A WHOLE-FARM INVESTMENT ANALYSIS OF SOME PRECISION AGRICULTURE TECHNOLOGIES

Brad Knight and Bill Malcolm

Department of Agriculture and Food Systems, University of Melbourne

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For a copy of the full report on which this paper is based, including the appendices with further details of results, contact the authors at b.malcolm@unimelb.edu.au.

Abstract

This study uses a farm in the Victorian Mallee over the period 1998 – 2005 to analyse whole-farm profitability and risks of investing in Precision Agriculture and Site-Specific Crop Management systems. To answer the research questions, a model to predict yield under PA management is developed to simulate paddock and activity gross margins. Analysis is conducted that enables judgements to be formed about merit of investing in some PA technologies.

The case study farm comprised 1400 hectares, with 900 hectares of cereals cropped each year. In this case, investment in Zone Management technologies did not meet the required return on capital. Using the relationship of paddock variability to profitability derived from the simulation data, in a year with median growing season rainfall, a variation of at least 2.5t/ha in yield across the paddock was required to meet the required rate of return on the Zone Management investment. A comparison using certain and uncertain seasonal knowledge assumptions indicated that seasonal variation has a much bigger impact on gross margins than spatial variation on this case study farm.

Two equipment guidance systems were evaluated. Both systems earned more than 8 per cent on capital invested. Real-Time Kinetic (RTK) guidance with a precision of 2cm and a capital cost of $50,000 was outperformed in economic terms by a $20,000, 10cm accuracy Sub-Metre guidance system. The analysis of RTK guidance profitability showed that it would be important that producers who invest in this technology also adopt supporting management practices that enhance crop gross margins or provide other benefits.

Investment in GPS guidance technology can be a worthwhile investment, provided the benefits per hectare are adequate and the capital cost is spread over sufficient hectares. This conclusion is endorsed by many Australian farmers who have moved towards GPS guidance.

Table of Contents

1 - Introduction

Before Precision Agriculture (PA) and Site-Specific Crop Management (SSCM), high degrees of within-paddock variability of production inputs and output were treated as inevitable because they were difficult to measure, let alone manage (Cook and Bramley 1998). Increasingly larger cropped areas and financial challenges, coupled with environmental challenges such as frequent variable and low rainfall, means the risk and consequences of getting things wrong is increasing (McDonough 2005, Cook *et al.* 1996). Whilst PA adoption is increasing in Australia, the precise environmental and economic benefits are largely unproven (Kondinin 2006, Zhang *et al.* 2002, Stafford 2000). The key to the economics of adopting PA technologies is the change in crop performance per hectare and the number of hectares over which the investment is spread. McBratney *et al.* (2005) identifies one of the major limitations of the literature has been the lack of whole-farm focus. Analysis at the whole-farm level is the key to determining net benefits and informing decisions about adoption or rejection of new technologies such as Precision Agriculture technologies.

In an activity as highly uncertain, volatile and uncontrolled as agriculture, more and more sophistication in decision-making, or more and more fine-tuning of applications of inputs, may not necessarily add to farm profit or farmer wealth. The effects of the big risky factors like weather and price may 'swamp' the potential benefits from greater precision in production decisions and methods. As well, as Pannell (2006) has recently reminded agricultural scientists and economists, production plans that represent a maximum profit or optimum way to do things are surrounded by a host of variations that generate very similar results, i.e. payoff functions are flat. There are many ways to run a farm system and achieve roughly similar 'best' outcomes. This is in part a result of the operation of the law of diminishing returns to extra inputs. This principle applies also to extra inputs of information to production decisions, and leads Pannell (2006) to surmise that the benefits of using precision farming technologies to fine-tune input levels is likely to be low.

The existence of flat payoff functions to changes to input mixes of farm plans around the optimum input mix means farm decision-makers will generally be better rewarded by focussing on investing in new technology and moving to new response functions than obsessing about searching for optimum input mixes for existing response functions. This is why the partial budgeting methods to inform decisions about adopting changes are so powerful. The question becomes: 'If I invest this amount of extra capital into the farm system, capital that has new technology embedded, is the expected extra return on the extra capital in the changed system, and the addition to wealth that results, sufficient to make the change worth doing?'

This question is asked of two equipment guidance systems, and of zone management of paddocks for more precise nitrogen applications. Answers are reported in the rest of this paper. A model for predicting yield under PA management to simulate paddock and activity gross margins is used. The results of the investment and risk analysis enable judgements to be formed about the contribution to profit of the precision agriculture technologies. The study concludes with a brief mention of limitations of the model and the research, as well as recommendations for future research in this area.

1.1 Definition of Precision Agriculture

Some definitions focus on the strategic nature of PA: its ability to obtain data and observations and convert this into information for future decision making (Blake *et al.* 2004, Lowenberg-DeBoer and Boehlje 1996). Other definitions focus on PA as a production system and an adaptation of management (McBratney *et al.* 2005, Seelan *et al.* 2003, van Meirvenne 2003, Nemenyi *et al.* 2003, Cook and Bramley 1998, Cook *et al.* 1996). Yet other studies bring PA into a wider context, where PA is defined as a philosophical shift in management to optimise long-term, site-specific and whole-farm productivity, and to minimise impacts on the environment (Whelan and McBratney 2000 and 2001).

At its most general, PA has been defined as information technology applied to agriculture (Lowenberg-DeBoer and Boehlje 1996). This basic definition is more wide-reaching than it may first appear, in that it does not define PA to the farm-gate, as do some other definitions. It is forward-looking because potential benefits of PA may also extend beyond the farm-gate, to the extent of tracking product, monitoring quality assurance and measuring environmental performance (McBratney *et al.* 2005). In this study, PA (SSCM) will be analysed specifically as a technology rather than a change in farm management system as not all potential benefits and costs of the system are considered.

Taking the above points into account, the definition of PA for this study is:

> ‘A system involving the use of technology in monitoring and controlling the production system, enabling data collection to improve information. Through the use of technology, it aims to optimise (spatially and temporally) long term, whole-farm productivity and minimise environmental impact of the farming system.’

Further, Site Specific Crop Management (SSCM) is the idea of doing the right thing, in the right place, at the right time (Bongiovanni and Lowenberg-DeBoer 2004). However, with the above definition of PA in mind, consider a more formal definition from Whelan and McBratney 2000):

> ‘Matching resource application and agronomic practices with soil and crop requirements as they vary in space and time within a field.’

Whelan and McBratney (2000) describe the essence of SSCM through implicitly outlining the objectives of SSCM. These are optimising production efficiency and quality, through matching resources more closely and in doing so minimising environmental impact and risk.

In Figure 1-1, PA/SSCM is further placed into context within the broader PA field. Site-Specific Crop Management offers a solution that may allow profitability and environmental objectives to be considered in risk management.

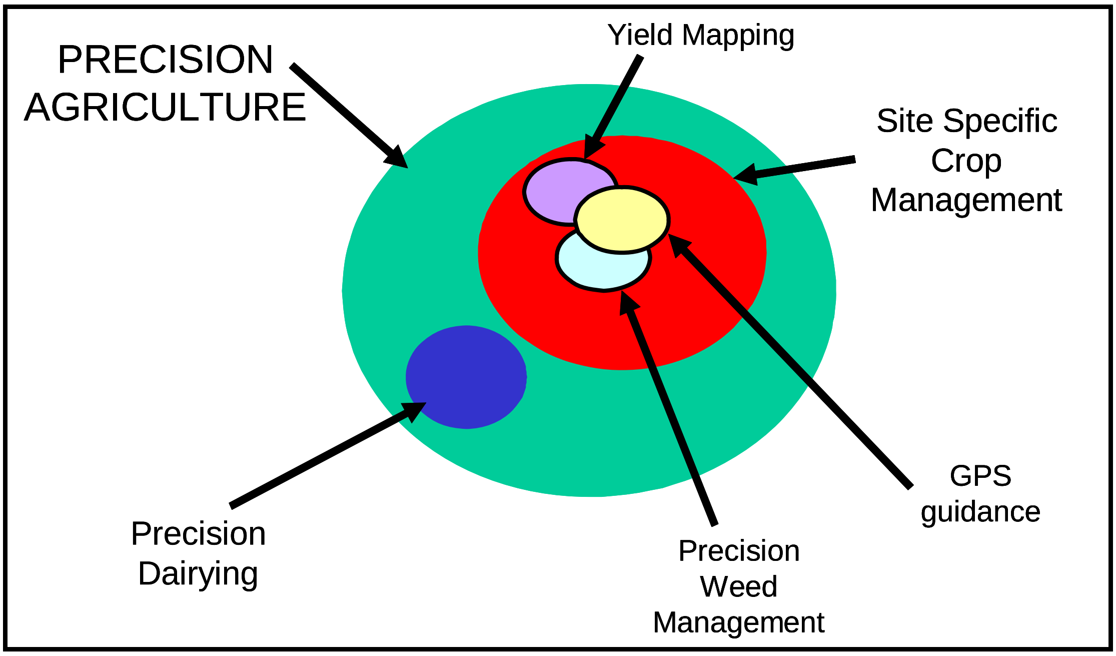

Figure 1-1 **Diagrammatic representation of PA/SSCM relationships**
(Adapted from Whelan and McBratney 2001)

1.2 Derivation of paddock management zones for a Zone Management Approach

Delineation of paddock Management Zones is the key to Site Specific Crop Management adoption. Variability has significant influence on agricultural production especially yield, soil and crop variability (Zhang *et al.* 2002).

