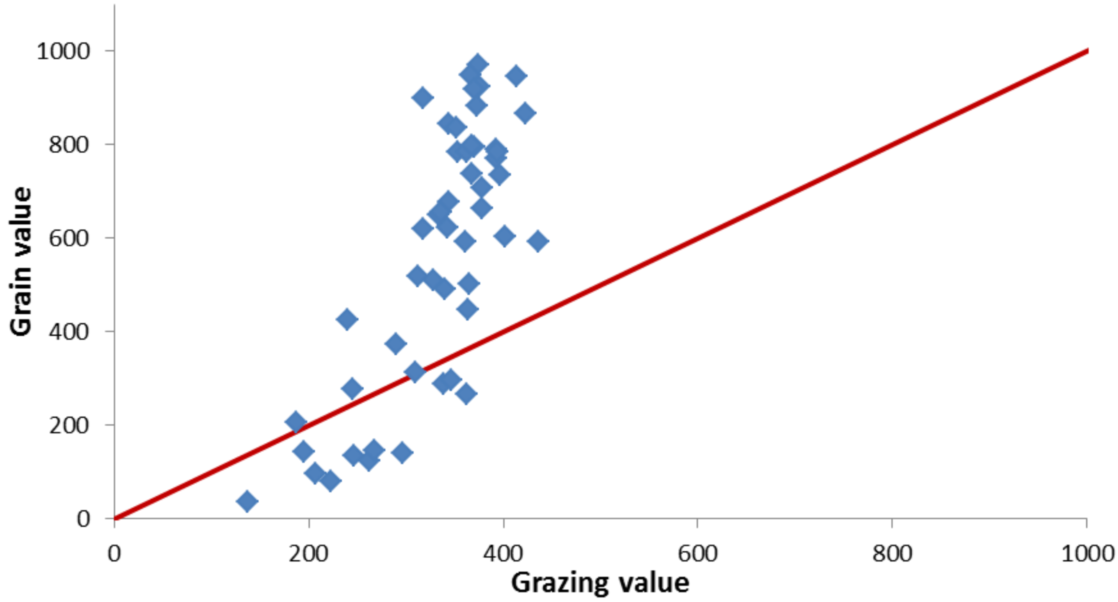

Figure 37: Grazing versus grain value Temora ($/ha)

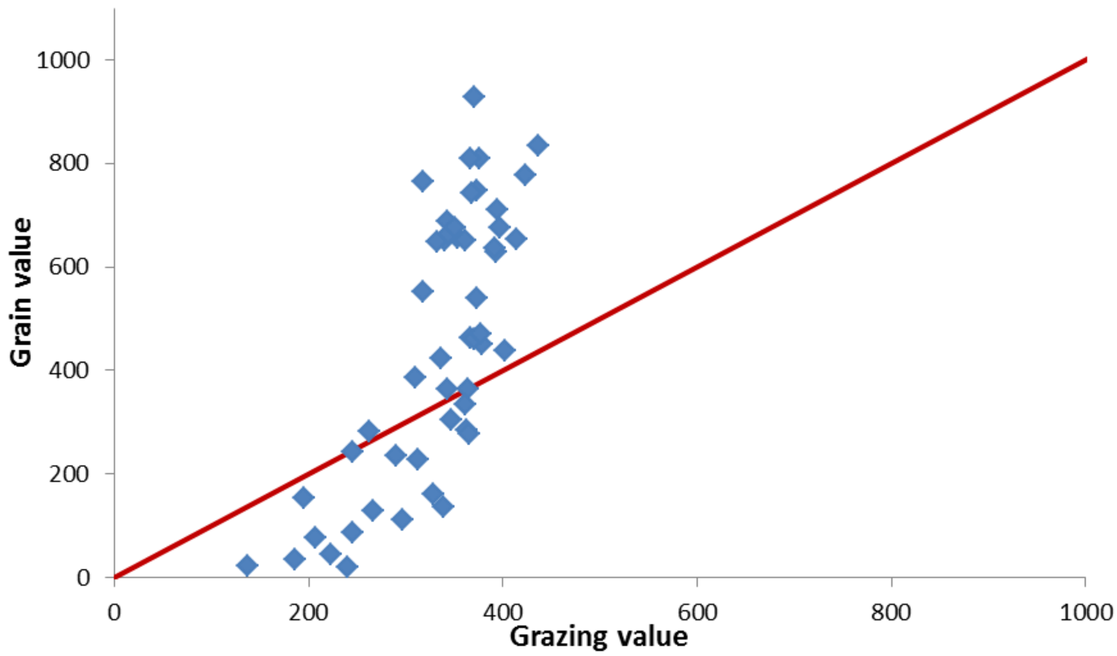

Figure 38: Grazing versus grain value Narrandera ($/ha)

Sheep enterprise gross margins were simulated using the model GrassGro (Moore *et al*. 1997). Historical weather files from SILO (Queensland Government 2013) were used consistent with the APSIM runs. The period of the simulation was from 1960 to 2010. From 1960 onwards temperature data is more reliable which is why this period was selected to generate pasture production and livestock gross margins. Gross margins were calculated based on revenue from wool and sheep sales taking into account variable production costs (shearing, animal husbandry, sale costs,

replacement and ram purchases, pasture costs and supplements). The settings for GrassGro are provided in Table 9.

Table 9: Livestock parameters in GrassGro

Parameter	Value
Breed	Merino
Standard reference weight (kg)	50
Greasy fleece weight (kg)	6
Fibre diameter (micron)	20
Fleece Yield (%)	69
Death rate – Adults (% per year)	5
Death rate – weaners (% per year)	7
Stocking rate (DSE per ha)	7.4

Commodity prices used in the analysis are based on 5 year average prices in Table 10. These prices were assumed to be constant over time to focus on the effects of climate change in transforming farm production.

Table 10: Commodity prices (5 year average)

Commodity	Price
Wheat ($/t)	200
Canola ($/t)	435
Sheep enterprise:	
Wool: 20 micron (c/kg)	840
Ewes (c/kg)	182
Ewe lambs (c/kg)	361
Wether lambs (c/kg)	361
Skin price ($/head)	5.00

Enterprise gross margins were produced for each activity of the farming system: wheat, canola, pasture, merino sheep. Based on the enterprise gross margins, representative farms were used to estimate a whole farm gross margin based on the farm specifications in Table 11. Generalised rotational practices were used to allocate proportions of land to each enterprise between canola C, wheat W and pasture P.

Table 11: Farm Specification

	Wheat Dominant Cropping	Mixed Farm	Sheep Dominant Mixed Farm	Sheep Only
Rotation	CWWCWW	CWWPPP	PPPPW	PPPP
Percent of farm area:				
Pasture	0	50	80	100
Wheat	67	33	20	0
Canola	33	17	0	0

The farm gross margins for each farm type and location are shown in Figures 39, 41 and 43. Corresponding phase diagrams appear in Figures 40, 42 and 44. Generally, wheat dominant cropping farms return a higher gross margin per ha compared to mixed, sheep dominant and sheep only farms, but associated with this is a greater variation of income.

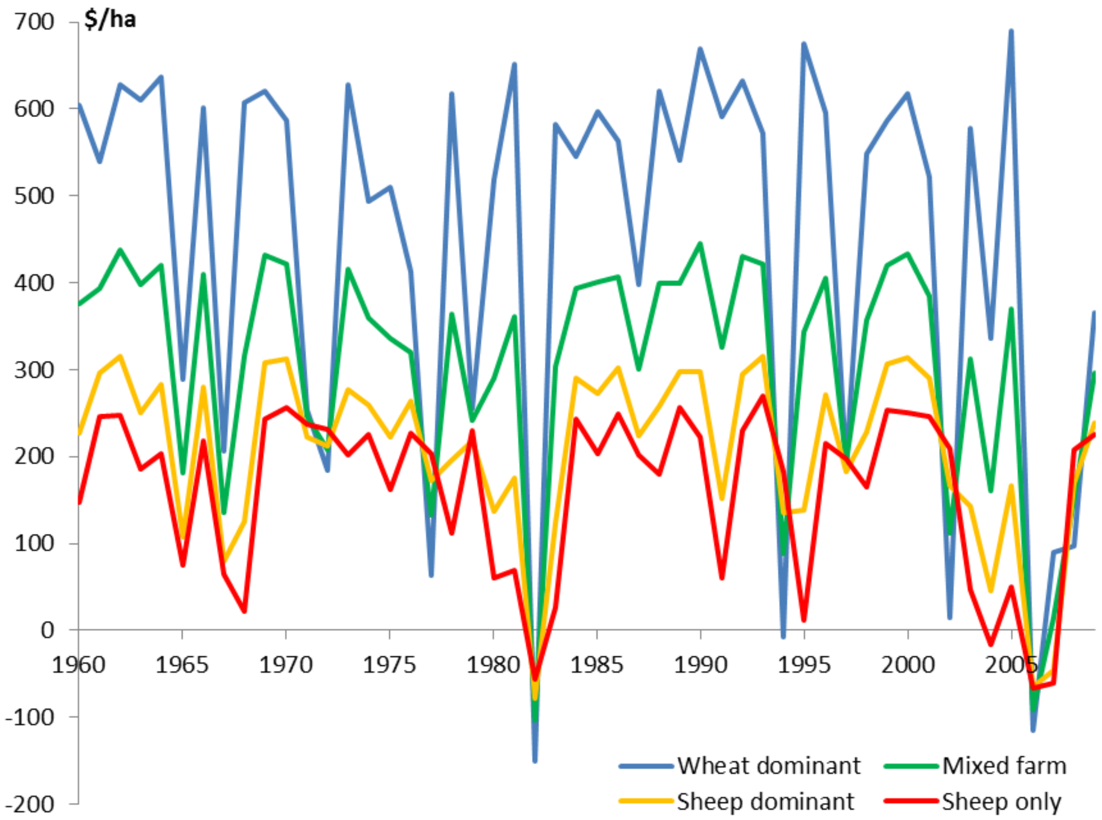

Figure 39: Comparative gross margins Cootamundra ($/ha)

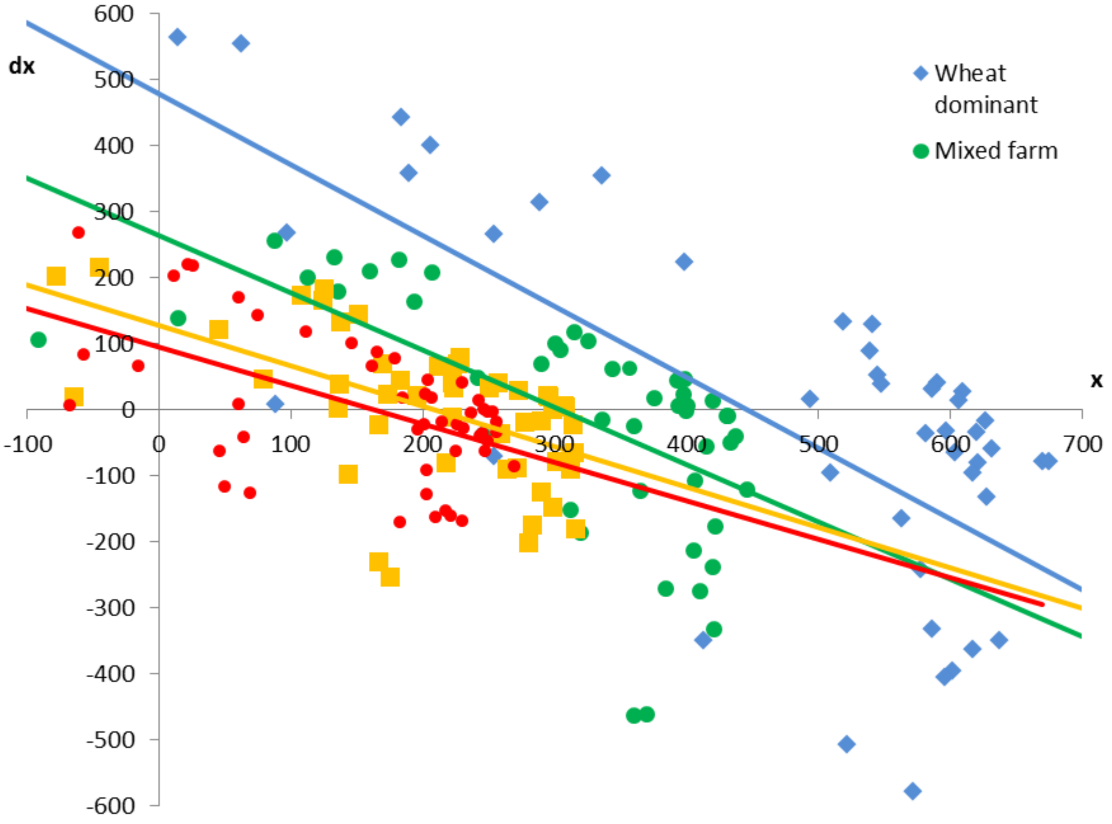

Figure 40: Cootamundra gross margin phase diagram ($/ha)

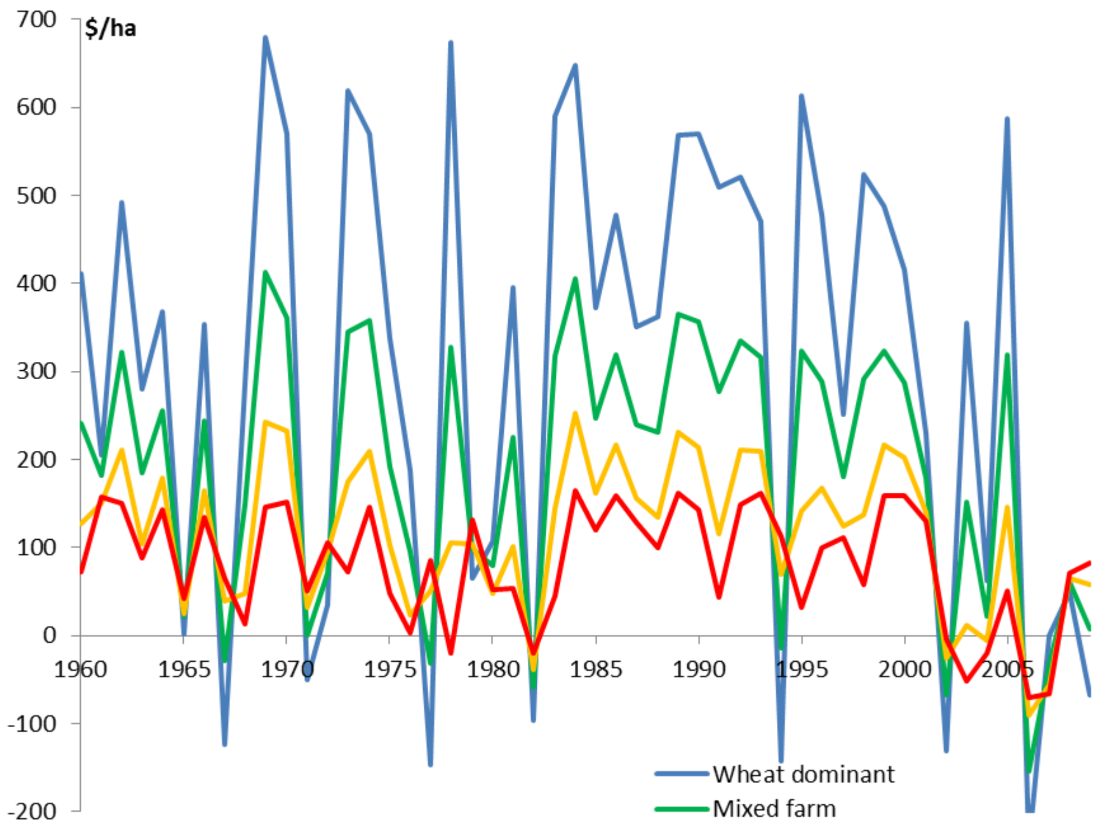

Figure 41: Comparative gross margins Temora ($/ha)

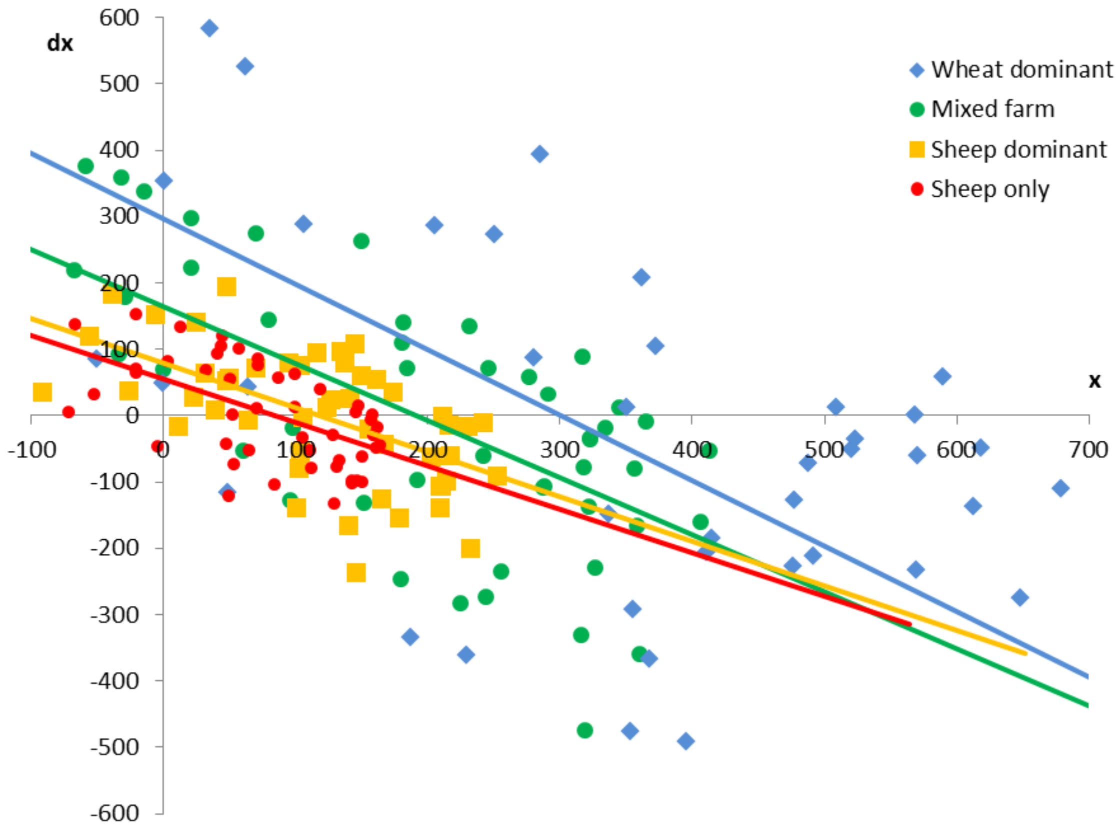

Figure 42: Temora gross margin phase diagram ($/ha)