A Management Zone is defined as 'a portion of a field that expresses a homogeneous combination of yield-limiting factors for which a single rate of a specific crop input is appropriate' (Zhang *et al.* 2002). Further, management zones should display significant differences in yield for variable rate application of crop inputs to be worthwhile (Cupitt and Whelan 2001). Ensuring that observed differences in crop yield between potential management zones is vital however can be difficult (Cupitt and Whelan 2001).

Whelan and McBratney (2003) provide an outline of a number of techniques used in the delineation of potential management zones, including:

- Polygons hand-drawn on yield maps or imagery
- Classification of remote sensed imagery from an aerial or satellite platform
- Identification of yield stability patterns across seasons using statistical methods such as correlation co-efficients, temporal variance or normalised yield classification
- Multivariate statistical analysis (cluster analysis) using seasonal yield maps and remotely sensed data that impacts yield.

Yield maps can provide a useful basis for zone delineation as they integrate all the compounding factors on crop growth such as soil and climate factors (Welsh *et al.* 2003). Welsh *et al.* (2003) also describe an average yield strategy to define paddock Management Zones, and when delineating zones normalised yields to account for the temporal variability of crop yields. Fisher and Abuzar (2005) also discuss a method of zoning paddocks based on high, medium and low-yielding areas and providing these zones are stable over time, can be managed to maximise the activity gross margin for each zone with confidence.

Seasonal variation in climatic conditions, causing crop development and performance to vary dramatically between crop years, can be large and difficult to predict in Australian conditions. Ambiguity because of climate variability that leads to temporal variability in yield and the yield classification of each zone is a common problem (Wong and Asseng 2004). A way to deal with this problem is described by Wong and Asseng (2004) who assign a probability to a spot in a paddock that it belongs to a particular ‘zone’ rather than assigning it a discrete zone. Deriving management zones based on historical yield tends to ‘smooth’ out seasonal variation, for this reason Welsh *et. al* (2003) do not recommend the use of historic yield data as the basis for varying N application rates. Welsh *et. al* (2003) assessed a strategy that took account of in-season crop variability that produced more promising results than the yield-based approach. They found that in general the most effective strategy would be a uniform management approach (Welsh *et. al* 2003).[1]

1.3 Crop yield modelling

Crop yield models range from relatively simple crop models such as described by Hammer *et al.* (1987) and Sinclair and Amir (1992) in O’Leary and Conner (1996a) to very detailed models such as APSIM (Lilley *et al.* 2003). For the purpose of this research, the crop model is designed to derive estimates of yields and input costs (nitrogen) for different precision agriculture methods.

O’Leary and Conner (1996a) developed a crop growth model, where crop growth is determined as a function of transpiration efficiency (TE) adjusted for temperature extremes and nitrogen deficiency. A similar measure to transpiration efficiency, water use efficiency (WUE) is used in this study, and is also adjusted for nitrogen deficiency but temperature effects on yield are not considered.

The yield model developed as part of this research can be categorised as a mechanistic model, as described by Cook and Bramley (1998). Cook and Bramley (1998) outline several studies that utilise mechanistic models for evaluating site-specific management by adapting such models over space. In addition, many fertiliser recommendations are based on the results of mechanistic models.

[1] There is a large body of literature relating to the delineation of management zones, most of which is highly technical. For further information on management zone delineation consult Whelan and Taylor (2005), Whelan and McBratney (2003), Welsh *et al.* (2003) and Fleming *et al.* (2000)

Simulation studies, where crop yield is modelled, typically overestimate the profitability of a PA technology because these models do not always consider yield-limiting factors (Lowenberg-DeBoer 2003). Whilst nitrogen limitations are considered in this study, other limitations such as pests and diseases are not taken into account. Further, reasons why a certain part of a paddock is consistently poor yielding are not investigated.

There are numerous studies using mechanistic models, but the extension of the approach has been questioned (Cook and Bramley 1998). Cook and Bramley (1998) outline the inherent difficulty in estimating site-specific soil fertility levels and the residual value of applied nitrogen. The model used in this research has been developed to assume that residual nitrogen levels are zero and that added nitrogen does not remain available within the soil because it is either taken up or lost from the system.

The Water Use Efficiency (WUE) concept is used extensively in southern Australia as a means of comparing crops, seasons and management options and predicting target or expected yield (Freebairn *et al.* 2004). The concept has been instrumental in models of crop yield and is used in the design of cropping strategies in dryland systems and identifying plant traits associated with tolerance to water deficit (Caviglia and Sadras 2001).Water Use Efficiency (WUE) is the ratio of grain yield to water use by crops and provides a measure of the technical crop productivity (French and Schultz 1984, Appendix II). It is an attempt to simplify the complex mechanisms relating water use and yield to a single measure (Angus and van Herwaarden 2001, Asseng *et al.* 2001).

1.4 Previous economic studies

Precision Agriculture has been given more attention in the literature about agriculture and soil science than in the agricultural economics literature (McBratney and Whelan 1999). The focus of past economic studies has been predominately partial budget analysis or spatial econometric analyses. McBratney and Whelan (1999) divide the benefits of precision agriculture into three broad categories: immediate private benefits, benefits from gains in private and social sustainability and benefits from changes in the environment. In this study, the focus is on immediate private benefits only. The adoption of technology in an Australian context relies solely on private benefits; the institutional framework within which Australian agriculture operates is not generally conducive to the correction of market failures (positive externalities or reduction in negative externalities). The decision maker (farmer) will not usually be rewarded financially for contributions to social sustainability and environmental benefits, so we must assume private benefits drive investment in PA technologies.

The basic principle at work with PA benefits is to increase the likelihood of achieving beneficial outcomes by using inputs better and increasing the difference between costs and income (Gross Margin) (Cook and Bramley 1998). A starting point for the study is that temporal uncertainty is so great that the optimal risk strategy is to continue with uniform treatment (McBratney *et al*. 1997).

There are several potential benefits of precision farming, including increased crop yields, applying inputs more cheaply through improved process control and reducing relocation of agrochemicals to the environment (Weiss 1996). Swinton and Ahmad (1996) also categorise benefits into those that affect profitability, business risk and environmental quality. Profitability depends on the extent of spatial variability of soil conditions, the size of a field and uncertainty about output and input prices (Murat and Madhu 2003). Increased crop yields may result due to carry-over benefits from applying ameliorants and variable rate information (Swinton and Ahmad 1996). Both controlled traffic and inter-row sowing through the enabling technology may result in yield benefits although these are difficult to quantify and can exhibit large temporal variation (Rainbow 2004).

Along with increased income from improved yields, improved input control can give gross margin benefits within seasons (Swinton and Ahmad 1996). Considerable savings occur with fuel, seed, chemical and fertiliser. Reduced overlap can reduce fertiliser, seed and spray use by 4% for a given yield (Rainbow 2004). Controlled traffic can lead to reduced draft requirement and more timely operations (Rainbow 2004). In addition, multiple inputs can typically be managed with the same SSCM investment.

Early economic evaluation in the US, such as that from Lowenberg DeBoer and Boehjle (1996), found that once the full cost of developing and implementing variable rate fertiliser is considered, it is unprofitable, especially if application was restricted to one or two fertilisers. This present study is restricted to only one agrochemical, nitrogen. This will be the minimum benefit possible, as the gains can be extended with the same technology to other practices such as variable rate herbicides and other fertilisers.

Cook *et al*. (1996) found under Australian conditions, that any major benefit from more accurate placing of phosphorus was outweighed by the risk of losses due to climatic uncertainties.

James and Godwin (2003) report that there was no economic benefit from variable rate application of nitrogen to different soil units based on historic yield, or any other form of zone delineation.

Ancev *et al.* (2004) outline a variable rate nitrogen case study on sorghum (1999-2000); using three different N rates across three management zones within the field. Based on results from a yield monitor, a response function was estimated for each zone (Ancev *et al.* 2004). The response functions show an almost linear response to N in each zone, with optimal nitrogen rates about 70kg/ha. Whilst this shows uniform management to be the best approach, the study indicated that the economic profit maximising nitrogen rate is 70kg/ha, compared to the average application of 210kg/ha. At this level of nitrogen, profit decreases and implications arise for environmental quality (Ancev *et al.* 2004).

Godwin *et al.* (2003) outline an economic analysis of the potential for precision farming in UK cereal production. They looked at several different PA/SSCM systems and determined the likelihood of profitability and break-even farm sizes, using a partial budget approach. They advised that the cost of practicing PA depends on the technology purchased, depreciation and current interest rates, and the area of crops managed.

McBratney *et al.* (2005) note that existing PA research lacks a whole farm focus with 90 per cent or more studies focussing on single fields on experimental farms or commercial farms. Further, they argue that perhaps the biggest generic deficiency is a well-constructed quantitative formulation of optimisation criteria for cropping management that includes environmental impact (McBratney *et al.* 2005).

2 - Materials and Methods

In this section the development of the yield and gross margin simulation model and the investment analysis framework is detailed. Sparse data, simplifying assumptions and models are used in some instances because some information is unknown or outside the scope of this research. Examples include manipulation, validation and cleaning of yield data, and the associated delineation of Management Zones. Whilst sophisticated yield prediction and forecasting models are available, such models are for answering different questions. As part of this, assumptions regarding the complex nature of crop-nitrogen interactions were used to simplify the analysis.

The materials and methods are presented in the sub-sections The Case Study Farm, Data Collection, Data Production and Data Output and Results.

2.1 The Case Study Farm/Paddocks

This study uses 11 paddocks totalling 1400 hectares of a farm near Birchip, in the Victorian Mallee. Median Growing Season Rainfall (GSR) (April to October) in this Mediterranean environment is 246mm per annum. Soils in the area are mostly Vertic Calcarosols generally with gilgai microrelief, with the depressions associated with gilgai often containing Vertosols (Rodriguez *et al.* 2006). Crop water use and production is highly related to the presence of gilgai and associated soil changes, as well as associated variability in the depth at which sub-soil constraints (high levels of salinity, sodicity, and boron) are found (Rodriguez *et al.* 2006).

The 11 paddocks chosen vary in size between 22ha and 200ha, ranging in empirical WUE between 14.18kg/mm/ha and 22.19kg/mm/ha. Paddock variability is also represented well, with standard deviations varying between 2.67 and 9.41, with the coefficient of variation (cv) of WUE of paddocks ranging between 0.18 and 0.42 (Table 2-1, Appendix X- Table X-1).

For the purposes of this research, monthly rainfall data from the Birchip Post Office is used in predicting yield, as well as historical rainfall deciles (from 1899 to 2005) in the formation of yield expectations (Appendix XIII).

2.2 Data collection

Specific data used as input to the model for predicting yields includes historical monthly rainfall data from the Birchip Post Office (1899 to 2005) in the Victorian Mallee region for the formation of deciles (Appendix XIII). More specifically, monthly rainfall data for the period 1998 – 2005 is used in conjunction with actual crop rotation data and empirical WUE estimates for individual paddock zones (derived from historical yield maps) to simulate yield and nitrogen use. Yield and nitrogen applied data is used to simulate activity gross margin, using input costs and price data for the area from data collected as part of a Birchip Cropping Group (BCG) Farming Systems Trial (Appendix XII). Precision Agriculture investment information, such as the cost of PA technology is drawn from several sources.

The raw data that is being used, as detailed above, requires some manipulation before it can be used in predicting yield. This is especially true of the yield data, which involved derivation of management zones. As outlined in the literature review, there are numerous approaches to deriving management zones. In this study an approach based on zoning paddocks by historical yields is used, with paddocks divided into zones of different potential productivity based on empirically derived estimates of Water Use Efficiency. A detailed outline of the method used is provided in the Appendices, but a brief summary of the method used is detailed below.

Geographically referenced individual data points in each yield data set were summarised into a reduced set of representative data points, with each of these new points representing a geographically referenced area of the paddock. This was done for each year and the same geographically referenced areas of paddocks were analysed to derive the empirical WUE (WUEe) for that part of the paddock. The distributions of these WUEe across each paddock were than analysed and each part of the paddock further defined into Management Zones.

Each Management Zone was then assigned a mean and standard deviation of WUEe based on the observed data. This method may have reduced some of the variability but represents overall paddock variation. The 11 paddocks chosen for the study were those that had the best yield data sets and had the highest occurrence of cereals in the rotation over 1998 – 2005.

Table 2-1. **Paddock details and the Marginal Gross Margin ($/ha) attributable to Zone Management**

	Paddock Details						Marginal Gross Margin Benefit Attributable to Zone Management over Uniform Management								1998 - 2005
Name	**Size**	**No Zones**	**WUE**	**SD**	**CV**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**Average**
Barrell	22	3	16.29	2.93	0.18	$2.57	$8.01		$7.95	-$0.01			$6.65	$5.03
Bishes West	152	4	17.16	3.21	0.19	$3.23					$7.02		$8.18	$6.14
Clovers East	120	4	14.18	2.67	0.19	$1.71		$6.87		-$0.04	$4.69	$1.48		$2.94
Far West	66	4	18.72	6.74	0.36	$7.33		$19.42		$0.00		$6.70		$8.36
Jack Sheans	140	3	17.43	4.81	0.28	$8.23		$25.96		-$0.03		$7.65	$15.95	$11.55
Jil Jil East	156	4	22.19	9.41	0.42	$3.54	$10.01		$8.24			$3.27	$6.61	$6.33
Landers	181	4	16.12	4.18	0.26	$5.76	$13.05		$12.95	-$0.08	$9.49		$9.50	$8.44
McKenzies North	110	5	14.88	3.07	0.21	$2.70		$9.91		-$0.01	$6.32		$7.39	$5.26
Perns	200	6	17.02	5.04	0.30	$4.44	$12.17			-$0.01	$8.98	$4.06		$5.93
Sandhill South	88	5	17.72	5.90	0.33	$4.88	$13.39		$11.18	-$0.15	$7.24	$2.95		$6.58
Spittles	160	4	12.34	5.27	0.43	$7.45		$22.17		-$0.01	$14.01		$17.19	$12.16
Totals	**1395**					**$51.84**	**$56.62**	**$84.32**	**$40.32**	**-$0.35**	**$57.75**	**$26.11**	**$71.46**	
Averages			**16.7**	**2.56**	**0.29**	**$4.71**	**$11.32**	**$16.86**	**$10.08**	**-$0.04**	**$8.25**	**$4.35**	**$10.21**	**$8.22**

2.3 Data Production - The Precision Agriculture Simulation and Investment Model (PASIM)

The Precision Agriculture Simulation and Investment Model (PASIM) is a Microsoft Excel based model that uses a yield potential model developed by French and Schultz (1984) to simulate yields under different PA systems. This simulation and investment model was developed as part of the study. Yields and nitrogen inputs are simulated and, with input cost and price assumptions, used to produce activity gross margin (AGM) results. A method called Monte Carlo simulation is used. This involves numerous iterations of the model using randomly sampled values for key input variables. Frequency distributions around the expected value of activity gross margins are produced. This information is used in discounted cash flow analysis to evaluate the return on capital and contribution to wealth (Net present value) of using the precision agriculture methods in question.

Two broad types of variables are used in PASIM, fixed variables and distributed variables. Fixed variables are those that are assigned a most likely value and are held constant for each iteration of the model, such as soil organic carbon, protein to nitrogen conversion factors and the nitrogen harvest index. Table XI-1 in Appendix XI has full details on these variables. Distributed (Crystal Ball) variables are those that have a probability distribution associated with them. Included in these variables are price and input costs, as well as growing season evaporation. Tables XII-1 and XII-2 in Appendix XII (obtainable from the authors) give a full account of these variables and the distributions assumed.

2.4 Basic Principles of PASIM

In the following section the basic components of the analytical method are discussed in further detail. The basic components of the model are the French and Shultz WUE measure, yield potentials and nitrogen budgeting, farmer expectations of rainfall, Activity Gross Margins and Uniform vs. Zone Management.

2.4.1 Water Use Efficiency in PASIM

The single most important concept underpinning the model is that of Water Use Efficiency. In the context of PASIM, the concept of Water Use Efficiency (WUE) is used successfully as an indicator of system performance (Freebairn *et al.* 2004). A justification of the use of this concept is outlined below.