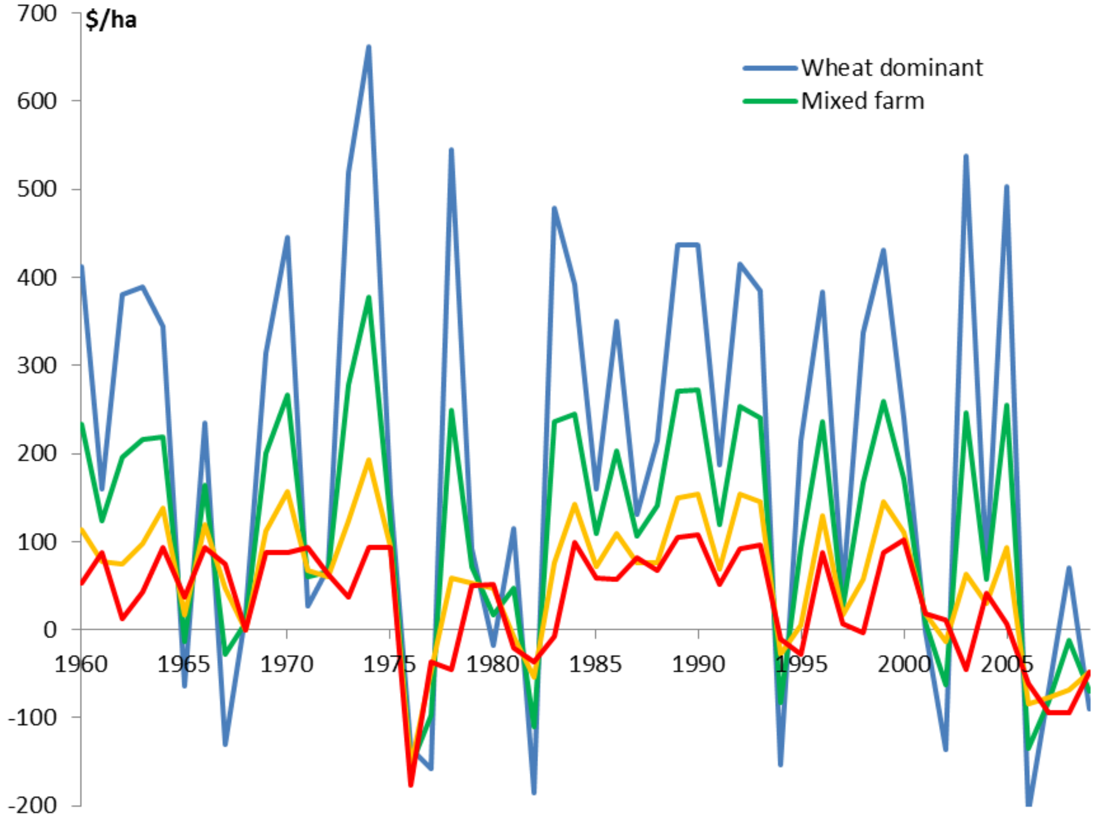

Figure 43: Comparative gross margins Narrandera ($/ha)

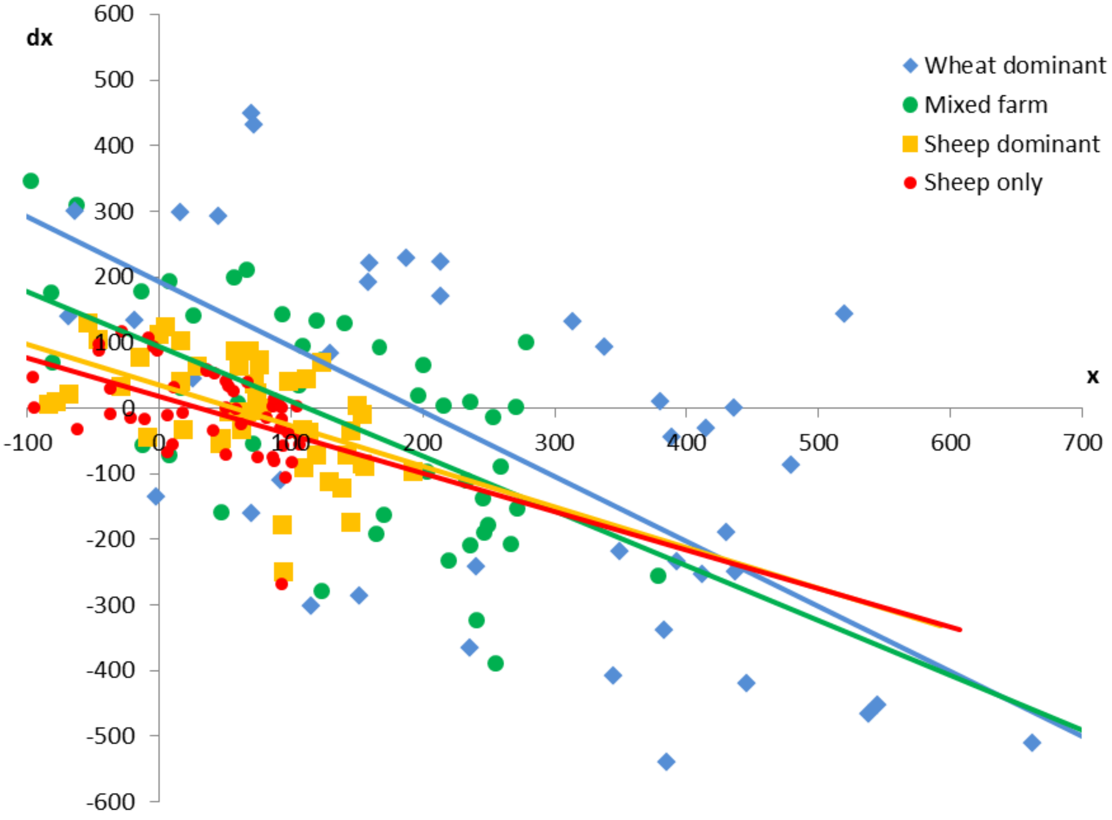

Figure 44: Narrandera gross margin phase diagram ($/ha)

Using GPS, we estimated the parameters for the phase diagrams. Results are in Table 12.

Table 12: Estimated Ornstein-Uhlenbeck parameters for gross margins in ($/ha)

Activity	Parameter	Cootamundra		Temora		Narrandera	
		70kg N	90 kg N	70kg N	90 kg N	70kg N	90 kg N
Wheat Dominant Cropping	b	-1.074	-1.059	-0.987	-0.974	-0.989	-0.993
	μ	446.40	462.40	300.20	294.20	194.70	174.40
	σ	231.50	266.00	267.80	298.30	236.30	257.60
	σ/μ	0.5186	0.5753	0.8921	1.014	1.214	1.477
Mixed Farm	b	-0.868	-0.880	-0.858	-0.861	-0.835	-0.849
	μ	303.60	311.50	190.40	187.50	112.10	102.10
	σ	137.20	153.70	149.60	164.80	133.40	143.90
	σ/μ	0.4519	0.4934	0.7857	0.8789	1.190	1.405
Sheep Dominant Mixed Farm	b	-0.611	-0.628	-0.669	-0.690	-0.620	-0.629
	μ	207.30	211.10	116.50	115.80	56.10	52.40
	σ	92.40	98.00	81.50	87.40	70.90	74.50
	σ/μ	0.4457	0.4642	0.6996	0.7547	1.264	1.422
Sheep Only	b	-0.582	-0.582	-0.654	-0.654	-0.585	-0.585
	μ	162.80	162.80	82.20	82.20	30.40	30.40
	σ	90.00	90.00	63.00	63.00	59.10	59.10
	σ/μ	0.5528	0.5528	0.7664	0.7664	1.944	1.944

We interpret μ as the mean attractor. For instance, at Cootamundra with 90kg N/ha in wheat dominant cropping regime the value of μ is 462.40. For any given year the expected gross margin is $462.40/ha. As we move along the transect towards less favourable growing conditions with the same N application rate, Temora has an average gross margin of $294.20/ha and Narrandera $174.40/ha. We can also examine the ratio of the deviation to the average gross margin to compare relative riskiness of production along the transect. Cootamundra is relatively profitable and

reliable. Temora is less profitable and reliable and Narrandera is unprofitable and extremely risky.

Adding sheep to the farming mix reduces profitability, but may not reduce the risk. Overall there appears to be a steady decline in the average gross margin as we move from wheat dominant cropping, to mixed farming, to sheep dominant mixed farming to sheep only farming. Initially in all locations, moving from wheat dominant cropping to mixed farming reduces the risk. Generally the same is true for moving from mixed farming to sheep dominant mixed farming, with the exception of Narrandera. In all locations moving to the final sheep only regime causes a sudden increase in the relative riskiness, in some cases more risky than the initial wheat dominant cropping regime.

For the ROADs analysis, we used entry costs and salvage values derived from ABARES data (S. Dharma, pers. comm., November 2012). A 90% rate of recovery on plant and equipment is assumed. Table 13 reports the entry costs and exit salvage values.

Table 13: Assumed activity entry costs and exit salvage values ($/ha)

Activity	Entry Cost	Exit Salvage
Wheat cropping	309	278
Mixed farm	207	186
Sheep dominant mixed farm	207	186
Sheep only	32	29

3.2.3 Results

Applying ROADs and TRIPS to the estimated parameters, we examined five representative decision problems. These are (1) entry into wheat dominant cropping with the possibility to exit, (2) exit from wheat dominant cropping with entry into mixed farming, (3) exit from mixed farming with entry into sheep dominant mixed farming, (4) exit from sheep dominant mixed farming with entry into sheep only farming, and (5) exit from sheep only farming. These results are presented in Table 14, for the option value w, the regime threshold x, the expected waiting time at the threshold T-t, and the probability of transformation from one regime to another P_{trans}. These results correspond to the 90kg N/ha scenario. The results for the 70kg N/ha are quite similar and are not reported.

For Cootamundra, the first decision, ‘Entry into wheat dominant cropping with the possibility to exit’ is the switch from holding money in the bank to investing in the growing of wheat. Each of the regimes has different risks, and switches will not happen immediately. The results in Table 14 indicate that we will wait until we observe a

threshold gross margin (*x*) of $487/ha before we commit to enter wheat production, and are willing to pay an option value (*w*) in forgone potential earnings of $197.20/ha while we wait until that threshold gross margin occurs. The expected waiting time at the threshold (*T*-*t*) of 0.80 years indicates that once we observe a gross margin of $487/ha we expect to enter wheat cropping within a year. The estimated value for the probability of transformation (P_{trans}) is 0.4471 which indicates that within a given 5 year time frame there is a 44.71% likelihood of crossing the threshold into wheat production at Cootamundra. This decision is also illustrated graphically in Figures 45 and 46. Figures 47 through 54 illustrate the decisions to move between the available regimes.

Table 14: Estimated option values ($/ha), threshold values ($/ha), expected times until exercise (years) and transformation probabilities (90kgN)

Decision		Cootamundra	Temora	Narrandera
Enter into wheat dominant cropping and possibly exit	w	197.2	192.6	192.9
	x	487.0	427.0	387.0
	T-t	0.8000	1.1000	1.8000
	P_{trans}	0.4471	0.2694	0.1249
Exit from wheat dominant cropping to enter crop dominant mixed farm	w	198.4	172.8	168.5
	x	178.0	138.0	118.0
	T-t	2.5000	1.1000	0.8000
	P_{trans}	0.0619	0.2348	0.3801
Exit from crop dominant mixed farm to enter sheep dominant mixed farm	w	117.8	093.4	105.2
	x	096.0	096.0	086.0
	T-t	3.3000	1.2000	1.1000
	P_{trans}	0.0327	0.2351	0.4426
Exit from sheep dominant mixed farm to enter sheep only farm	w	127.6	110.4	134.5
	x	156.0	116.0	066.0
	T-t	0.5000	0.8000	0.4000
	P_{trans}	0.2658	0.5011	0.5805
Exit from sheep only farm	w	11.8	11.4	22.5
	x	19.0	19.0	9.0
	T-t	0.2000	0.3000	0.9000
	P_{trans}	0.0434	0.1273	0.3486

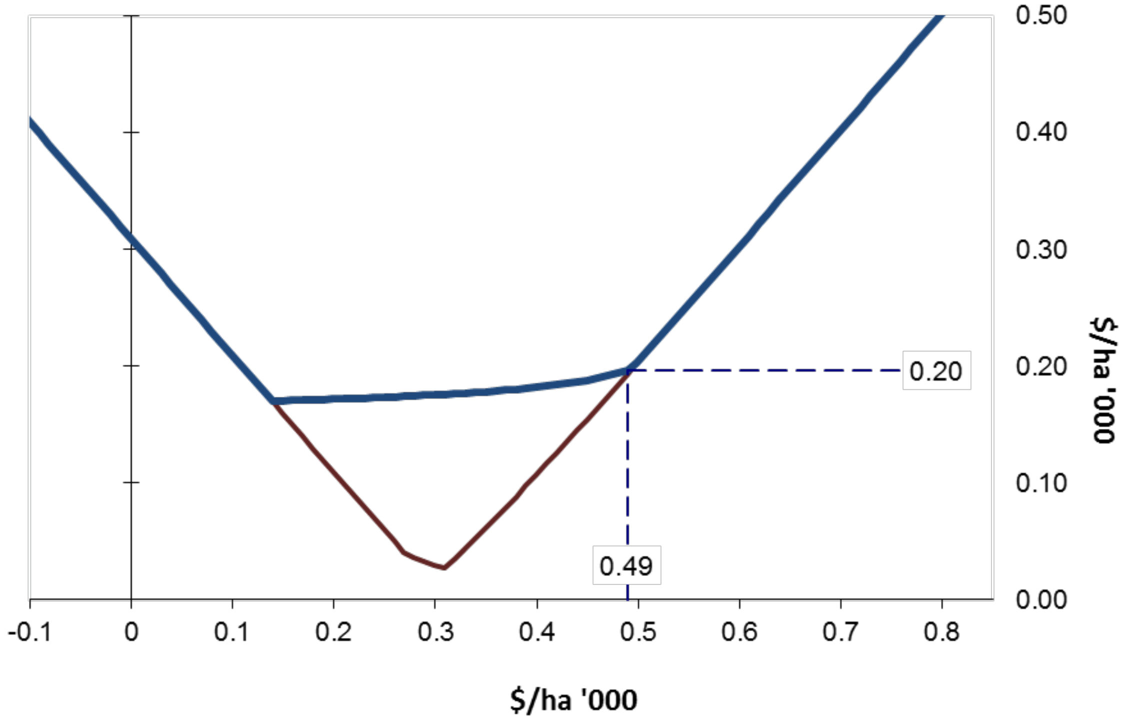

Figure 45: Option value and threshold – Cootamundra enter into wheat dominant cropping and possibly exit

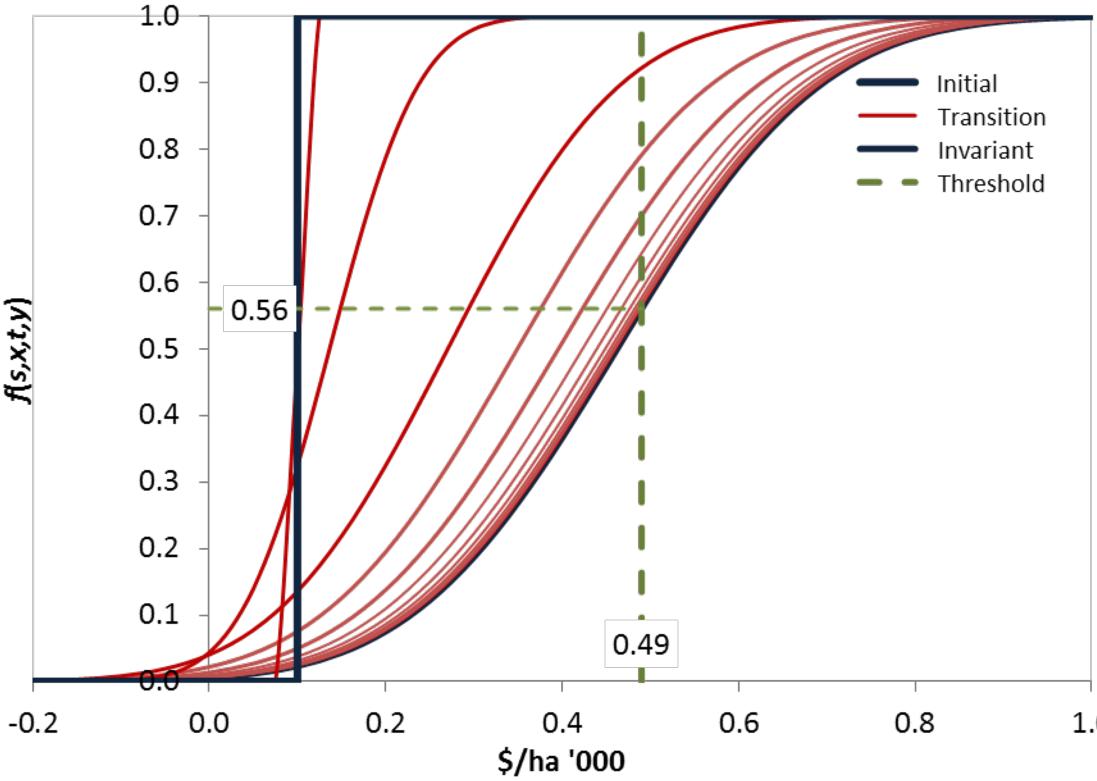

Figure 46: Transformation probability – Cootamundra enter into wheat dominant cropping and possibly exit

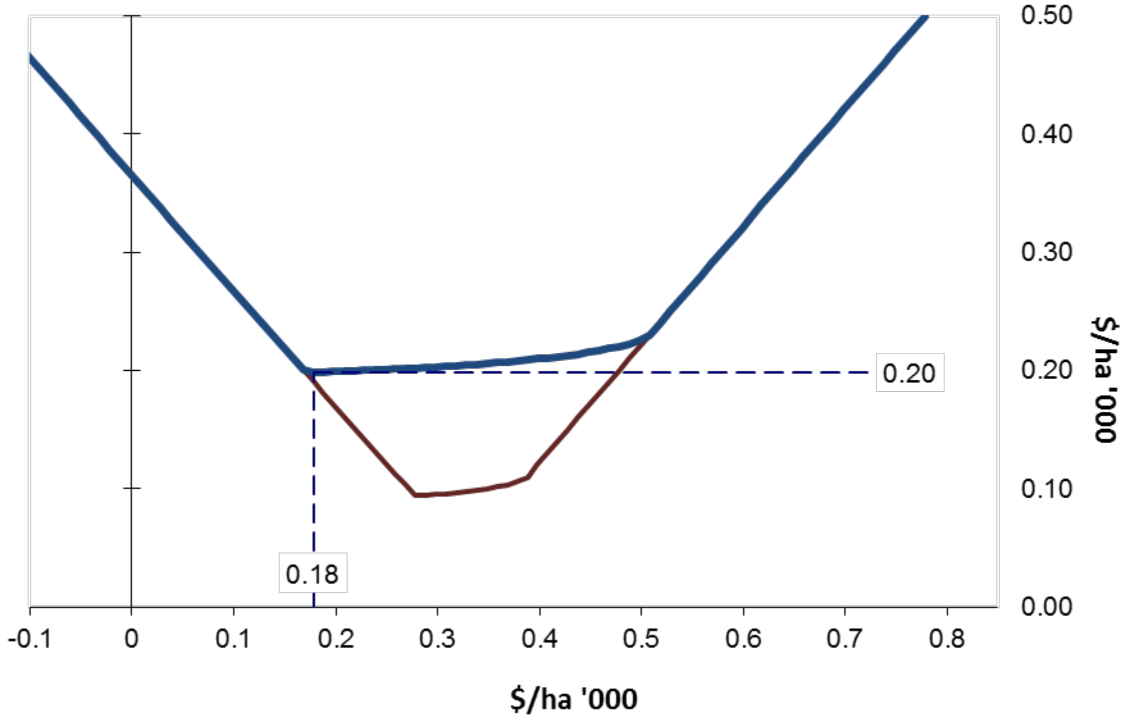

Figure 47: Option value and threshold – Cootamundra exit from wheat dominant cropping to enter crop dominant mixed farm

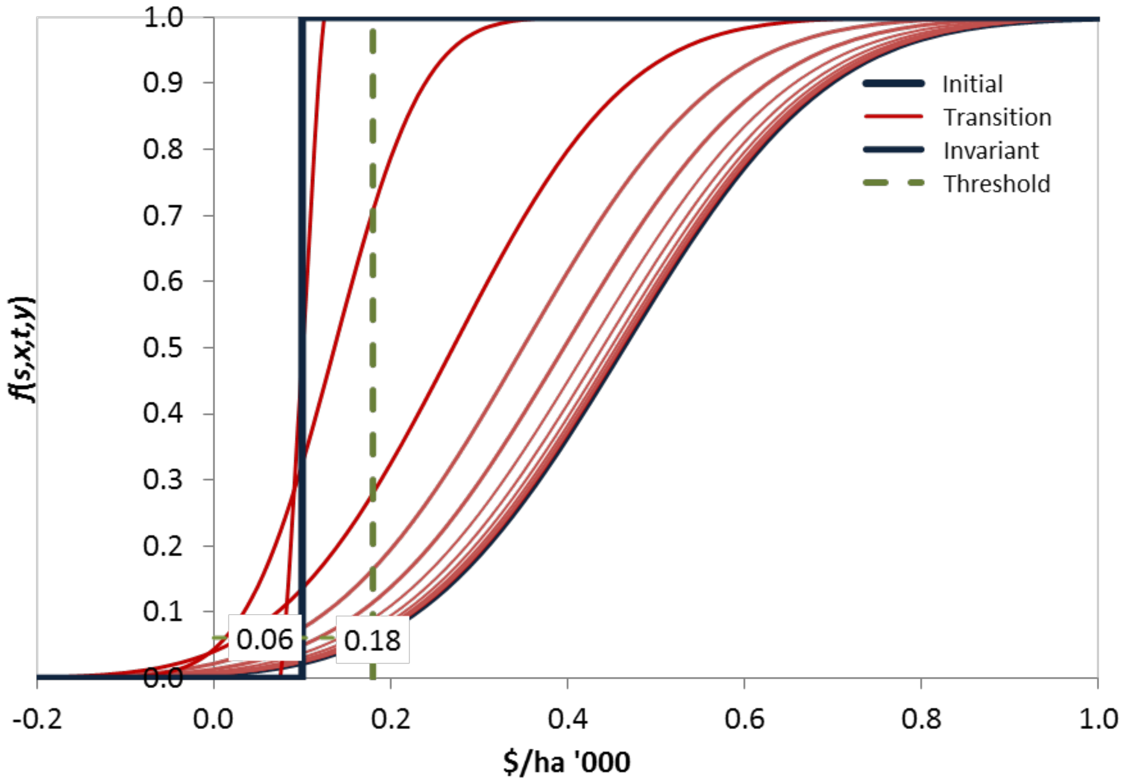

Figure 48: Transformation probability – Cootamundra exit from wheat dominant cropping to enter crop dominant mixed farm

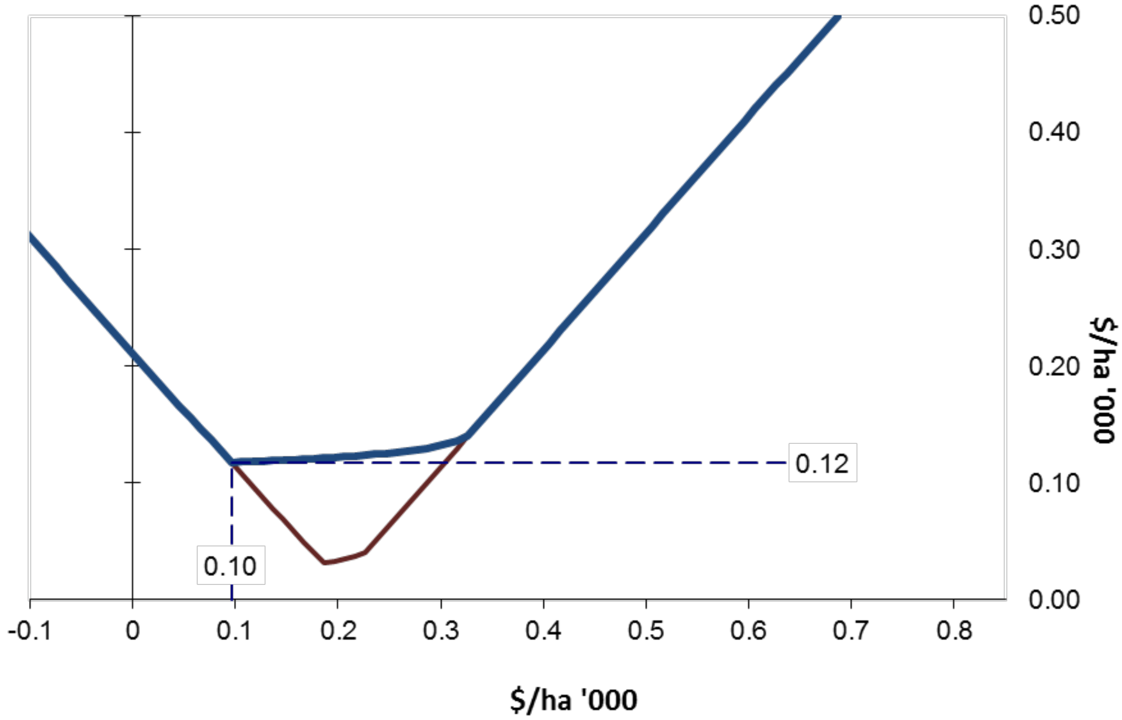

Figure 49: Option value and threshold – Cootamundra exit from crop dominant mixed farm to enter sheep dominant mixed farm

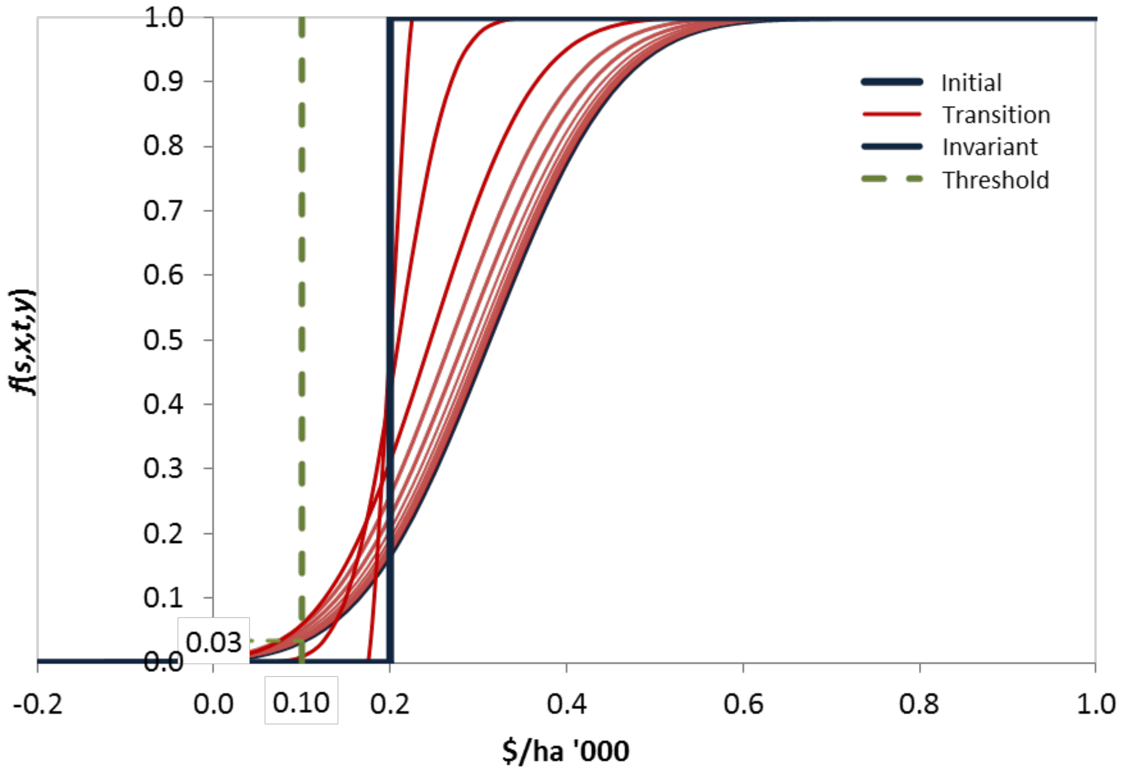

Figure 50: Transformation probability – Cootamundra exit from crop dominant mixed farm to enter sheep dominant mixed farm

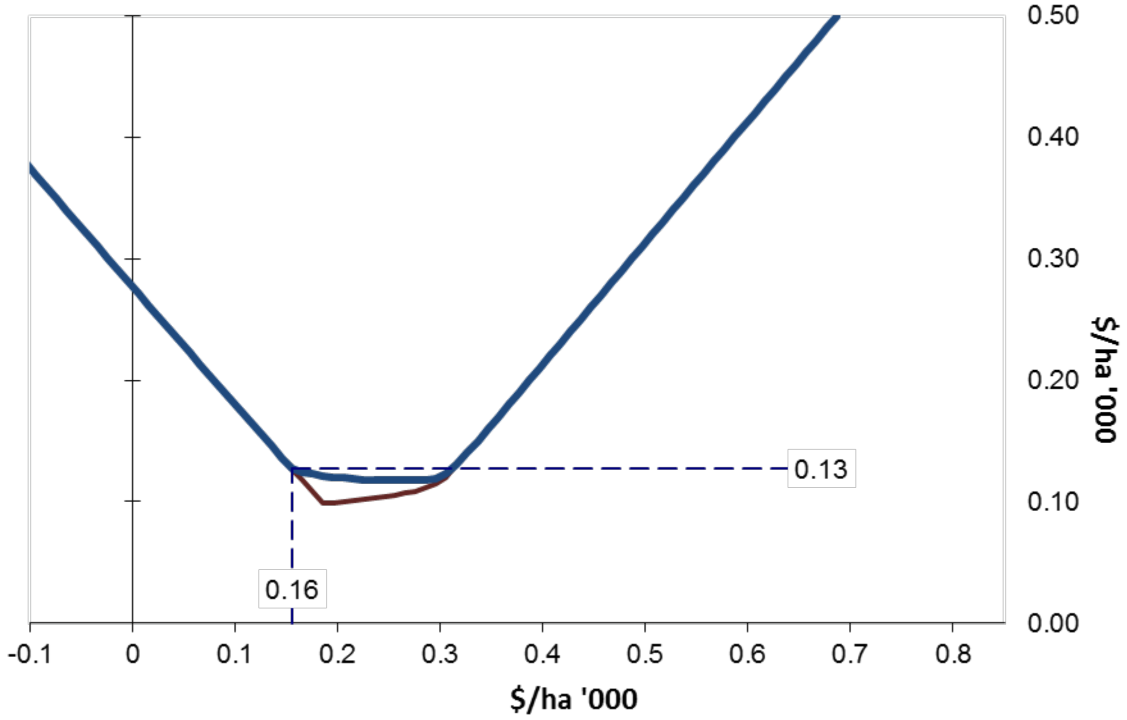

Figure 51: Option value and threshold – Cootamundra exit from sheep dominant mixed farm to enter sheep only farm

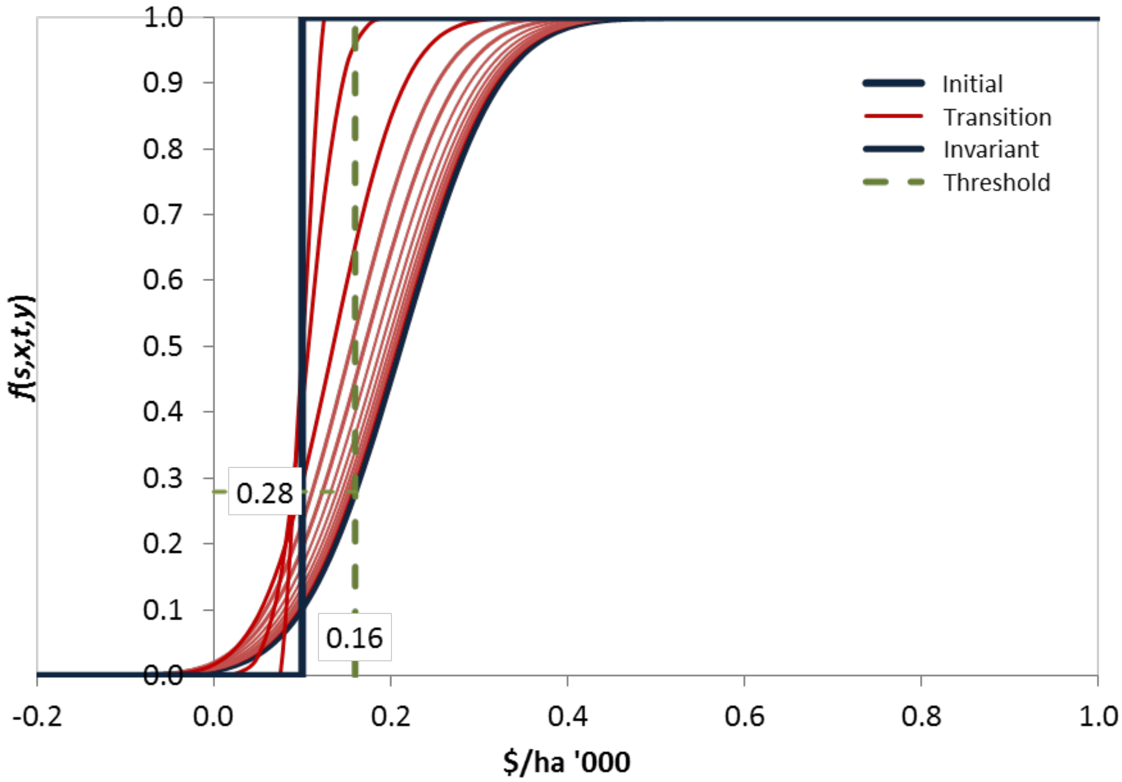

Figure 52: Transformation probability – Cootamundra exit from sheep dominant mixed farm to enter sheep only farm