Predicting crop yield is complicated. Measuring and interpreting water use efficiency and nitrogen use efficiency in the field are often hampered by the complexity of crop systems. This is compounded by seasonal variability in rainfall and conditions of crop development and the variation in crop responses to soil types and agronomic management (Asseng *et al.* 2001). Soil type has a large impact on both WUE and the efficiency of nitrogen use, because of different water-holding capacity’s of the soils, soil evaporation and the interaction between these factors, rainfall patterns and management (Asseng *et al.* 2001, Siddique *et al.* 1990).

Variability of climate and soil properties interact in such a way that rainfall information alone will provide an incomplete picture of the effect of climate variability on yield (Rodriquez *et al.* 2006). In addition, the specific interaction of the crop with pests, diseases, weeds and the distribution of GSR is not accounted for. Whilst it is widely accepted that management of fertiliser is one of the most important tools for the improvement of WUE, PASIM does not account for the impact of fertiliser and nutrition on WUE (Caviglia and Sadras 2001).

The results of the analysis depend considerably on the results of applying the French and Schultz yield model and on the use of empirical WUE (WUEe) to define the difference in performance of different paddock zones. This is based on the judgement that the crop performance is the best indicator of underlying soil factors (Ehlert and Adamek 2005). WUE derived from empirical data acts as a proxy for the complex soil-water-atmospheric interactions that are beyond the scope of this study.

The use of empirical WUE will go some way to overcoming limitations over other methods of estimating yields. Through using WUEe as the proxy for these complex interactions, adequate nutrition is assumed in those years from which WUE is estimated. April–October rainfall adjusted for soil evaporation is used to predict crop water use, as April–October rainfall is considered the effective growing season rainfall in the Mediterranean climatic zone of Australia (Asseng *et al.* 2001, French and Schultz 1984).

The seasonal water use of a crop consists of both crop transpiration and soil evaporation (Asseng *et al.* 2001). Soil evaporation is not constant. It is variable across seasons, soil types and management inputs, with the literature reporting variance between 14% and 75% of total evapotranspiration (Asseng *et al.* 2001, Cooper *et al.*, 1987, French and Schultz 1984, Angus *et al.*1980). Soil evaporation is positively related to seasonal rainfall, and also depends on the distribution of rainfall, soil type and nitrogen fertility (Cooper *et al.* 1987). Other terms in the water balance, surface runoff and deep drainage are assumed to be zero. These are usually negligible on flat land in semiarid and sub humid environments (Angus and van Herwaarden 2001). Further, it is assumed that all soil moisture is extracted during the growing season, despite the possibility of sub-soil constraints that result in soil moisture remaining at the end of the growing season. Again, the use of empirical WUE for determining yields ensures the model accounts somewhat for the possibility of sub-soil constraints. In this model, soil evaporation is assumed to be the same for each month of the growing season (Appendix XII).

2.4.2 Yield potentials and Nitrogen in PASIM

The only nutrient accounted for endogenously is nitrogen, making nitrogen and water status the only two factors limiting yield. In reality, there are many more possible yield-limiting factors; the reasonable assumption is that these two factors account for the majority of yield limitations in any year. Lopez-Bellido *et al.* (2005) outline a similar model for predicting yield and nitrogen use. They use this model to quantify the potential value of management forecasts of wheat yields, profits, and excess nitrogen application.

Welsh *et al.* (2003) ask that once variability in yield potential within a field is identified, should more or less nitrogen be applied to the good areas of the field and the opposite to the poor areas? In using PASIM, it is not possible to assess this question because the model was designed as such to assume that low yielding parts of the paddock are governed by water limitations, not nitrogen.

There is a focus on nitrogen management for several reasons: the main one being that it is the easiest to model and often the single most important variable input. A single application of nitrogen fertiliser at sowing is the simplest strategy for applying nitrogen, but faces the total risk of uncertain seasonal conditions (Sadras and Baldock 2004).

Several important features of nitrogen and its activity in the plant-soil-atmosphere environment are outlined below.

For this model, an empirically derived model for estimating the efficiency of nitrogen uptake proposed by Kelly *et al.* (n.d.) in a northern New South Wales study is used. This study related nitrogen fertiliser use efficiency to the protein level of the grain (Equation VII-3 – Appendix VII). The value of wheat grain and the profitability of the crop are linked to quality, which is closely linked to grain protein percentage (Anderson and Hoyle 1999). Many studies report that as nitrogen nutrition improves, so does grain protein (Noulas *et al.* 2004, Palta and Fillery 1995). Nitrogen nutrition effects on protein are not accounted for, a constant target and actual protein level is assumed in this study (12% for wheat and 10% for barley), which may be a limitation of the model. Using the assumed protein levels, the factors representing the efficiency of recovery of nitrogen fertiliser are 55% (inverse 1.82) for wheat and 68% (inverse of 1.46) for barley (Table XI-1 – Appendix XI). These estimates are in line with those reported in the literature. Typically not more than 50–60% of applied nitrogen fertiliser is recovered under average growing conditions (Noulas *et al.* 2004).

Research has shown that the efficiency of nitrogen fertiliser recovery varies considerably from year to year and is influenced by soil type, crop rotation and the supply of soil nitrogen (residual and mineralized) (Lopez-Bellido *et al.* 2005). Despite this, these factors are held constant over the period 1998 – 2005 as a simplifying assumption.

The amount of soil organic matter (OM) indicates the inherent soil fertility in most soil types. Of particular interest is the ability of OM to provide mineralisable nitrogen, phosphorus and sulphur as this influences the requirements for the application of fertiliser (Whelan 1998). A mineralisation factor of average 0.15, ranging between 0.12 and 0.18, is used (Table XII-2). Soil OM is predicated by soil organic carbon (OC%). Soil OC is constant across all zones at 1.0% as Whelan (1997) reports research by Spain *et al.* (1983) that found the typical coefficient of variation of OC% in Australian agricultural soils is between 10-20% when measured on a 10m grid.

The availability of nitrogen is the sum of nitrogen applied as fertiliser (adjusted by the efficiency factor) and nitrogen supplied from the soil (Lopez-Bellido *et al.* 2005, Equation IV-1 – Appendix IV). As soil nitrogen is assumed to be zero, the sole contributor to nitrogen supplied by the soil is nitrogen which is mineralised during the growing season.

The model is adjusted for nitrogen limitation through the use of nitrogen limited yield, which is the nitrogen available divided by a nitrogen requirement factor Ne (Equations IV-1-3 – Appendix IV). Nitrogen Harvest Index (NHI %) is the proportion of total plant nitrogen in the seeds at maturity and rarely exceeds 80% in bread wheat (Noulas *et al.* 2004, Table XI-1 – Appendix XI). Despite research showing that NHI declines as the rate of nitrogen application is increased, the assumption in PASIM is that it is independent to the level of nitrogen applied (Palta and Fillery 1995). Further, seed nitrogen concentration is converted into a protein percentage via a protein to nitrogen conversion figure, assumed as 5.7 for wheat and 6.25 for Barley (Mosse 1990, Table XI-1 – Appendix XI). Given assumed protein levels the Ne figure for wheat is 27.7kgN/t of grain and for barley this is 21.05kgN/t grain (Equation IV-2 – Appendix IV).

2.4.3 Modelling of Farmer Expectations about Rainfall

Anderson *et al.* (1977) outline that a decision problem occurs when a decision maker feels consequences are important, causing uncertainty about the best thing to do, creating a risky choice. Management options and tools can help reduce uncertainties or at least provide more realistic estimates of the possible outcomes (Freebairn *et al.* 2004). One such decision problem is the application of nitrogen fertiliser, with the management option being a tactical application of nitrogen fertiliser based on an expectation of likely yield potential and nitrogen requirements.

It is important for PASIM to account for this uncertainty in decision making. This means that nitrogen application cannot be simulated based on known rainfall (and known water limited yield potential), so an expectation is required to simulate decision making.

Freebairn *et al.* (2004) describe a simple tactical decision framework where current conditions combined with future expectations lead to a decision. PASIM was developed to consider several decision problems facing primary producers. One such question is the matching of nitrogen supply to nitrogen requirements. Included is the estimation of stored soil moisture at sowing, the use of a rainfall expectations model, adjustment of sowing nitrogen application to account for seasonal variation risk and the ability to carry out a split nitrogen application.

Building the model based around WUE and yield potentials required accounting for how farmers make decisions based on rainfall. In particular, a decision rule in the model accounted specifically for the decision making process of primary producers with regard to the development of rainfall expectations (Appendix III).