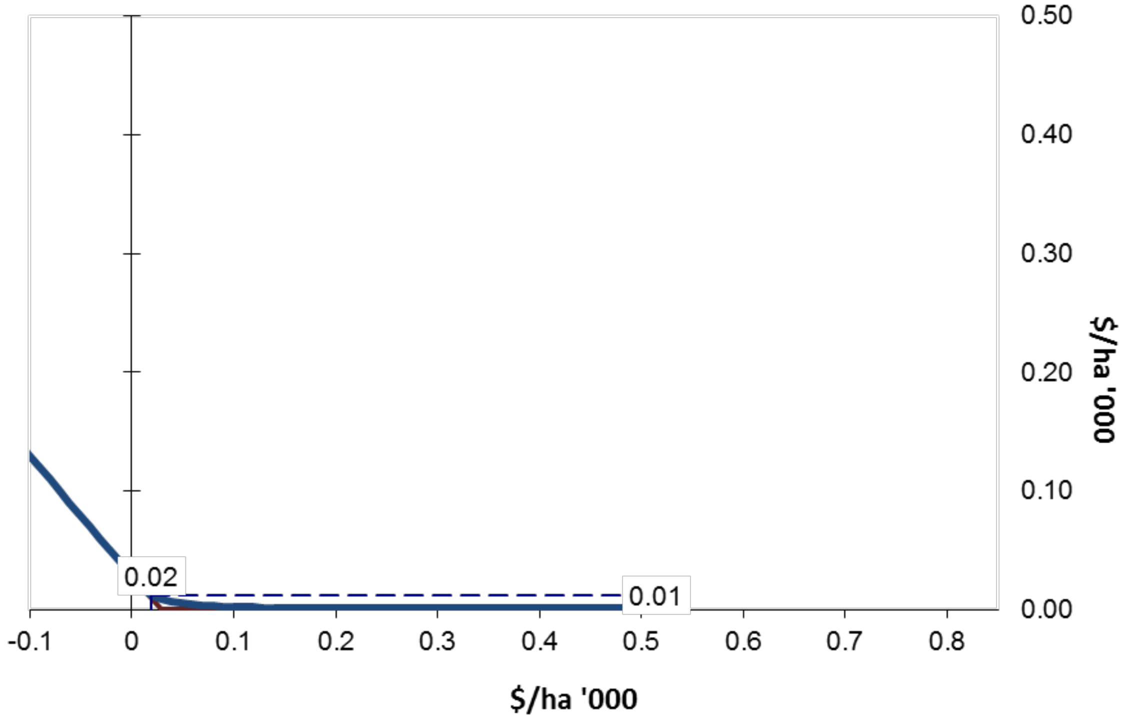

Figure 53: Option value and threshold – Cootamundra exit from sheep only

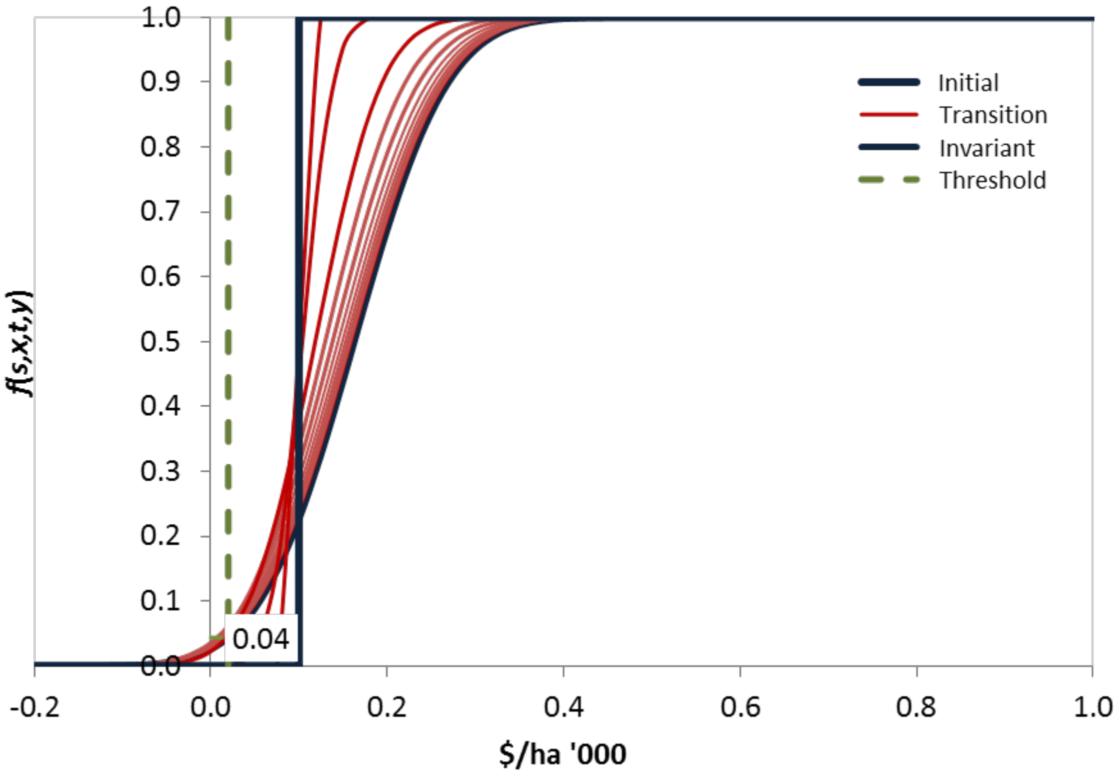

Figure 54: Transformation probability – Cootamundra exit from sheep only

3.2.4 Spatial analogues for climate change in New South Wales

We use the spatial and temporal analogues approach (Hayman *et al.* 2010; Nidumolu *et al.* 2012) to provide clues as to how each of the study sites is likely to respond to

adverse climate change. We do this by examining the series of decisions to (1) 'Exit from wheat dominant cropping only to enter crop dominant mixed farm', (2) 'Exit from crop dominant mixed farm to enter sheep dominant mixed farm', and (3) 'Exit from sheep dominant mixed farm to enter sheep only farm'.

For example, in Table 14 the decision at Cootamundra to 'Exit from wheat dominant cropping only to enter crop dominant mixed farm' has an associated transformation probability (P_{trans}) of 0.0619. That is, in a given 5 year period the likelihood of exiting a wheat dominant cropping regime and entering a mixed farming production regime is 6.19%. At Temora this likelihood is 23.48%, and at Narrandera it is 38.01%. This indicates that if meteorological conditions at Cootamundra become more similar to the current conditions at Temora, then the probability of crossing the threshold rises from 6.19% towards 23.48%, and rises even further if conditions at Cootamundra come to resemble those at Narrandera.

3.2.5 Climate change expectations in NSW

Climate change projections are based on a range of emissions scenarios. The scenarios represent different assumptions about factors likely to affect CO_2 emissions and possible climate system responses. CSIRO (Pierce *et al*. 2007) developed a set of climate change projections based on experiments from 23 of the best available global climate models. While rainfall is the most difficult to predict, the CSIRO research provided a range of projections for rainfall impacts. Rainfall in southern areas of Australia ranged from -15% to little change under the 2050 low emissions scenario (B1) to -20% to little change under the 2050 high emissions scenario (A1F1). The climate models indicated rainfall was likely to decline in southern areas of Australia particularly in the winter and also in spring for eastern areas.

Efforts have been made to downscale the climate change projections from global models to a regional scale. The Department of Environment, Climate Change and Water (DECCW) released regional climate projections based on research undertaken by the University of NSW. The projections were based on the A2 emissions scenario only and used four climate models observed to work well for south eastern Australia (DECCW, 2010). Based on this work, the climate change expectations for south western NSW for 2050 are for higher temperatures, a shift in rainfall pattern from winter to summer dominance and a decline in total annual rainfall, most notably in the winter growing season.

There is a high degree of uncertainty around regional projections particularly with respect to rainfall patterns. The projections for rainfall ranged from a 20 to 50% decrease in winter rainfall with a decrease of up to 50% in spring and autumn. Summer rainfall was reported as likely to increase by 10 to 50%. The variation in rainfall between the three transect sites shown in Table 6 falls within the range of the DECCW (2010) regional scale projections and at the higher end of the CSIRO (Pierce et al. 2007) projections for south eastern Australia.

Given the current state of climate research, it appears likely that Cootamundra could come to resemble Temora and Temora could come to resemble Narrandera. Narrandera is already an extremely risky location for farming and might transform completely out of agriculture.

3.3 *Western Australia*

Western Australia is a major wheat producer – wheat is the dominant crop and Western Australia is the largest producer and exporter of wheat in Australia. Wheat is generally regarded as the most profitable land-use (Doole and Weetman 2009), with sheep grazing on sown pasture typically in rotation with cereal crops (Hobbs, 2003). In Western Australia, wheat is grown across four bio-geographical regions identified in the Interim Bio-geographical Regionalisation of Australia (IBRA 2013) as (1) the Geraldton Sandplains, (2) the Avon Wheat Belt, (3) the Mallee and (4) the Esperance Plains.

Western Australia's climate is Mediterranean, consisting of hot and dry summers, and cool and wet winters, with annual rainfall ranging from around 300mm per year in the east to around 600mm per year in the west (Hobbs 2003). The growing season is from late April / early May until October each year. The Department of Agriculture of Western Australia has divided the region into agro-ecological regions to group areas with similar crop performance. These regions are based on four isohyets and five lengths of growing season. In Figure 55, rainfall varies from low in the east, through medium and high to very high in the west. The length of the growing season is shortest in the north and longest in the south. For example, Region L1 in the northeast has low rainfall and the shortest growing season. Region H5 in the south has high rainfall and the longest growing season and is subdivided into eastern, central and western subregions. The most productive regions are shown in blue in the figure.

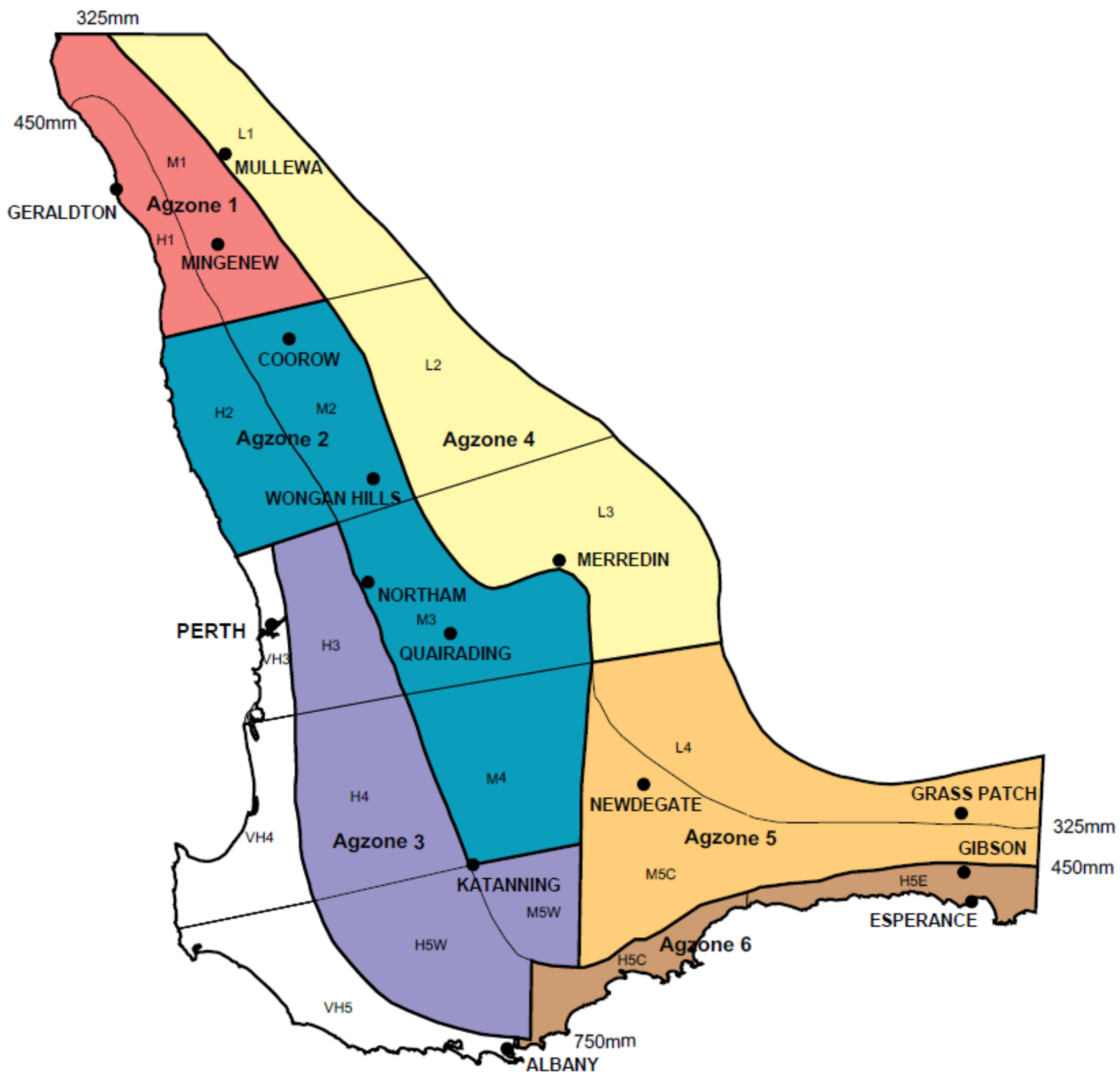

Figure 55: Map of Western Australian agro-ecological regions

3.3.1 Climactic Considerations

Significant climactic factors influencing wheat production are rainfall, solar radiation and temperature, typically in that order of importance. Wheat yields are generally a function of the timing of rainfall within the growing season as well as the quantity (Stephens and Lyons 1998). The timing of rainfall is most important in the southern regions that are susceptible to water-logging. Water-logging occurs in one out of four seasons in areas with an annual rainfall less than 500mm and in almost every season in areas where annual rainfall exceeds 600mm (CSIRO 2005).

Wheat is predominantly produced in areas with less than 500mm of annual rainfall and over 40% of production is from areas receiving less than 325mm (Cramb 2000). Most of the Western Australian wheat belt falls into the low and medium (300-450mm) rainfall zone that stretches from Mullewa to Gibson following easterly from the 450mm isohyet. The high rainfall zone stretches from Perth to Albany and Katanning to Boyup

Brook. Traditionally this high rainfall area was used for pastures and sheep production and currently only 23% of the region is used for cropping (CSIRO 2005).

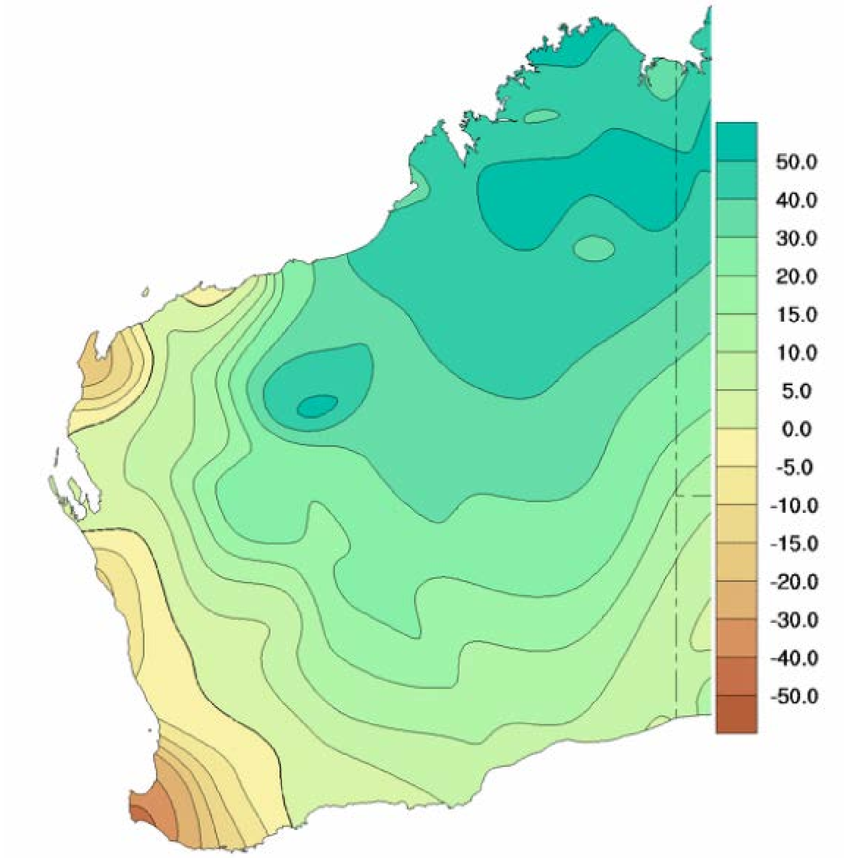

Figure 56: Trend in annual total rainfall for Western Australia 1950-2011 (mm/10yrs) (Source: www.bom.gov.au/climate/change)

Figure 56 illustrates that the rainfall has decreased sharply (brown shading) in the south west and increased dramatically in the north (green shading). Indian Ocean Climate Initiative (IOCI 2010) research has found that for the past six decades rainfall trends have been dramatic. The south-west of Western Australia, once considered to be Australia's most reliable wheat growing region, has experienced a decline in winter rainfall since the late 1960s, with rainfall consistently below average from May to July (IOCI 2010; van Gool and Vernon 2005). In early winter months the atmospheric conditions have become more stable with fewer low pressure systems and more prevalent high pressure systems; however, the rainfall associated with each system has decreased since 2000 (IOCI 2010). Temperature is important for crop development with the optimum level for wheat ranging from 23^0C to 25^0C (Hacket 1999; Cramb 2000). Temperature also plays a significant role in the prevalence of frost risk, which impacts wheat yields in some regions. The risk of frost is greatest in the high rainfall zones of the south (Cramb 2000).

3.3.2 Farming systems

The soils of south-western Australia are generally light and sandy and vary from loams to clays and deep sands. Fertility is low, largely due to the age of the soils and their

high degree of weathering from exposure (Cramb 2000). Wheat is tolerant to a range of soil qualities but, in general, high yields are obtained where soils are well drained, have good physical characteristics and no barriers to root penetrations, no extremes in PH, are non-saline and have adequate nutrient supply (Anderson and Moore 1998). Although there are wide variations in soil type and fertility, the sandy surface soils are generally deficient in major and minor nutrients. The low clay content means a low capacity for retention of most applied nutrients and a low water holding capacity. There is also a risk of rising water tables and dryland salinity in some areas (Cramb 2000).

Areas that have sand-plain soils within the medium to low rainfall regions have relied on wheat and lupin rotations (McTaggart and Peake 2005). During the 1980s and 1990s, simple 1:1 rotations of wheat and lupins were a prominent and profitable land use. Rotations with lupins and cereals are still very common; however, lupins are now sown less frequently. Instead, canola or pasture may be rotated with wheat (Harries and Peek 2008). In areas with medium to heavy textured soils within the medium and low rainfall regions, broad acre farming relies on continuous cereal production (wheat, barley, oats), although pulse and oilseed production, and pasture for sheep grazing, are also quite common (McTaggart and Peake 2005). High rainfall areas are typically dominated by livestock enterprises, usually sheep production (McTaggart and Peake 2005; CSIRO 2005).

Of these, wheat is generally regarded as the most-profitable agricultural land-use and thus dominates other cropping and livestock activities (Doole and Weetman 2009). Bell and Moore (2012) suggest that increases in climate variability will make mixed crop-livestock farming systems more attractive. Doole and Weetman (2009) suggest that herbicide resistance may result in a return to the traditional ley system with wheat alternating with pastures and sheep. They note, however, a slow but steady shift towards continuous-cropping systems that exclude livestock production, especially on large broad acre farms. This trend is attributed to low profitability of livestock enterprises (Kopke *et al.* 2007) and the ongoing difficulties in rural labour markets (Kingwell and Pannell 2005). The increasing adoption of controlled-traffic farming and the preferences of many young producers for growing wheat are thought to be contributing factors.

3.3.3 Expectations of Climate Change

Climate models predict changes to growing conditions in the Western Australian wheat-belt; carbon dioxide concentrations and temperatures will increase and winter rainfall will decline. More than 90% of climate models predict that there will be winter drying across the south-west of Western Australia at the end of this century compared to last century (IOCI 2010). Increased temperatures will reduce soil moisture, increase disease risk and have a direct effect on growth (van Gool and Vernon 2005). The extent of these changes can only be confirmed in the future; however, several studies have examined the implications of climate change for wheat production in Western Australia under various scenarios.

Using a simulation model, Ludwig and Asseng (2005) studied the effect of higher carbon dioxide levels, increased temperature, and changes in rainfall on wheat yield and grain protein concentrations. For three different locations on a north-south

transect, they explored models of higher temperatures (2, 4 and 6^{0}C), elevated carbon dioxide levels (525ppm and 700ppm) and five different rainfall scenarios. Higher carbon dioxide increased yields especially at drier sites while higher temperatures had a positive effect in cooler and wetter regions in the south. Results differed spatially. In the northern part of the wheat-belt, higher temperatures had a negative effect on yields, whilst in the southern part, higher temperatures had the opposite effect.

The main factor limiting wheat production in Western Australia is rainfall. Since the mid-1970s the region has experienced a significant decrease in winter rainfall and, as Ludwig and Asseng (2005) predict, reduced rainfall will cause a reduction in yields in both the northern and central regions, with clay soils more severely affected. As partial compensation, lower rainfall may increase protein levels, but elevated carbon dioxide may have the opposite effect (Ludwig and Asseng 2005).

Using rainfall and temperature to predict yields, but ignoring carbon dioxide levels, Van Gool and Vernon (2005) estimate reductions in potential yield in the north and south of the agricultural zone, with a large reduction in the far north as a result of reduced rainfall and increased temperatures. Western areas of the agricultural zone should experience increases in potential yield arising from reduced rainfall, resulting in less water-logging and fewer disease problems, and an increase in minimum temperatures and fewer incidences of frosts. Overall, climate change is likely to result in widely spread reductions in wheat yields compared to a small area of increased yields: 34% compared to 8%, respectively.

Ludwig *et al.* (2009) found that growing season rainfall (May to October) decreased by an average of 11% and the total rainfall in June plus July decreased by 20% across nine sites. As deep drainage is highly correlated with annual rainfall, reduced rainfall could potentially reduce the spread of dryland salinity, resulting in benefits that compensate for diminished rainfall. They suggest that rainfall during June and July already exceeds crop demand and a reduction may have little effect. In higher rainfall areas, water logging and nitrogen leeching are serious problems. Consequently, drier rainfall scenarios under climate change may be beneficial. However, Howden *et al.* (2010) question whether initial benefits are likely to be short lived as further reductions later in the century reduce soil moisture.

Overall, Western Australian rainfall projections indicate drier autumn and winter conditions during the growing season and wetter summer patterns (Farre *et al.* 2011). Temperature is projected to increase. Climate change is expected to shift climactic zones and wheat production from north to south (Kingwell 2006; Howden *et al.* 2010).

3.3.4 Data

For Western Australia, we obtained estimates of yields, summaries of variable and committed costs of operation, and the operating size in hectares of alternative enterprises, based on actual farm-level data held in-confidence by farm advisors. The data for 155 farmers across 9 agro-ecological regions (H4, H5, M1, M2, M3, M4, M5, L2 and L3 in Figure 55) during the period 2002-11 were used to estimate Ornstein-Uhlenbeck stochastic differential equations. Figures 57 – 65 show the system dynamics of a representative farm within each agro-ecological zone; parameter

estimates are presented in Table 15. In addition, the committed costs of production for wheat dominant cropping, which differs slightly by zone, are in Table 16. The committed costs of sheep dominant grazing were unclear in the data and have been assumed to be zero for this analysis.

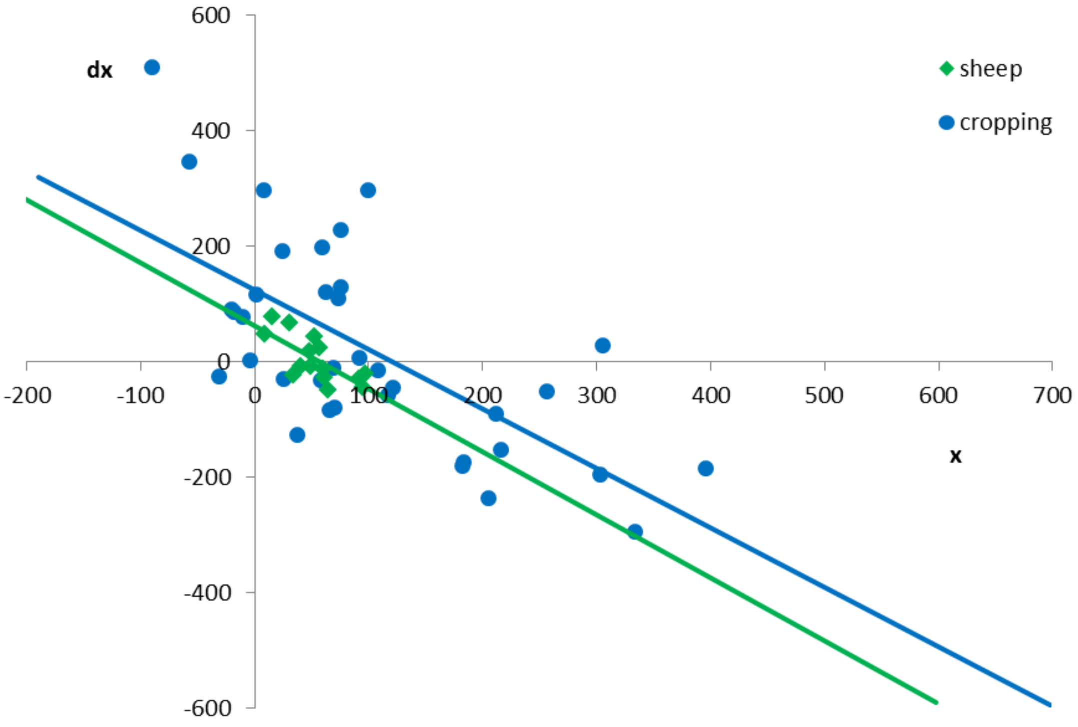

Figure 57: L3 region cropping and sheep gross margin phase diagram ($/ha)

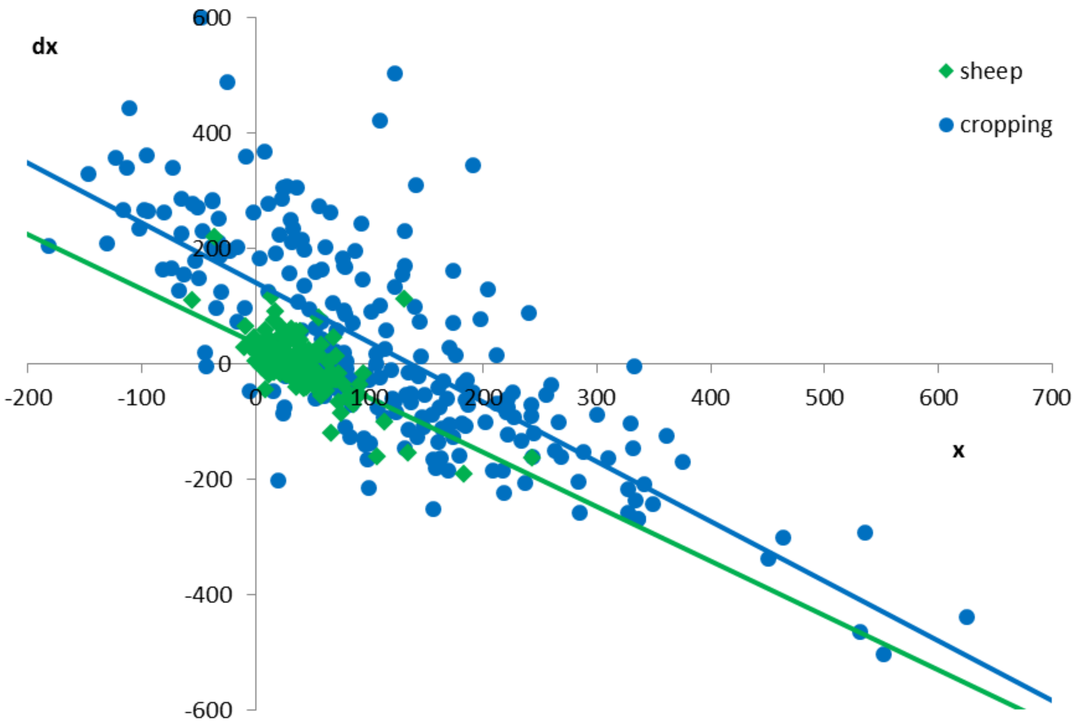

Figure 58: L2 region cropping and sheep gross margin phase diagram ($/ha)

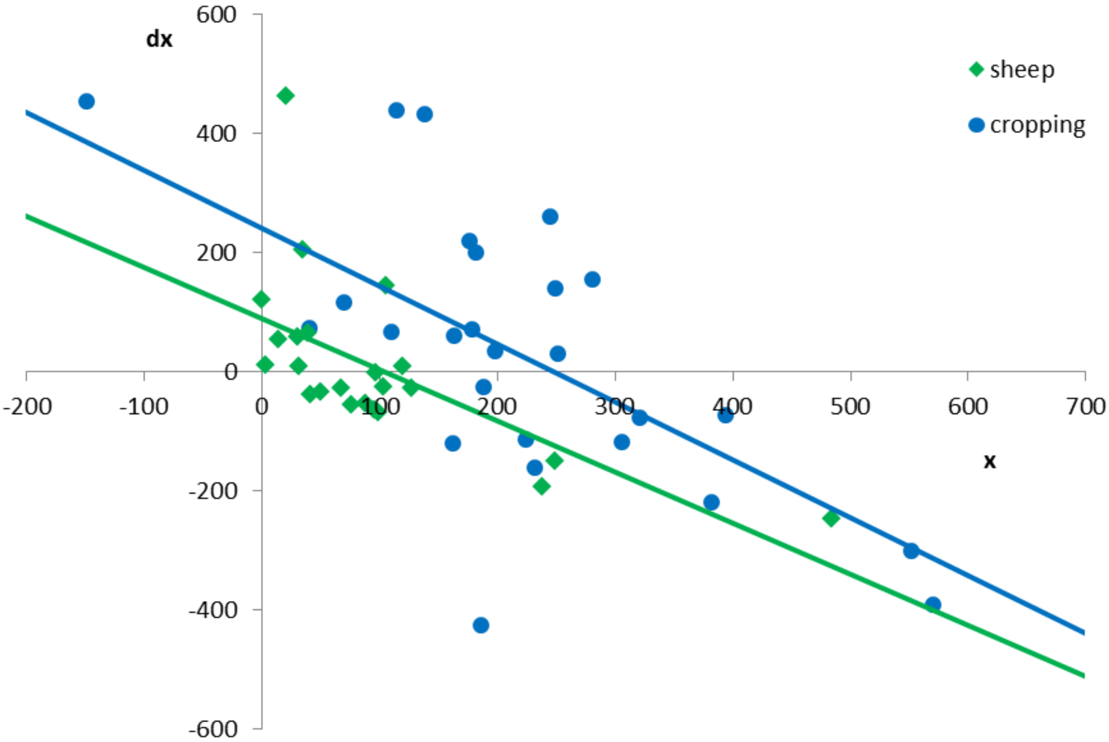

Figure 59: M1 region cropping and sheep gross margin phase diagram ($/ha)

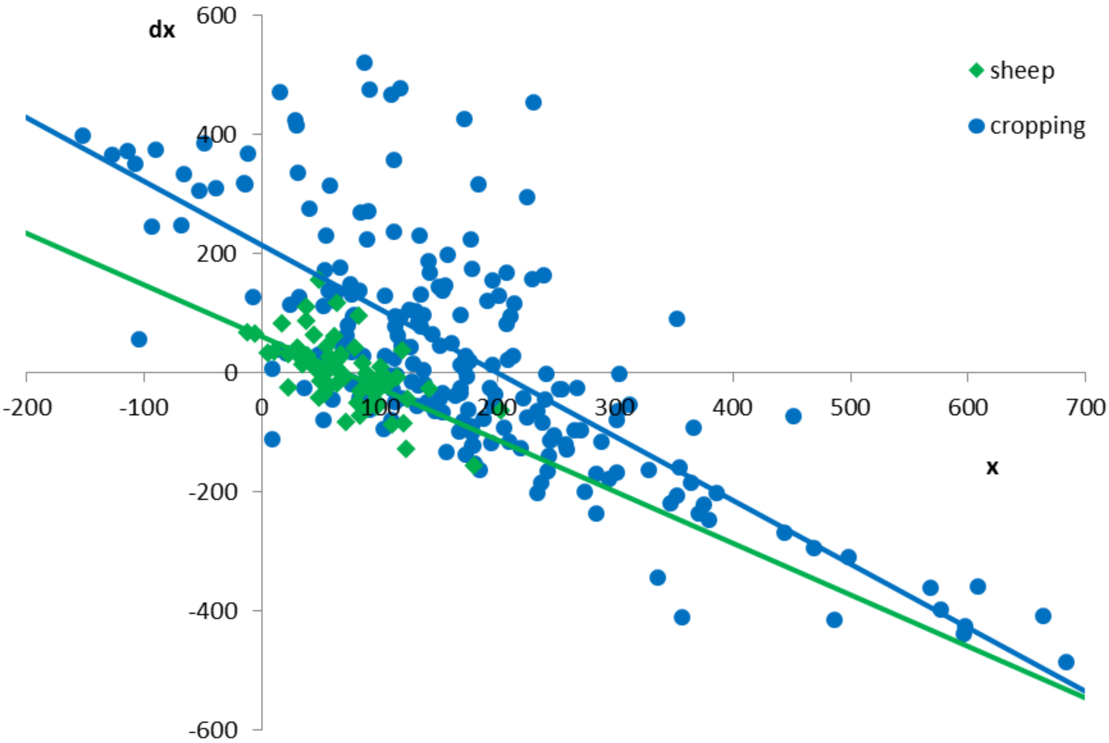

Figure 60: M2 region cropping and sheep gross margin phase diagram ($/ha)