2.4.4 Activity Gross Margins

Gross Margin per hectare is a measure of gross income less variable costs per hectare in any one year, and is derived from yield predictions and assumptions made about input and output costs. Estimates of activity gross margins are used in a Discounted Cash Flow analysis for the investment analysis.

In Table 2-2 is shown the information required to estimate activity gross margins. Further information on gross margin formulas are given in Appendix V.

Table 2-2. Information required in deriving simulated Gross Margins

Aspect	Information Required
Sowing	Expected Yield Nitrogen requirements Fertiliser Nitrogen to apply
TD	TD Expected Yield TD Nitrogen requirements Fertiliser Nitrogen to apply
Nitrogen-Yields	Nitrogen Theoretical Yield (NTy)
Water-Yields	Base Water Limited Yield (BWy) Precision Agriculture adjusted Wy (PAWy)
Predicted Yield	Minimum of NTy and PAWy
Total Income	Price Predicted Yield
Total Costs	$N Cost Of Productions and Operation overlap percentages for Sowing, Spraying, Harvest, Other, TD Harvest Rate for yield >1mt
Gross Margins	Total Income - Total Costs

2.5 The Comparisons

Broadly, there are three comparison points in this study, farmer practice without the technology, cost savings from reduced overlap using the technology and technology with cost savings and other gross margin benefits, such as added yield.

There are several comparisons conducted in this study to analyse profitability and risk questions of precision agriculture technologies. These are outlined below.

Firstly, two types of Precision Agriculture technology are analysed:

- Zone Management equipment - Uniform Management vs Zone Management
- GPS guidance systems (Sub-Metre and Real Time Kinetic)

Several analyses are conducted:

- Investment Analysis
- Investment Breakeven: The cost of technology and area managed under crop (hectares)
- Impact of seasonal uncertainty (Perfect vs. Imperfect Knowledge)
- Nitrogen Limitation costs

Perfect and Imperfect Knowledge scenarios are used to highlight the impact of seasonal uncertainty on Gross Margins and subsequent investment profitability and risk. The Imperfect Knowledge scenario is reality. The farmer does not know what how season will turn out. There is uncertainty about rainfall. In the Perfect Knowledge scenario, forthcoming seasonal conditions (rainfall) are presumed to be known at sowing, so that inputs can be matched exactly to suit the season. In the Imperfect Seasonal Knowledge scenario forthcoming rainfall conditions are not known at sowing and the farmer must develop expectations as to what rainfall may occur. Comparing the two scenarios enables comment to be made on seasonal/temporal variation versus spatial variation.

2.5.1 The Base Case

The Base Case will be referred to throughout the analysis. This involves the following aspects

- 8 year period for the case study farm, 1998 - 2005
- Imperfect Seasonal Knowledge (seasonal uncertainty)
- Farmer practice – Uniform Management, No GPS guidance, actual costs and returns
- 11 paddocks, 1400 hectares, on average 886ha cereals (wheat and barley) sown annually

2.5.2 Uniform Versus Zone Management

The net benefits are estimated of uniform management of paddocks of the case study farm and of delineating zones within these paddocks and treating them separately with nitrogen. Zone Management is made possible through the investment of around $36,000 in enabling technology. Both strategies utilise the same basic principles for predicting yield, with nitrogen the only variable being analysed. It is assumed that all other inputs are applied equally between the two scenarios.

Under Uniform Management, the average WUE of a paddock is used to form estimates of yield potentials that in turn effect the uniform nitrogen application. Under Zone Management, the average WUE of each zone is used to formulate different nitrogen application decisions between each zone. It is assumed that the empirically derived means and variation of WUE (WUEe) of delineated paddock zones are correct. Uniform nitrogen application results in over and under-application of nitrogen to different zones compared to a Zone Management approach (Appendix IV - Equation IV-7).

As noted by Pannell (2006), there are many good reasons why uniform management of paddocks with variable characteristics makes good sense, including the existence of flat payoffs around the optimum to marginal changes in inputs and the consequent low value of more information about these inputs Whelan and McBratney (2000) provided this null hypothesis for validating scientifically the concept of site specific crop management:

> Given the large temporal variation evident in crop yield relative to the scale of a single field, then the optimal risk aversion strategy is uniform management (Whelan and McBratney 2000)

2.5.3 GPS Guidance systems

Information on implement width and the overlap under different GPS guidance scenarios are essential to analysing the investment. Implement widths necessary for the analysis of GPS guidance benefits are outlined in Table 2-4. In addition to widths, overlap estimates are required for the different types of guidance (Table 2-3). The No Overlap case has the largest overlap, and is the base case for comparison (Table 2-5). A research report by the Kondinin Group (2003) on GPS guidance technology is used to obtain information about the precision of different GPS guidance technologies and their cost (Table 2-3)[2]. The RTK Guidance System is assumed to have an accuracy of two centimetres overlap (Table 2-5). In addition, it is assumed that the reported level of precision in the literature is correct and the technology is such that the operation consistently achieves such accuracy.

[2] The identities of makes of these alternative technologies are not important; they are not the focus here; and so are not identified. Whilst the accuracies and capital costs used in the analysis are of technologies that are available, the emphasis in the research is on estimating the implications for a particular case study farm of adopting alternative technologies with a range of accuracies and capital costs. As such, no implications are intended about the appropriateness of alternative models for different farm businesses. Such questions have to be answered on a case by case basis.

In this analysis comparison is made for the case study farm between not using a precision guidance system and using either of two guidance systems:

- A guidance system with precision of 10cm and capital cost of $20,000. This is called Sub-Metre Guidance.
- A guidance system with precision of 2cm and capital cost of $50,000. This is called RTK Guidance, with hydraulic steering assist.

As well as benefits from reducing overlap by using GPS guidance, the possibility of benefits from extra yield and GM benefits from greater ability to plant crops precisely using RTK guidance, in the form of inter-row sowing and controlled traffic benefits are included in the analysis. The basis for the estimates of increases in gross margin achievable from yield benefits made possible by GPS guidance systems are given in Tables XI-1 and XII-1 of the Appendices.

Benefits of Zone Management result from relocating nitrogen spatially to increase yields and reduce costs. It is assumed that variable rate nitrogen application is possible to the same level under both Sub-metre GPS guidance and the RTK guidance systems. In Tables 2-6, 2-7 and 2-8 is given the assumed costs for the various technologies used in PASIM and the investment analysis.

Table 2-3. Comparison of costs savings due to reduced overlap for different guidance brands over simulated period 1998 to 2005 (from Kondinin 2003)

DGPS Signal	Receiver 1	Receiver 2	Receiver 3	Receiver 4	Receiver 5	Receiver 6	Receiver 7	Receiver 8
Visual	Visual 1	Visual 2	Visual 3	Visual 4	Visual 5	Visual 6	Visual 7	Visual 8
Cost GPS Signal ($)	$7,645.00	$8,740.00	$8,800.00	$7,150.00	$7,590.00	$10,989.00	$7,150.00	$10,989.00
Cost Visual ($)	$6,801.00	$0.00	$14,850.00	$3,025.00	$8,360.00	$0.00	$3,025.00	$0.00
Total Cost	$14,446.00	$8,740.00	$23,650.00	$10,175.00	$15,950.00	$10,989.00	$10,175.00	$10,989.00
Ongoing Costs ($/yr)	$500.00	$500.00	$500.00	$500.00	$500.00	$500.00	$500.00	$500.00
Precision R50 (m)	0.10	0.30	0.40	0.20	0.10	0.30	0.70	0.70
Precision R90 (m)	0.20	0.40	1.30	1.00	0.60	0.90	1.30	1.30

Table 2-4 Implement width information for the case study farm

	Implement Width (m)
Sowing	9.1
Spraying	27.4
Harvest	9.1
TD	27.4

Table 2-5 Guidance scenarios information for PASIM

	IRS	Overlap (cm)				Other PA
PA Type	**% Yield benefits**	**Sowing**	**Spraying**	**Harvest**	**TD**	**% Yield benefits**
No overlap	0.00%	0	0	0	0	0%
Sub-Metre	0.00%	10	10	10	10	0%
RTK	90.00%	2	2	2	2	100%
None	0.00%	75	150	75	150	0%

Table 2-6 Marginal Costs of Zone Management over Uniform Management

Marginal Cost Zone - Uniform	Upfront	Ongoing (pa)	Salvage
Cost of Zoning Paddocks	$10,000.00	$ -	$ -
Consultants/Advisory	$ -	$ 2,600.00	$ -
VRT Air-Seeder (additional cost above a standard seeder)	$20,000.00	$ -	$ -
Training/Education	$ 1,000.00	$ 500.00	$ -
Office Software/Hardware	$ 5,000.00	$ 500.00	$ -
TOTAL	**$36,000.00**	**$ 3,600.00**	**$ -**