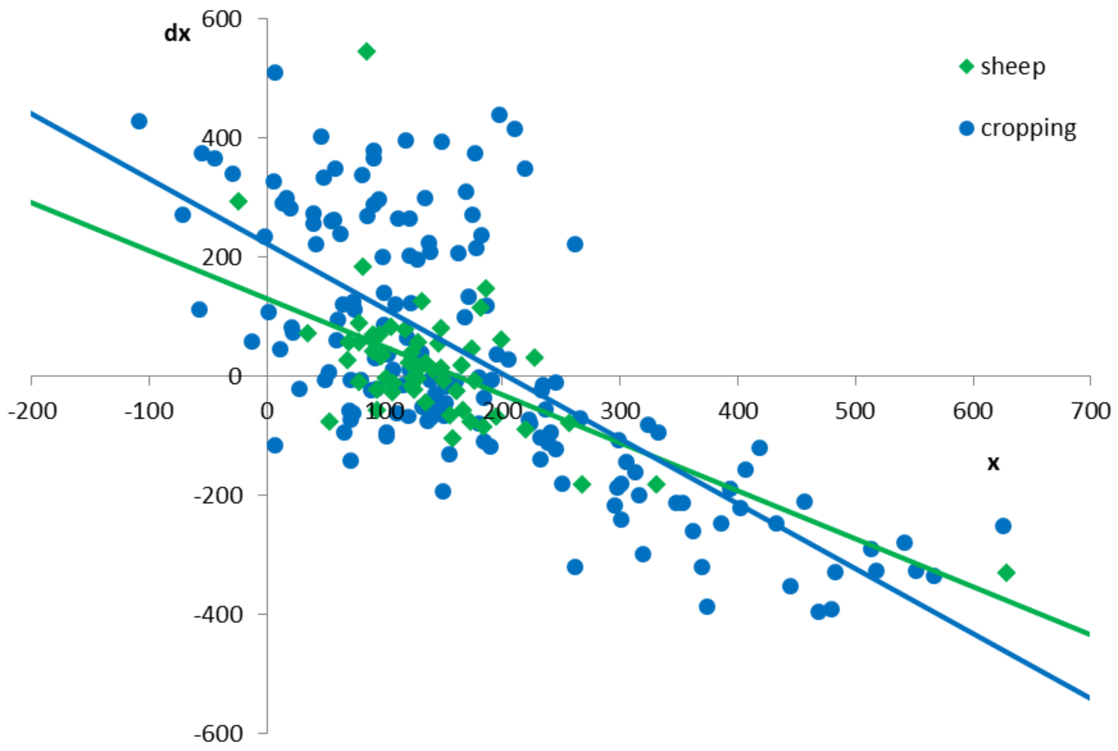

Figure 61: M3 region cropping and sheep gross margin phase diagram ($/ha)

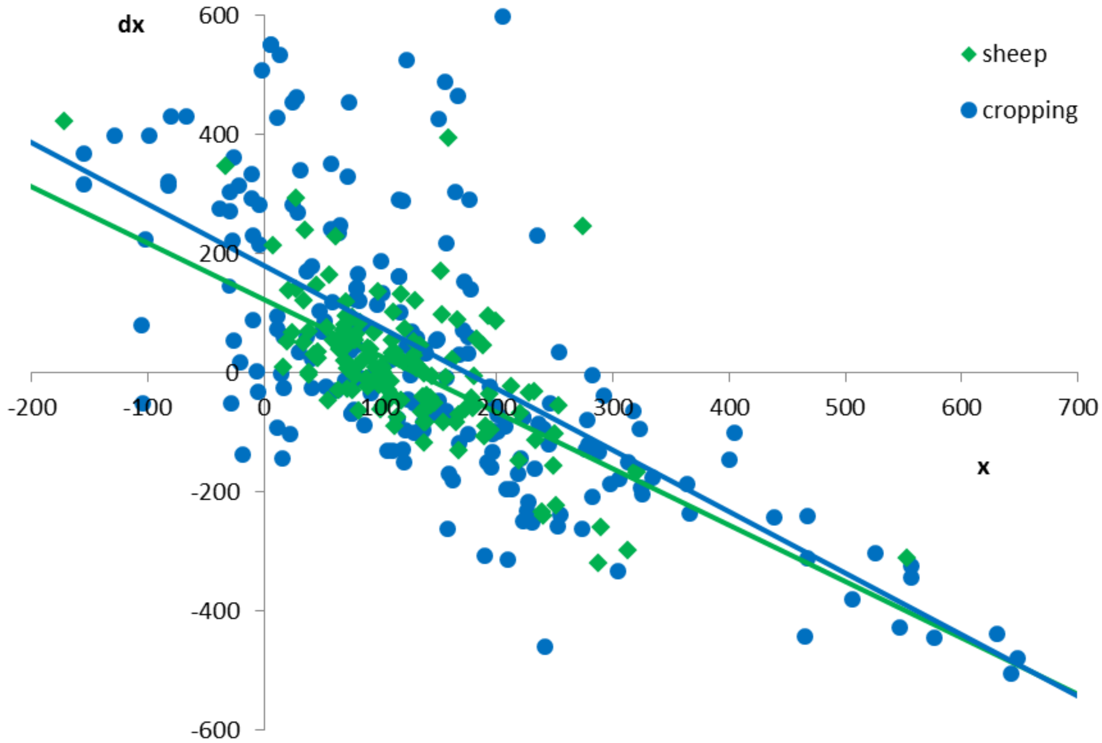

Figure 62: M4 region cropping and sheep gross margin phase diagram ($/ha)

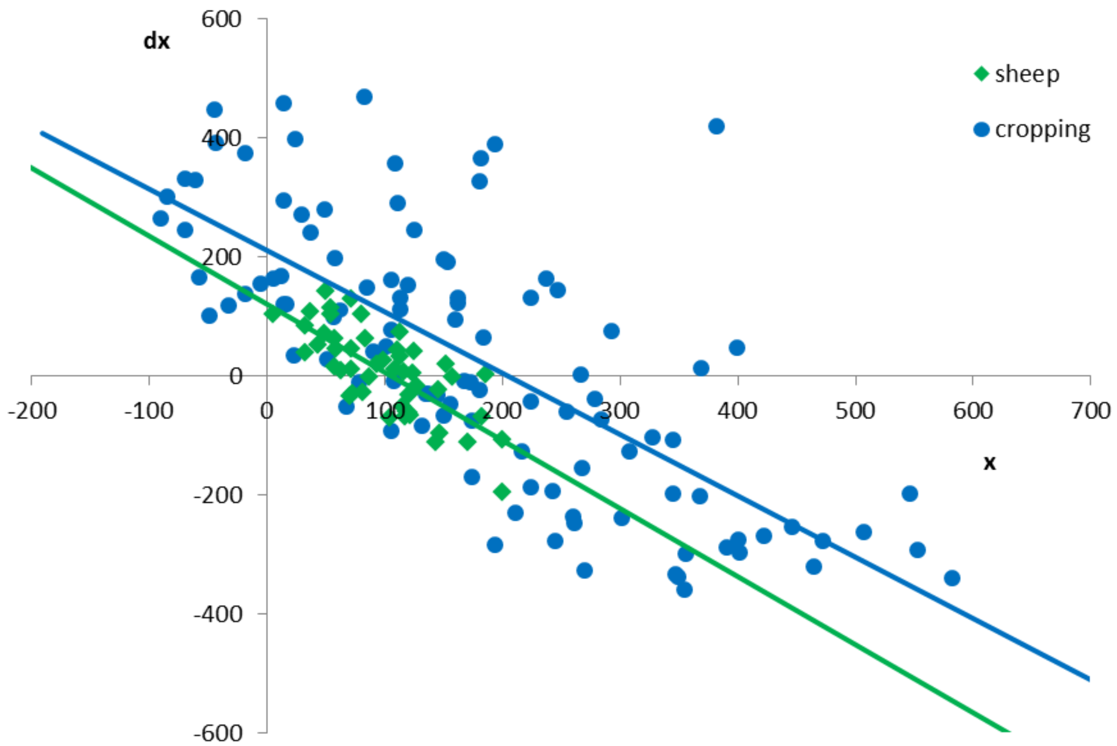

Figure 63: M5 region cropping and sheep gross margin phase diagram ($/ha)

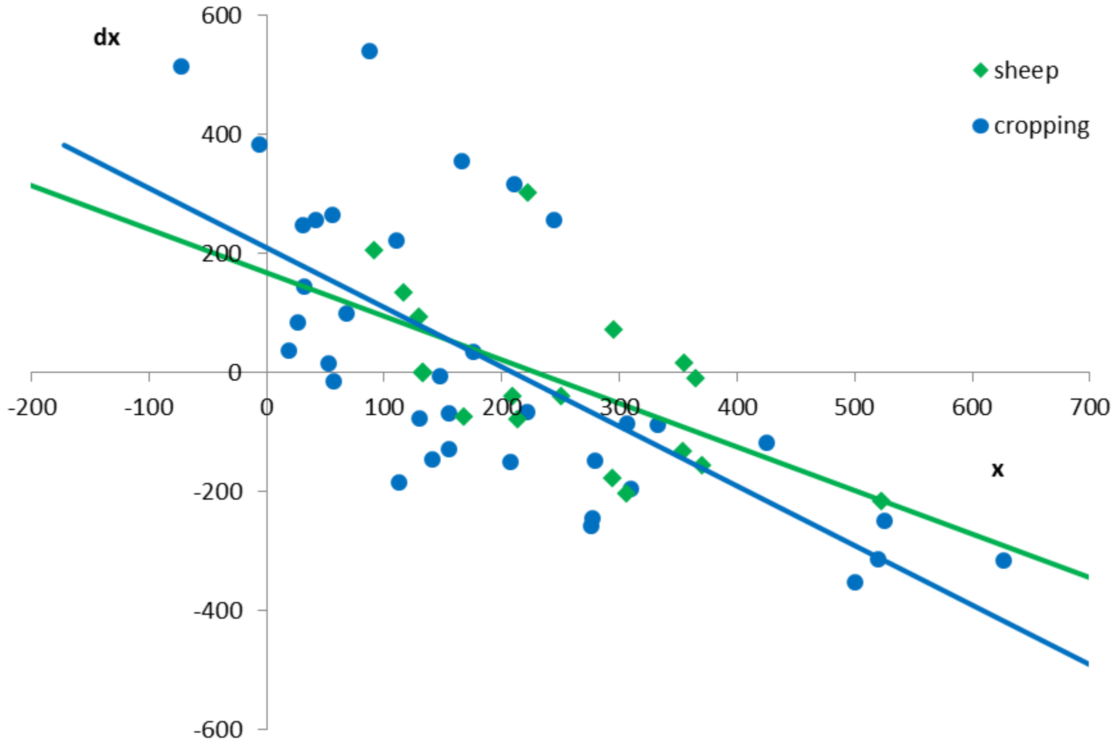

Figure 64: H4 region cropping and sheep gross margin phase diagram ($/ha)

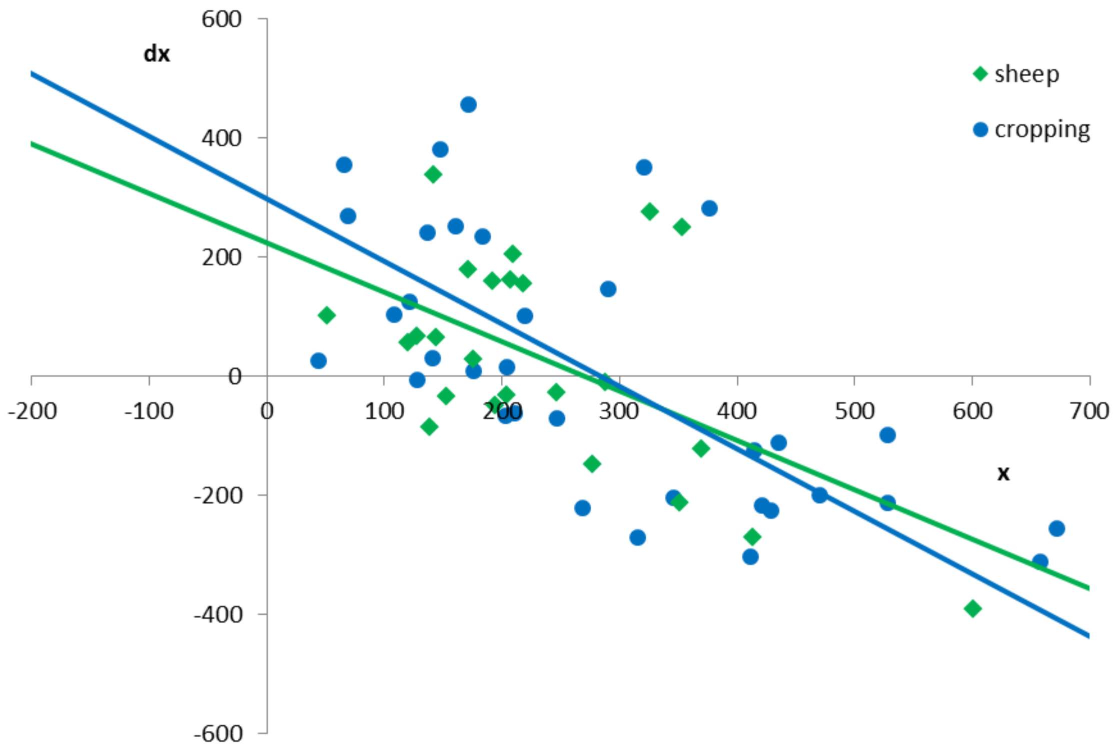

Figure 65: H5 region cropping and sheep gross margin phase diagram ($/ha)

Table 15: Estimated Ornstein-Uhlenbeck parameters for gross margins in ($/ha)

Activity	Parameter	H4	H5	M1	M2	M3	M4	M5	L2	L3
Wheat	b	-0.9988	-1.0493	-0.9699	-1.0684	-1.0924	-1.0331	-1.0315	-1.0349	-1.0294
	μ	208.1	284.4	246.5	198.6	203.4	173.9	204.5	135.4	120.5
	σ	171.8	191.4	174.4	138.9	156.9	173.1	153.1	120.5	132.2
	σ/μ	0.8256	0.6730	0.7075	0.7005	0.7714	0.9954	0.7487	0.8900	1.097
Merino Grazing	b	-0.7309	-0.8291	-0.8584	-0.8663	-0.8061	-0.9478	-1.1444	-0.9437	-1.0914
	μ	226.9	269.3	103.4	70.2	161.0	130.1	106.4	37.5	56.4
	σ	115.8	150.9	111.2	42.7	91.9	86.0	49.2	35.9	28.8
	σ/μ	0.5104	0.5603	1.075	0.6083	0.5708	0.6610	0.4624	0.9573	0.5106

Table 16: Committed costs of cropping production ($/ha)

Activity	H4	H5	M1	M2	M3	M4	M5	L2	L3
Wheat	98.15	81.79	59.27	58.63	61.94	64.99	57.66	48.18	45.26

Table 17: Estimated option values ($/ha), threshold values ($/ha), expected times until exercise (years) and transformation probabilities

Decision		H4	H5	M1	M2	M3	M4	M5	L2	L3
Enter into wheat dominant cropping and possibly exit	w	135.4	197.7	184.9	137.3	145.6	134.7	147.4	99.1	100.5
	x	218.0	272.0	239.0	189.0	202.0	185.0	198.0	138.0	135.0
	T-t	0.8900	0.8400	0.7400	0.9100	0.7200	0.8500	0.8600	0.8800	0.7700
	P_{trans}	0.4679	0.5370	0.5236	0.5398	0.5052	0.4637	0.5240	0.4878	0.4382
Exit from wheat dominant cropping to enter sheep only farm	w	204.8	236.0	169.0	126.2	158.9	147.5	143.0	88.6	94.5
	x	68.0	62.0	-21.0	-1.10	32.0	25.0	8.0	-2.0	5.0
	T-t	0.1600	1.6100	2.9900	2.8900	1.9500	1.6400	2.5800	2.6800	2.1200
	P_{trans}	0.1271	0.0480	0.0172	0.0146	0.0552	0.1107	0.0341	0.0524	0.1075
Exit from sheep only farm	w	10.8	12.6	14.3	2.5	6.0	5.4	1.4	2.9	0.5
	x	-10.0	-10.0	-10.0	0.0	0.0	0.0	0.0	0.0	0.0
	T-t	0.0800	0.0900	0.2260	0.1770	0.1560	0.1500	0.0820	0.2910	0.1490
	P_{trans}	0.0071	0.0091	0.0926	0.0160	0.0137	0.0196	0.0006	0.0782	0.0021

In Table 15, we interpret μ as the mean attractor of either a wheat dominant or sheep system. For instance, in the H4 zone, wheat has a value for μ of 208.1. In any given year the expected gross margin is $208.1/ha. As we move to lower rainfall regions, such as M1, the average gross margin is $246.5/ha and in L2 is $135.40/ha. The rise in average gross margin between H4 and M1 reflects an improvement in the growing conditions for wheat, before declining in the low rainfall zone of L2. We can also calculate the ratio of parameter σ to μ as a measure of relative riskiness of production. For wheat dominant cropping, H4 has a value of 0.8256, and M1 and L2 have values of 0.7075 and 0.8900, respectively. Overall, the medium and high rainfall zones are the most profitable and least risky wheat regions, except perhaps for zones H4 and M4 in the middle of the state. The southern zones are more profitable and relatively less risky for sheep production.

3.3.5 Results

Applying ROADs and TRIPS to these estimated parameters, we examined three representative decision problems. These are (1) entry into wheat dominant cropping with the possibility to exit, (2) exit from wheat dominant cropping with entry into sheep dominant grazing, (3) exit from sheep dominant grazing. Results are presented in Table 17, for the option value *w*, the regime threshold *x*, the expected waiting time at the threshold *T*-*t*, and the probability of transformation from one regime to another P_{trans}. For example, the first decision for H4 'Entry into wheat dominant cropping with the possibility to exit' gives the conditions for withdrawing money from the bank and investing in the growing of wheat.

Each of the regimes has different risks, and the switch will not happen immediately. The results in Table 17 indicate that we will wait until we observe a threshold gross margin (*x*) of $218/ha before we commit to enter wheat production, and are willing to pay an option value (*w*) in forgone potential earnings of $135.4/ha while we wait to see whether the threshold gross margin appears. The expected waiting time at the threshold (*T*-*t*) of 0.89 indicates that once we observe a gross margin of $218/ha we will get in to wheat cropping within a year. The estimated value for the probability of transformation (P_{trans}) is 0.4679 which indicates that within a given 5 year time frame there is a 46.79% likelihood of crossing the threshold and entering wheat production in the H4 region. This decision is also represented graphically in Figures 66 and 67. Figures 68 and 69 represent the decision at H4 to exit wheat dominant cropping and enter merino grazing.

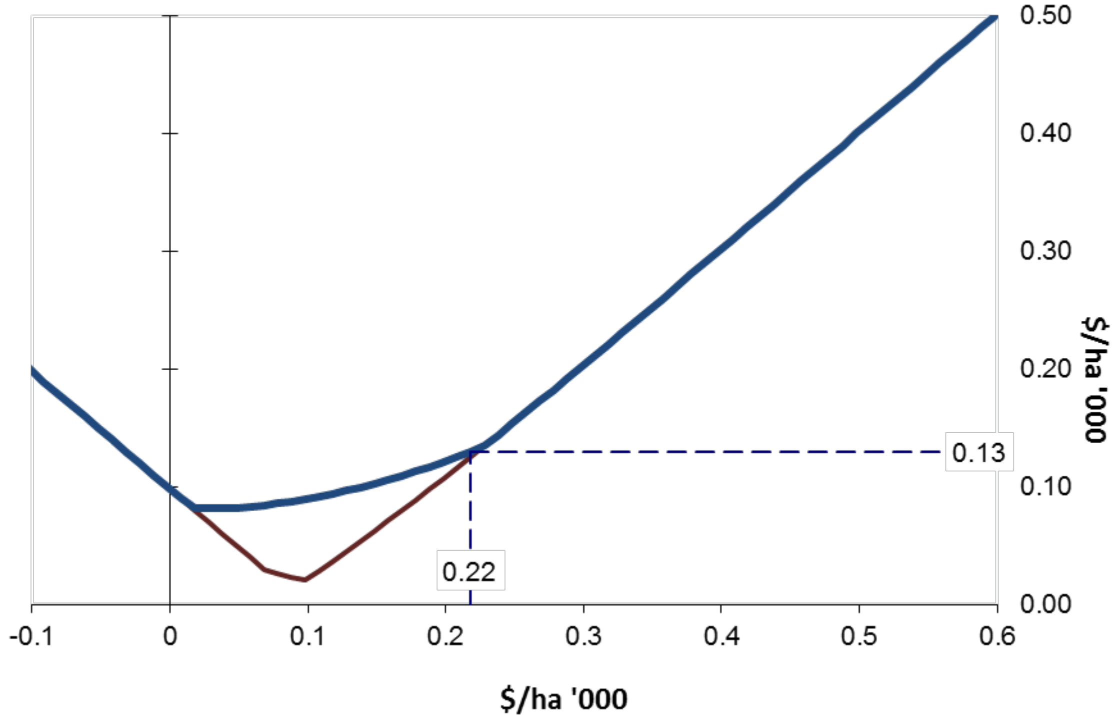

Figure 66: Option value and threshold – H4 region enter into wheat and possibly exit

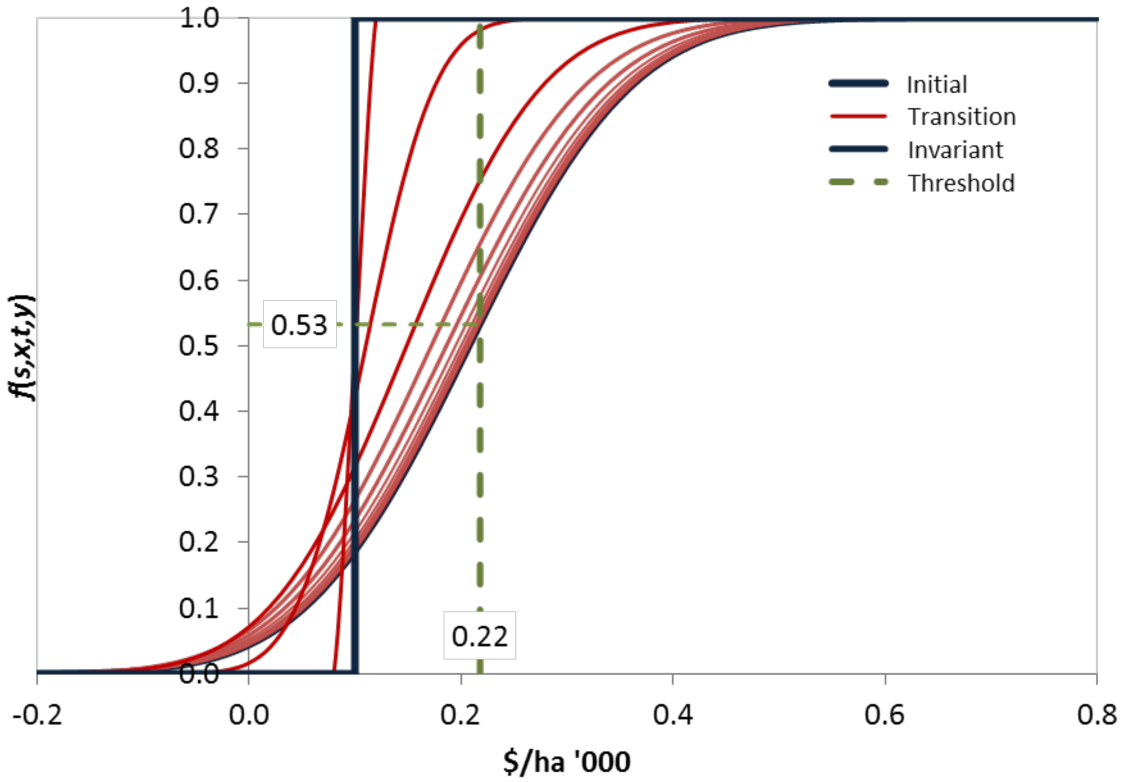

Figure 67: Transformation probability – H4 region enter into wheat and possibly exit

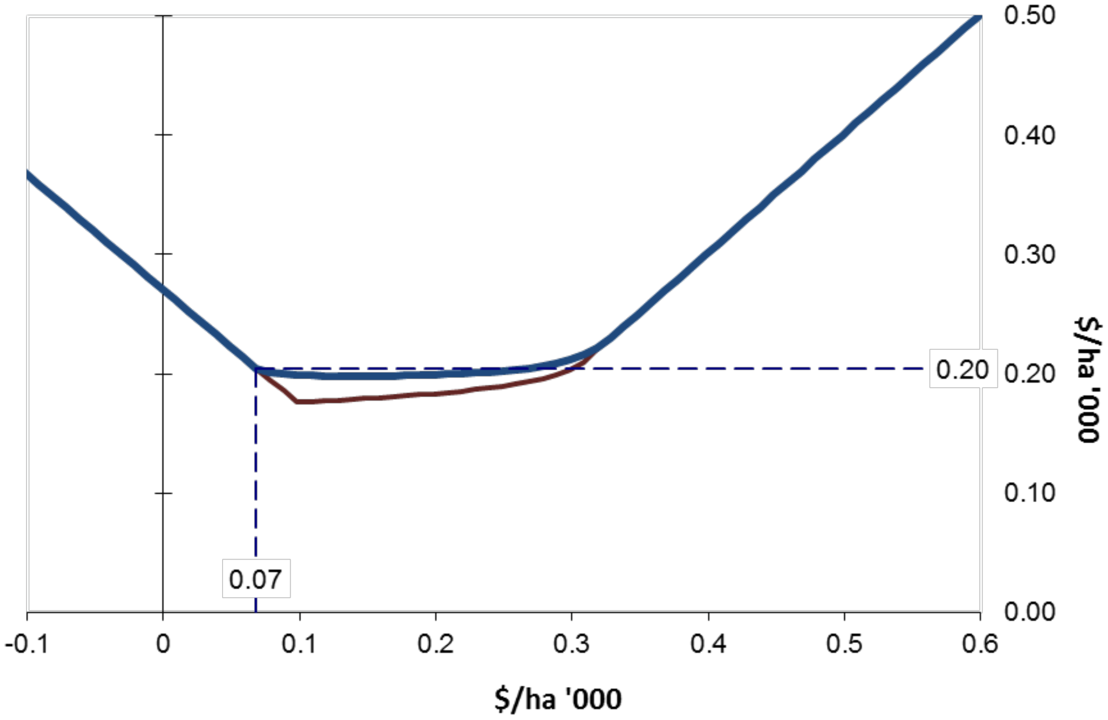

Figure 68: Option value and threshold – H4 region exit from wheat and enter into merinos

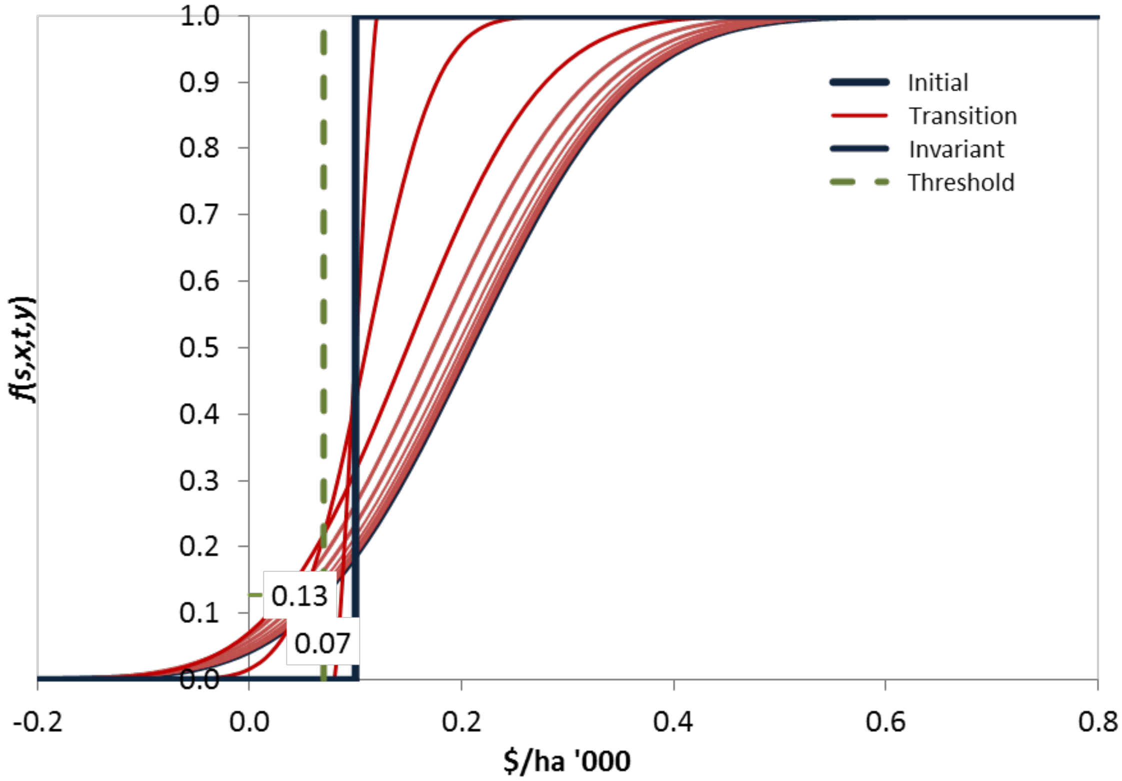

Figure 69: Transformation probability – H4 region exit from wheat and enter into merinos

In Table 17, the results for all agro-ecological zones are similar, regardless of high, medium or low rainfall. The probability of crossing the threshold and entering wheat dominant agriculture is high everywhere. The probability of switching out of wheat into sheep is low everywhere. For those producers already in sheep, the probability of exiting production and no longer farming is almost nil.

In summary, as the climate changes and Western Australia becomes hotter and drier, the southern agro-ecological zones will more resemble the northern zones as they exist now. Wheat production may become less profitable and more risky, but it will remain the dominant form of agriculture in Western Australia.

4. DISCUSSION AND SYNTHESIS

The sustainability of Australian crop and livestock farms is threatened with climate change and increasing climate variability. This research project examines the thresholds for transformational change in wheat dominant agricultural systems across Australia under climate change. This project also aims to build research capacity in the economic analysis of adaptive and transformative responses to climate change by applying the ROADs (Real Options for Adaptive Decisions) framework to agricultural production under climate change.

Applying the ROADs framework has allowed us to assess the effect on farmers' decisions of the effects of climate change on crop and pasture production. By using transects across space as an analogue for climate over time, this project has quantified the thresholds between alternative production regimes where agricultural systems are expected to transform from wheat to mixed cropping, livestock, or extensive grazing. We have estimated the system dynamics of crop and livestock systems and used the system dynamics to calculate the option values that growers will pay to avoid mistakenly switching between production regimes. We have also used new developments in real options analysis to estimate the expected time until producers will switch between production regimes under climate change and the transformation probabilities for these regime shifts.

This project used case studies in South Australia, New South Wales, and Western Australia to enable a comparison across the range of agricultural production conditions that characterize wheat-dominated agriculture in Australia.

1. In South Australia, a spatial transect across Goyder's Line provided an analogue for climate change based on current conditions at Hawker, Orroroo and Clare. This transect models a transition from cropping systems under conditions of relatively high and reliable rainfall near the coast to extensive grazing systems and desert under low rainfall conditions to the north. The average annual growing season rainfall is 486mm at Clare, 225mm at Orroroo and 201mm at Hawker.

2. In New South Wales, a transect based on characteristic farming systems in the south of the state from the east to the west provided a model of possible transitions with climate change based on current conditions at Cootamundra, Temora and Narrandera. This transect models a transition from high to low rainfall, starting with an average of 404mm of annual growing season rainfall at Cootamundra, reduced by 18% to 331mm at Temora, and reduced by a further 20% to 226mm at Narrandera.

3. In Western Australia, a spatial-temporal analogue was based on agro-ecological zones that give similar crop performance. This represents nine different combinations of rainfall level and length of growing season. Typical annual rainfall levels range from around 600mm in the west to about 300mm in the east. The length of the growing season is shortest in the north and longest in the south.

These three case studies ensure the range of agricultural systems with wheat-dominated agriculture is represented. The case study of South Australia represented a

theoretically interesting starting point for developing the real options analytical framework of adaptation and transformation under climate change. This is because the historical importance of Goyder's Line means that alternative production systems in South Australia largely reflect rainfall conditions. This contrasts with the case study of New South Wales where the diversity in production systems and enterprise types also reflects a greater range of land types, financial structures, and social influences. APSIM models for South Australia and New South Wales were used to link rainfall to yields, by taking into account these differences in agricultural systems.

The case study of Western Australia is important because it is the largest wheat producing state in Australia, but also because it has already experienced a reduction in growing season rainfall since mid-1970s. Another interesting feature of agricultural systems in Western Australia is that shifts from mixed crop-livestock farming systems to continuous-cropping systems involve the removal of infrastructure that is important for pastoral enterprises. This reduces flexibility in the choice of enterprise system and introduces a degree of irreversibility in regime transitions between these two agricultural systems. As a comparison with APSIM simulations, for Western Australia, we were provided with summaries from actual farm data that could be used to estimate gross margins for the real options analytical framework.

The three different case studies represent three different possible sequences of regime transition in Australian wheat-dominated agriculture with climate change.

1. In South Australia, the transition consisted of four decision problems between the two regimes of wheat cropping and merino grazing: (1) entry into wheat-only cropping with the possibility to exit, (2) exit from wheat-only cropping with the possibility to enter merino grazing, (3) entry into merino grazing with the possibility to exit, and (4) exit from merino grazing.

2. In New South Wales, the transition consisted of five decision problems: (1) entry into wheat-dominant cropping with the possibility to exit, (2) exit from wheat-dominant cropping with entry into mixed farming, (3) exit from mixed farming with entry into sheep-dominant mixed farming, (4) exit from sheep-dominant mixed farming with entry into sheep-only farming, and (5) exit from sheep-only farming.

3. In Western Australia, the transition consisted of four decision problems: (1) entry into wheat-dominant cropping with the possibility to exit, (2) exit from wheat-dominant cropping with the possibility to enter merino grazing, (3) entry into merino grazing with the possibility to exit, and (4) exit from merino grazing.

The decision problems modelled for South Australia consist of switching into and out of wheat cropping and merino grazing. For New South Wales, additional regimes of mixed farming and sheep-dominant mixed farming are included in the analysis. For Western Australia, the sequence of decision problems modelled is similar to that for the case study of South Australia except that a wheat-dominant cropping regime is modelled rather than a wheat-only cropping regime.

From the model results, the switches between alternative production regimes are described using four key numbers. These are the option value, the threshold gross margin, the expected waiting time at the threshold, and the probability of transformation from one regime to another. For example, in the case study of South Australia we estimate that a representative farmer at Clare who is not currently growing wheat but who has the option to enter wheat-only cropping would value this option at a price of $240/ha. This option price is the value to our farmer of preserving the option to enter into wheat-only cropping, since the opportunity cost of entering includes giving up the flexibility to enter later. Our farmer pays this option value in the form of any losses from remaining in the current regime plus any forgone income they would have expected to earn by switching to the alternative regime, whilst they wait to observe the threshold for switching to the alternative regime.

We estimate the threshold for entering into wheat at Clare as a gross margin of $549/ha. In a riskless world, our decision-maker would start growing wheat as soon as the gross margin was positive, but because returns are uncertain our farmer will wait until gross margins exceed the threshold. The average time our farmer at Clare will wait after observing the threshold price is estimated as 0.04 of a year. This means that on average our farmer at Clare can be expected to quickly commit to entering wheat-only cropping after observing the threshold.