Table 2-7 Costs of Sub-Metre Guidance: Receiver 1 – Visual 1 Combination (0.10m R50 Precision)

Marginal Cost Guidance	Upfront	Ongoing (pa)	Salvage
Signal Receiver – 1	$ 7,645.00	$ 500.00	$ -
Visual Equip – 1	$ 6,801.00	$ -	$ -
Steering Assist	$ 5,000.00	$ -	$ -
TOTAL COSTS	**$19,446.00**	**$ 500.00**	**$ -**

Table 2-8 Costs of RTK Guidance: Base Station with Hydraulic Steering Assist (0.02m Precision)

Marginal Cost Guidance	Upfront	Ongoing (pa)	Salvage
Base Station	$20,000.00	$ -	$ -
Signal Receiver – 1	$ 7,645.00	$ -	$ -
Visual Equip – 1	$ 6,801.00	$ -	$ -
Steering Assist	$15,000.00	$ -	$ -
TOTAL COSTS	**$49,446.00**	**$ -**	**$ -**

3 - Results and Discussion

In this section, the significant findings of the study are presented that enable the key research questions to be answered.

3.1 Uniform versus Zone Management

Under the Base Case outlined above, over the period 1998 – 2005, the median simulated average farm gross margin is $76/ha. In the bottom 10% of possibilities (assumption details), this is $25/ha and in the top 10% of scenarios it is just over $132/ha (Figure 3-1). The Base Case showed significant variation of simulated median whole farm gross margin between years also, with $-143/ha (simulated range between -$181/ha to -$88/ha) in the drought year of 2002 to a +$177/ha in 1999 (range $35/ha and $390/ha) (Table 3-1). If the Base Case were undertaken with seasonal certainty (Perfect Seasonal Knowledge) the simulated farm average gross margin increased by on average $15/ha/yr (Figure 3-1).

The gross margins from a full SSCM system involving Zone Management and RTK guidance were better than for the base case under all states of nature (Figure 3-1). Zone Management with RTK guidance returned, on average over the 8 year period, a whole farm gross margin of $133/ha. (undiscounted). This was $58/ha greater than the Base Case (Figure 3-1). In all years of the analysis Zone Management with RTK outperformed Uniform Management with no GPS, by as little as $33/ha ($62/ha – $29/ha) in 2004 to $136/ha ($312/ha – $176/ha) in 2000 (Tables 3-1 and 3-3). In the drought year of 2002, Zone Management with RTK guidance reduced losses by an average of $30/ha (-$113/ha – -$143/ha) compared to the base case (Tables 3-1 and 3-3).

A major source of yield benefits from Zone Management is an increase in nitrogen availability in those zones with a WUE greater than the paddock average. As this analysis shows, uncertainty about weather (temporal or seasonal variation) can have a large impact on the ability to meet crop nitrogen requirements, particularly on zones with high yield potential. Spatial variation is addressed by SSCM, but it is important to analyse the impact of temporal variation on the benefits of SSCM technology.

Temporal variation in seasonal conditions was the biggest cause for nitrogen limitation costs, not spatial variation on this case study farm. Whilst Zone Management does reduce the costs of nitrogen limitation, as outlined above, the biggest benefit would come from increased certainty about the water-limited potential yield. In 3 of the analysis years (2000, 2001 and 2005) seasonal uncertainty increased the cost of nitrogen limitation by 200%; in 2 other years (1999 and 2003), this was greater than 1000% (Table 3-4). Seasonal uncertainty increased the magnitude of the costs imposed by nitrogen limitations, caused by missed opportunities for yield and profit.

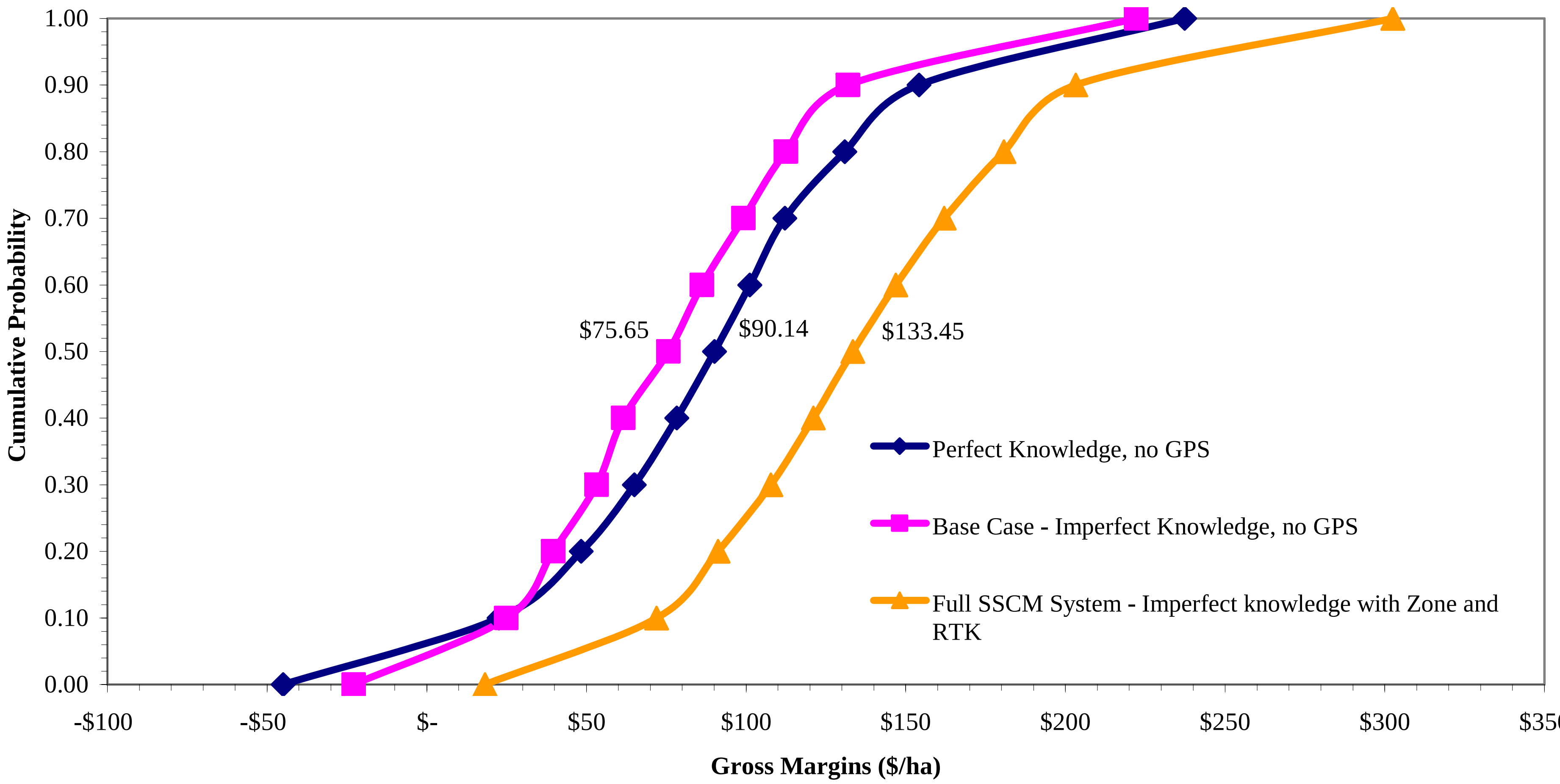

Figure 3-1. **Distributions of simulated Whole-Farm Average AGM over the period 1998 - 2005 (Comparison between scenarios)**

Table 3-1 **Cumulative Distributions of simulated Whole-Farm Average AGM over the period 1998 - 2005 under the Base Case - Imperfect seasonal Knowledge under a Uniform Management strategy with no GPS guidance**

	1998	1999	2000	2001	2002	2003	2004	2005	Average
Mean	$27.93	$177.18	$175.80	$110.67	-$142.58	$81.62	$29.65	$154.63	$76.86
Standard Deviation	43.06	64.68	68.70	53.14	16.04	41.44	29.63	50.39	41.58
Min	-$ 72.57	$ 35.36	$ 30.79	-$ 9.73	-$181.16	-$ 15.71	-$ 53.15	$ 18.01	-$ 22.85
10%	-$ 26.06	$ 97.43	$ 89.79	$ 44.61	-$161.61	$ 29.39	-$ 8.26	$ 94.08	$ 24.91
20%	-$ 8.72	$ 120.23	$ 115.88	$ 62.79	-$155.37	$ 44.28	$ 5.04	$ 111.09	$ 39.58
30%	$ 3.59	$ 138.39	$ 132.83	$ 77.88	-$151.17	$ 56.14	$ 12.45	$ 125.15	$ 53.23
40%	$ 13.22	$ 157.41	$ 153.73	$ 94.42	-$148.18	$ 67.73	$ 20.63	$ 136.67	$ 61.54
Median	$ 23.46	$ 172.19	$ 169.70	$ 106.66	-$143.87	$ 79.39	$ 27.77	$ 152.45	$ 75.65
60%	$ 36.27	$ 191.55	$ 191.51	$ 120.00	-$139.83	$ 91.02	$ 35.02	$ 167.38	$ 86.19
70%	$ 50.96	$ 212.19	$ 214.05	$ 138.95	-$135.73	$ 104.34	$ 44.52	$ 181.33	$ 99.17
80%	$ 66.72	$ 237.27	$ 237.25	$ 158.93	-$129.24	$ 117.49	$ 54.71	$ 196.82	$ 112.52
90%	$ 85.31	$ 258.72	$ 269.66	$ 179.45	-$120.82	$ 137.08	$ 66.27	$ 217.90	$ 131.97
Max	$ 158.67	$ 390.59	$ 404.57	$ 286.29	-$ 88.02	$ 227.63	$ 141.81	$ 349.23	$ 222.15

Table 3-2 **Cumulative Distributions of simulated Whole-Farm Average AGM over the period 1998 - 2005 with Perfect Seasonal Knowledge under a Uniform Management strategy with no GPS guidance technology**

	1998	1999	2000	2001	2002	2003	2004	2005	Average
Mean	$4.21	$220.02	$188.72	$113.79	-$127.48	$124.83	$18.18	$172.55	$89.35
Standard Deviation	66.25	77.85	73.42	58.06	15.76	51.70	44.78	56.56	49.45
Min	-$ 188.14	$ 57.55	$ 40.41	-$ 38.95	-$ 170.72	-$ 11.48	-$ 150.18	-$ 7.48	-$ 44.94
10%	-$ 98.87	$ 117.63	$ 93.43	$ 40.34	-$ 148.13	$ 57.30	-$ 43.92	$ 103.18	$ 22.65
20%	-$ 50.20	$ 151.38	$ 123.07	$ 63.87	-$ 140.66	$ 79.97	-$ 16.62	$ 127.43	$ 48.36
30%	-$ 17.37	$ 173.41	$ 145.84	$ 82.58	-$ 136.51	$ 96.11	$ 4.94	$ 141.79	$ 64.97
40%	$ 1.41	$ 195.84	$ 166.15	$ 97.26	-$ 132.61	$ 108.89	$ 14.69	$ 155.36	$ 78.33
Median	$ 16.71	$ 214.87	$ 184.92	$ 112.58	-$ 127.78	$ 123.17	$ 25.10	$ 169.82	$ 90.14
60%	$ 28.46	$ 236.47	$ 204.53	$ 125.71	-$ 123.63	$ 135.50	$ 32.21	$ 182.33	$ 101.14
70%	$ 43.85	$ 261.69	$ 223.18	$ 144.48	-$ 118.08	$ 147.98	$ 42.73	$ 202.40	$ 112.08
80%	$ 59.07	$ 288.20	$ 252.49	$ 161.96	-$ 114.02	$ 168.38	$ 52.26	$ 220.32	$ 130.86
90%	$ 81.27	$ 325.33	$ 286.34	$ 192.65	-$ 107.70	$ 195.51	$ 69.73	$ 250.30	$ 154.16
Max	$ 161.96	$ 451.08	$ 410.52	$ 293.66	-$ 78.96	$ 285.68	$ 115.43	$ 327.24	$ 237.34

Table 3-3 **Cumulative Distributions of simulated Whole-Farm Average AGM over the period 1998 - 2005 with Imperfect Seasonal Knowledge under a Zone Management strategy with RTK guidance technology**

	1998	1999	2000	2001	2002	2003	2004	2005	Average
Mean	$59.49	$218.46	$312.96	$190.71	-$112.51	$141.15	$62.53	$216.05	$136.10
Standard Deviation	47.73	72.69	96.18	70.55	19.61	51.06	33.54	58.42	51.15
Min	-$ 59.89	$ 59.71	$ 110.18	$ 25.23	-$ 162.61	$ 20.83	-$ 20.82	$ 81.16	$ 18.28
10%	-$ 0.69	$ 121.84	$ 183.29	$ 97.31	-$ 136.66	$ 76.00	$ 22.51	$ 141.44	$ 71.96
20%	$ 20.77	$ 154.26	$ 229.23	$ 129.88	-$ 129.50	$ 96.02	$ 34.15	$ 164.57	$ 91.19
30%	$ 32.13	$ 177.34	$ 260.33	$ 150.67	-$ 122.34	$ 112.10	$ 45.10	$ 182.86	$ 107.78
40%	$ 45.73	$ 195.76	$ 280.69	$ 169.37	-$ 117.82	$ 126.03	$ 51.58	$ 198.75	$ 121.06
Median	$ 56.28	$ 214.78	$ 308.36	$ 188.14	-$ 113.43	$ 140.63	$ 60.53	$ 213.07	$ 133.45
60%	$ 70.04	$ 236.31	$ 334.52	$ 207.13	-$ 108.45	$ 152.53	$ 69.24	$ 229.00	$ 146.85
70%	$ 83.87	$ 254.19	$ 363.35	$ 223.37	-$ 102.98	$ 167.77	$ 78.03	$ 244.66	$ 162.05
80%	$ 100.53	$ 282.20	$ 396.16	$ 253.24	-$ 97.14	$ 184.97	$ 90.24	$ 266.27	$ 180.72
90%	$ 121.38	$ 315.39	$ 435.98	$ 284.02	-$ 87.58	$ 206.71	$ 109.19	$ 294.02	$ 203.19
Max	$ 213.91	$ 431.92	$ 589.00	$ 402.62	-$ 37.65	$ 294.07	$ 188.76	$ 419.79	$ 302.54

Table 3-4 **Cost of Nitrogen Limitations ($/ha) under different management types (Zone vs Uniform and Split N strategy) and knowledge scenarios (Perfect vs Imperfect seasonal knowledge)**

Scenario	Year	1998	1999	2000	2001	2002	2003	2004	2005
All N at Sowing									
Imperfect Knowledge, no GPS	Uniform	$3.33	$112.88	$62.95	$37.20	$0.00	$96.47	$8.89	$50.82
	Zone	$0.00	$107.22	$49.94	$26.40	$0.00	$94.46	$2.39	$39.61
	Zone - Uniform	**$3.33**	**$5.66**	**$13.01**	**$10.80**	**$0.00**	**$2.01**	**$6.50**	**$11.20**
Perfect Knowledge, no GPS	Uniform	$15.03	$31.85	$32.16	$21.17	$0.39	$21.99	$13.15	$25.40
	Zone	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
	Zone - Uniform	**$15.03**	**$31.85**	**$32.16**	**$21.17**	**$0.39**	**$21.99**	**$13.15**	**$25.40**
Split N Decision (Top-Dressing)									
Imperfect Knowledge, no GPS	Uniform	$3.71	$106.42	$64.83	$38.12	$0.00	$79.89	$8.94	$50.60
	Zone	$0.00	$100.53	$52.14	$28.06	$0.00	$76.97	$2.00	$40.33
	Zone - Uniform	**$3.71**	**$5.89**	**$12.69**	**$10.06**	**$0.00**	**$2.92**	**$6.95**	**$10.27**
Perfect Knowledge, no GPS	Uniform	$15.16	$31.87	$31.41	$21.40	$0.26	$22.09	$13.18	$25.33
	Zone	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
	Zone - Uniform	**$15.16**	**$31.87**	**$31.41**	**$21.40**	**$0.26**	**$22.09**	**$13.18**	**$25.33**

3.2 Net Investment Benefits in Zone Management

For the 1400 ha case study farm, with an average of 886 ha of cereals cropped annually, with an 8% discount rate, the investment in Zone Management technologies does not meet the required rate of return. The mean simulated NPV of -$27,000, or -$4/ha/yr (Table 3-5). Further, the simulated range of outcomes is very wide, from between -$37/ha/yr to +$30/ha/yr (Table 3-5). The important point to note is that there are a critical number of hectares of crop needed to justify the capital cost involved. If over 2000 hectares were cropped per year in this farm system, Zone Management would meet the required rate of return of 8% on extra capital, with a positive NPV of $10,000, or $0.65/ha/yr, a return slightly above 8% real p.a. The range of outcomes widens, varying between -$37/ha/yr to +$42/ha/yr. The minimum potential return simulated of -$37/ha is the same for the Base Case and 2000 ha cropped. The potential maximum return increased by $12/ha (Table 3-6). This indicates that there may be a floor on the potential losses.