The average waiting time at the threshold tells us how long we can expect our farmer to wait after first observing the threshold, but by itself, this does not allow us to estimate how likely it is that our farmer will switch to wheat cropping. To estimate this probability, we have extended the real options methodology to calculate the probability of a regime switch within a given period of time. Based on this approach, we estimate the probability of entering wheat production at Clare within a given 5 year time period as 53%. Whereas estimates of option values, thresholds, and expected waiting times at regime thresholds facilitate comparisons within the case studies, the probabilities of transformation allow broader comparisons between the three case studies. These are summarised for South Australia and New South Wales in Table 18.

Table 18: Comparison of transformation probabilities for New South Wales and South Australia

South Australia			New South Wales		
Decision	**Transect**	**P_{trans}**	**Decision**	**Transect**	**P_{trans}**
Entry into wheat with possibility to exit	Clare	53%	Entry into wheat dominant cropping with possibility to exit	Cootamundra	45%
	Orroroo	39%		Temora	27%
	Hawker	24%		Narrandera	12%
Exit from wheat and enter merinos	Clare	0%	Exit from wheat dominant cropping only to enter crop dominant mixed farm	Cootamundra	6%
	Orroroo	9%		Temora	23%
	Hawker	22%		Narrandera	38%
Entry into merinos with possibility to exit	Clare	60%	Exit from crop dominant mixed farm to enter sheep dominant mixed farm	Cootamundra	3%
	Orroroo	58%		Temora	24%
	Hawker	53%		Narrandera	44%
Exit from merinos	Clare	0%	Exit from sheep dominant mixed farm to enter sheep only farm	Cootamundra	27%
	Orroroo	1%		Temora	50%
	Hawker	5%		Narrandera	58%
			Exit from sheep only farm	Cootamundra	4%
				Temora	13%
				Narrandera	35%

Examining the decision to 'Exit from wheat and enter merinos' in Table 18 we can see that Clare has a transformation probability (P_{trans}) of virtually zero. There is little likelihood of exiting a wheat production regime and entering a merino production regime. At Orroroo this likelihood is 9% and at Hawker it is 22%. This indicates that if climate at Clare becomes more similar to the climate at Orroroo, then the probability of crossing the threshold becomes significant and even more significant if Clare comes to resemble Hawker. Farms along the transect are very likely to switch to merinos in response to climate change, but very unlikely to exit merinos and abandon farming altogether.

Also in Table 18 we can see that at Cootamundra the 'Exit from wheat dominant cropping only to enter crop dominant mixed farm' decision has a transformation probability of 6%. At Temora, a switch is much more likely at 23%, and at Narrandera it is 38%. This indicates that if Cootamundra becomes more similar to Temora, then it becomes likely that agriculture will be transformed in response to climate change. However, it is unlikely that cropping will ever disappear from Cootamundra. The same cannot be said for Temora and for Narrandera, especially. Indeed the probabilities of

sheep only production and even exiting from sheep and abandoning farming altogether are highly likely at Narrandera.

Western Australia is different. Climate change is predicted to be more severe than elsewhere in Australia, but wheat dominant agriculture is more resilient in Western Australia. Farmers will choose to continue growing wheat. Table 19 summarises the probabilities of switching from wheat dominant agriculture to sheep and potentially switching out of sheep to abandon agriculture altogether.

Table 19: Comparative transformation probabilities for Western Australia

Western Australia						
Decision	**Zone**	**P_{trans}**	**Zone**	**P_{trans}**	**Zone**	**P_{trans}**
Enter into wheat dominant cropping and possibly exit	**H4**	47%	**M1**	52%	**L2**	49%
	H5	54%	**M2**	54%	**L3**	44%
			M3	51%		
			M4	46%		
			M5	52%		
Exit from wheat dominant cropping to enter sheep only farm	**H4**	13%	**M1**	2%	**L2**	5%
	H5	5%	**M2**	1%	**L3**	11%
			M3	6%		
			M4	11%		
			M5	3%		
Exit from sheep only farm	**H4**	1%	**M1**	9%	**L2**	8%
	H5	1%	**M2**	2%	**L3**	0%
			M3	1%		
			M4	2%		
			M5	0%		

The probabilities of entering wheat are high and the probabilities of exiting wheat are low in all agro-ecological zones. Farmers in the high rainfall zones are more likely to switch to sheep, but very unlikely to exit sheep and abandon farming. The medium rainfall zones are wheat dominant and will remain wheat dominant, with the possible exception of M4 in the centre of the state. The low rainfall zones are also strongly wheat dominant. Even as the climate dries and becomes warmer, farmers in the low rainfall zones of Western Australia will choose to grow wheat.

In summary, this research has modelled the major determinant of the impact of climate change on agricultural productivity – the decisions made by farmers. We find that research into the impacts of climate change which does not consider farmers' decisions

can be misleading. Even though the climate is predicted to change more in Western Australia, the effect on farmers' decisions will be less. In all agro-ecological zones of Western Australia, a transformation away from wheat dominant agriculture is very unlikely. Farmers along Goyder's line in South Australia are somewhat more likely to switch out of wheat. By contrast, our results suggest the farmers in southern New South Wales are quite likely to transform their systems away from wheat and into mixed farming systems. The reason, surely, is that New South Wales has better climate and soils and farmers can more easily diversify. The Mediterranean climates and sandy soils of Western Australia and South Australia leave farmers with fewer options to transform their systems.

5. GAPS AND FUTURE RESEARCH DIRECTIONS

During this research project several questions have been raised which we had neither the time nor resources to answer. In one sense these are gaps in previous research, in another, these are fertile grounds for future research. Here we elaborate on three such gaps and avenues for future research.

5.1 Specifying stochastic differential equations

We have spent some time examining various forms of stochastic differential equations (SDE) with which to characterise the dynamics of the agronomic systems. Traditional analysis in real options applies a form of SDE known as Geometric Brownian Motion (GBM), chiefly due to the existence of Black-Scholes analytical solution for the option price. However, dynamics characterised by GBM cannot take negative values (*i.e*. gross margins or profits less than zero) and are explosive with no tendency to revert to equilibrium. GBM does not seem a reasonable model for an agronomic production system. Indeed, GMB is best used to model exponential growth such as for stock market prices.

Instead, we applied a form of SDE known as an Ornstein-Uhlenbeck process which can take negative values and is attracted toward equilibrium, although it characterises the system dynamics as linear. That is, the tendency to revert to equilibrium is the same whether we find ourselves at some point much higher or lower than the equilibrium. Discussion with project collaborators and primary producers more generally leads us to believe that a characterisation of agronomic dynamics in this way has limitations. For example, we might think of high quality farm land as having more good seasons than bad. The tendency for the system to revert to average conditions is stronger and therefore more rapid in below average conditions, and weaker and therefore slower in above average conditions. An example might be the M3 agro-ecological zone of Western Australia shown in Figure 61. Non-linear system dynamics are not yet understood well enough to estimate the stochastic differential equations and calculate option values, thresholds and probabilities.

Our choice of an Ornstein-Uhlenbeck process in this research reflects a number of considerations, chief among them is that we understand the process and it is well known in the literature, making our results more accessible to policy-makers and to practitioners seeking to replicate our analysis. A related consideration is the existence of analytical solutions for the transition and transformation probabilities which we reported here. Future research into alternative forms of SDEs would surely yield interesting results in the analysis of agronomic systems subject to climate change.

5.2 Findings and the role of prices

In the New South Wales and South Australia case studies we made some assumptions about the prices of both outputs (wheat, wool and sheep meat) and inputs (fertiliser, herbicides, labour, capital, *etc*.) which reasonably reflect current conditions. Using actual data in the Western Australia case study meant that prices of inputs and outputs were embedded in the farm earnings and were unknown to us. The difference between these two approaches is important because we know that farmers will adjust their mix

of inputs depending on the relative prices of inputs to outputs and their expectations about the season. The corollary is that the transformation of Australian agriculture depends upon prices which depend upon the transformations of agriculture around the world in response to climate change.

Prices are very important for a small agricultural exporter like Australia. Prices, like year to year farm yields are stochastic processes and like yields they are also highly likely to be affected by climate change. Indeed there is a substantial body of literature projecting long term increases in the real price of agricultural commodities due to a combination of climate change and population stress. In principle, it is possible to include a stochastic series of prices alongside the stochastic yield series to generate a gross margin series in which there are direct impacts of climate change on a farmer's yields and indirect impacts through changing world supply and, hence, prices.

Further research on the effect of prices would likely find some very interesting results. If global wheat yields are likely to decline with adverse climate change, wheat prices are likely to rise. Rising prices may either partially, completely or overly compensate for declining yields. We may see farmers enter wheat production as the climate becomes hotter and drier because rising wheat prices more than compensate for the decreased yields and increased risks. How climate change will affect global food production and prices is important future research for Australian farmers and consumers concerned about food security.

5.3 Sharing the risks of climate change

Australian farmers are not the only ones threatened by climate change. Other industries in Australia are threatened and farmers in other countries are threatened. Between the northern hemisphere and the southern hemisphere, between South America and Australia, climate risks are negatively correlated. An obvious way to deal with a changing climate is to share the risks around the world. While there is catastrophic insurance cover for infrastructure subject to natural hazards, there is limited ability to share production risks. Farmers in Australia diversify their yield risks by buying farms in different geographical locations. This is an expensive form of insurance. Another form of insurance is being piloted in many parts of the world, index insurance. Instead of insuring perils directly, contracts are written on an index of weather or climate. For example, communities in Peru can buy an index to insure against an El Nino event which causes flooding. No similar insurance is available to farmers, industries and communities in Australia.

The ROADs framework used in this project could also be applied to the design of index insurance under climate change and risks. The index could be estimated using GPS, the pure price of risk calculated by ROADs and the probabilities of getting a payout on the insurance calculated by TRIPS. Brokers and aggregators are willing to write the contracts and reinsurers in the Northern Hemisphere are keen to diversify their risks to the Southern Hemisphere. The unanswered question is whether the indexes can be designed well enough for farmers and communities to buy them.

5.4 Future research directions

The methods and tools developed in this research project help bridge the gap between the existing scientific knowledge of the biophysical consequences of climate change and the likely responses of social and economic systems. The decisions made by farmers are the key to understanding the impact of climate change on agricultural productivity and food security. The added risks from climate change affect farmers' willingness to invest in new production technologies or diversification. These decisions are responses to uncertainties about climatic, social and market systems and will ultimately determine the resilience of rural communities subject to climate change.

As farmers in Australia adapt and the quantity and quality of their products evolve, so too, farmers in other parts of the world will adapt to climate change. International commodity markets will respond and, in turn, change the adaptation decisions of Australian farmers. The ROADs framework, developed in this study, provides an approach to examine Australia's international position as a producer, processor and exporter of agricultural commodities. By examining decisions from the farm level to the level of international trade, critical thresholds in climatic and market conditions may be identified. By applying the ROADs framework to assess Australia's competitiveness, policy-makers could draw important insights for strategic planning and policies to adapt appropriately to climate change.

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GLOSSARY OF TERMS

Arithmetic Brownian Motion: one of two non-ergodic, non-stationary processes with known analytical solutions for the transition probabilities. It is the stochastic equivalent of a constant growth or decay. This stochastic process can be positive or negative but tends toward either minus or plus infinity. The scale is unbounded as the time horizon increases. It is not commonly used.

Chance: uncertainty with the possibility of good luck. There are other definitions. In this study, we use the common meaning.

Conditional expectations: an application of a stochastic differential equation as a Martingale. Expectations about the future are conditional upon the current state of the system and the length of the future time horizon for calculating the expected value.

Doob-Meyer Decomposition: the reason statistical estimation equations have additive errors and stochastic differential equations have an expected change and a deviation. Any function of a Martingale is identically equal to its conditional expectation plus or minus a deviation from its expected value.

Ergodic system: a system which is attracted toward equilibrium and has a bounded scale which reaches an asymptote as the time horizon increases.

Finite difference method: a numerical method for solving differential equations. It was invented by engineers and is the most accurate method commonly used in finance to solve option pricing problems. A more accurate method used in engineering is the finite element method.

Fixed or committed cost: a cost that does not change with an increase or decrease in the quantity of goods or services produced. Fixed costs are expenses that have to be paid by an enterprise regardless of activity level.

Gamma process: one of two ergodic processes with known analytical solutions for the transition probabilities. Sometimes called a Feller process, it is one of an infinite number of processes which will converge to an invariant gamma distribution. Even though it is a good representation of many stochastic processes, it is rarely used because it is hard to calculate.

Geometric Brownian Motion: one of two non-ergodic, non-stationary processes with known analytical solutions for the transition probabilities. It is the stochastic equivalent of exponential growth or decay. This stochastic process must always be positive but otherwise is explosive because its scale is unbounded as the time horizon increases. It is the most commonly used stochastic process in finance because it gives analytical solutions to portfolio and option pricing problems. It is the stochastic process underlying the famous Black-Scholes option pricing formula.

Incremental Adaptation: Actions to maintain the essence and integrity of an incumbent system or process. Incremental adaptation actions are minor adjustments that essentially allow an individual, firm or community to continue doing what they are doing. (Productivity Commission 2012)

Information: a collection of knowledge about all the events that have happened and all the events that have not happened. Therefore, the set of information grows, even if nothing happens. If information is complete, there is certainty. If information is incomplete, there is uncertainty and the possibility of risk or chance.

Invariant probability: what most people mean when they say 'probability'. There are a large collection of functional forms commonly called probabilities. These functional forms are the limit as the time horizon goes to infinity of a transition probability for an ergodic system. Because some parameters of the transition probability disappear in the limit, an infinite number of systems can converge to the same invariant probability. Hence, it is impossible to estimate a stochastic process using an invariant probability.

Itô stochastic calculus: one of two popular stochastic calculi, the other being the Stratonovich calculus. Unlike ordinary calculus under certainty, there are an infinite number of stochastic calculi. Only the Itô calculus, however, is consistent with expectations and probabilities. The rules of integration and differentiation differ from the rules of ordinary calculus and create a second derivative in option pricing formulas.

Location: the parameter which anchors a distribution to some point. For a symmetric distribution it is at the center. For an asymmetric distribution it is at the left edge.

Markov process: a dynamic system which has a probability. All the information needed to form the probability is contained in the current state of the system. Probabilities can be for discrete or continuous states of the system, leading to discrete or continuous probability distributions.

Martingale: a dynamic system which has an expected value. All the information needed to form the expectation is contained in the current state of the system.

Monte Carlo simulation: the simulation of a stochastic differential equation. To be consistent with expectations, the system must be a Martingale. To be consistent with probabilities, the system must be a Markov process. In both cases, the simulations must use Itô stochastic calculus, otherwise the Martingale and Markov properties are destroyed.

Ornstein-Uhlenbeck process: one of two ergodic processes with known analytical solutions for the transition probabilities. It generalises the normal process to allow faster or slower rates of convergence toward equilibrium. Like the normal process, it and can be positive or negative. It is the most commonly used stochastic process after Geometric Brownian Motion.

Real options: an extension of financial options to real world decisions about adaptation and transformation. An option is a right but not an obligation. This flexibility has a value called the option price. It is calculated as the benefits that would accrue under the obligation subtracted from the benefits that accrue with the option. Since the option is more flexible, it always has a higher value and a positive option price. Where financial options are a contract between a buyer and seller, real options are an individual investment decision. Where financial options must be exercised at or before an expiry date, real options are perpetual and can be exercised at any time. This makes the calculation of real option prices more difficult. It also means that the option

price and the exercise threshold are decisions by an investor, rather than provisions of a contract.

Risk: uncertainty with the possibility of bad luck. There are many other definitions of risk. In this study, we use the common meaning.

Salvage value: the estimated value that an asset will realise upon its sale at the end of its useful life.

Scale: the parameter which determines the spread of the distribution and whether the tails of the distribution are fat or thin. For a symmetrical distribution it is a positive or negative deviation from the location. For an asymmetric distribution it is a positive deviation from the location.

Stationary system: an ergodic system which is in equilibrium every time it is observed and, hence, can be described by its invariant probability. For a rapidly moving Ornstein-process, the system must be observed fewer than once every 5 time periods. For a slower moving normal process, the system must be observed fewer than once every 7 or 8 time periods. Most statistical analyses assume a stationary Gauss-Markov process which is another name for the invariant normal probability.

Stochastic differential equation: a mathematical model of a Martingale or a Markov process. It has an expected change and a deviation which are sufficient for calculating expectations and probabilities.

Stochastic process: a mathematical representation of an information set. For decisions, an assumption called the law of large numbers is required so that expectations can be formed. The mathematical model of an expectation is a Martingale. If the further assumption of a central limit theorem is made, probabilities exist. The mathematical model of a probability is a Markov process.

Sunk cost: a cost that has been incurred and cannot be recovered. Sunk costs are fixed costs with no salvage value.

Transformational Adaptation: A change in the components of a system from one form, function or location to another. In other words, transformational actions involve a fundamental shift in how, where or what things are done (Productivity Commission 2012).

Transformation probability: the probability that a system crosses a threshold into another regime and is transformed. It is calculated as the transition probability at the point where a stochastic process equals the threshold.

Transition probability: an application of a stochastic differential equation as a Markov process. Transition probabilities are conditional upon the current state of the system and the length of the future time horizon for calculating the probability. Only four analytical solutions for probabilities are known and, for the most part, probabilities must be calculated by numerical methods such as Monte Carlo simulation. Transition probabilities differ from the Bayesian representation of probabilities. Transition probabilities are functions of the time horizon and assume the current state of the

system is observed. Bayesian probabilities do not include time and assume a diffuse prior distribution, as if little is known about the current state of the system.

Uncertainty: a lack of certainty because information is incomplete. There are many other definitions of uncertainty. In this study we use the common meaning.

Variable cost: a cost that varies depending on the quantity of goods or services produced by an enterprise. In total, these rise as output increases and fall as output decreases.

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