It is important to remember exactly what aspects of precision agriculture are being analysed and the case study farm (environment and empirical WUE estimates). The investment in the case study farm was unprofitable because it was spread over insufficient hectares. Or, the case study paddocks were not sufficiently variable to justify investing to gain the benefits of reducing the adverse effects of variability. In this case, the small net benefit from the greater precision of input application seems consistent with the notion of flat pay off functions around the optimum in farm systems.

Table 3-5 **NPV ($ and $/ha) between 1998 - 2005 at discount rate of 8% for different PA technologies (avg sown 884.5ha/yr)**

Measure	**RTK Guidance (No other GM Benefits)**	**RTK Guidance (Inc. other GM Benefits)**	**Zone Management**	**Sub-Metre Guidance**
Total Returns				
Mean	**$12,452.58**	**$129,435.14**	**-($27,693.91)**	**$31,992.31**
Standard Deviation	$7,331.63	$11,631.59	$88,240.47	$7,334.92
Minimum	$7,085.49	$98,554.38	-($259,486.56)	$26,455.43
Maximum	$68,756.31	$184,043.11	$209,736.12	$88,152.10
Total Upfront Costs	$49,446.00	$49,446.00	$36,000.00	$19,446.00
Ongoing per Year	$0.00	$0.00	$3,600.00	$500.00
Returns per hectare/year				
Mean	**$1.76**	**$18.29**	**-($3.91)**	**$4.52**
Standard Deviation	$1.04	$1.64	$12.47	$1.04
Minimum	$1.00	$13.93	-($36.67)	$3.74
Maximum	$9.72	$26.01	$29.64	$12.46
Total Upfront Costs	$6.99	$6.99	$5.09	$2.75
Ongoing per Year	$0.00	$0.00	$0.51	$0.57

Table 3-6 **NPV ($ and $/ha) between 1998 - 2005 at discount rate of 8% if sow on average 2000ha of cereals per year**

Measure	**RTK Guidance (Inc. other GM Benefits)**	**Zone Management**	**Sub-Metre Guidance**
		NPV	
Mean	**$375,796.50**	**$10,385.33**	**$97,057.94**
Standard Deviation	$26,750.07	$219,281.13	$13,319.60
Minimum	$302,116.85	-($592,943.62)	$86,107.93
Maximum	$486,136.46	$671,459.37	$198,981.79
Total Upfront Costs	$49,446.00	$36,000.00	$19,446.00
Ongoing per Year	$0.00	$3,600.00	$500.00
		NPV per hectare/year	
Mean	**$23.49**	**$0.65**	**$6.07**
Standard Deviation	$1.67	$13.71	$0.83
Minimum	$18.88	-($37.06)	$5.38
Maximum	$30.38	$41.97	$12.44
Total Upfront Costs	$3.09	$2.25	$1.22
Ongoing per Year	$0.00	$1.80	$0.25

3.3 Breakeven

There is a positive linear relationship between the cost of technology and the break-even hectares to be sown each year (Figure 3-2). Under the base technology cost assumptions for Zone Management, the break even (zero NPV) hectares is 1670ha. If the cost of the technology could be reduced to $10,000, the break-even is 904ha (Figure 3-2).

3.3.1 Break-even Paddock Variation

Analysing the size of the farm which to spread the investment over is quite straight-forward, however analysing the ‘break-even’ amount of spatial variation within paddocks on a farm is complicated. Break-even in the context of this analysis is the level at which the farmer would be indifferent between using Zone Management technology or not. It is not mean paddock WUE that influences the benefit of Zone Management over Uniform Management, it is the variation of WUE around the paddock mean. The Coefficient of Variation (standard deviation divided by mean: CV) measure was found to be the best measure to assess the break-even level of paddock variation.

The ‘noise’, or uncertainty, surrounding the estimates of zone WUE is shown by the relationship derived from the simulation data that for every 0.1 increase in CV above 0.17, there is on average a $3.30/ha/yr increase in the benefit of Zone over Uniform Management, before the costs of technology are considered.

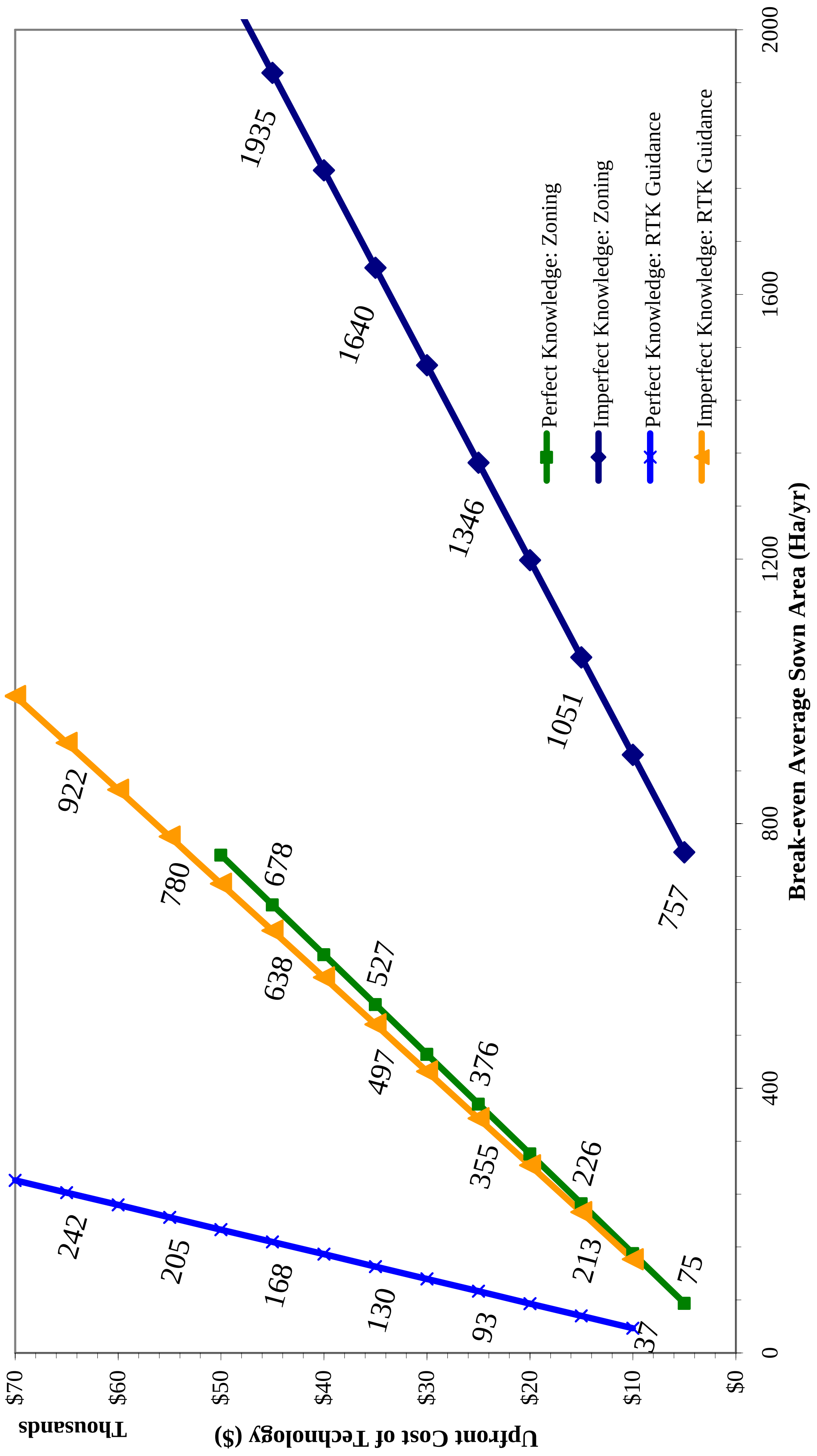

Figure 3-2. Break-even analysis of PA technologies against both area sown (ha/yr) and cost of the enabling technology

If the cost of guidance is considered sunk, a Zone Management system on this farm would cost about $5.60/ha/yr, making the break-even paddock variation a CV of 0.34 (Table 3-5). If the cost of RTK guidance is now considered, at about $7/ha/yr, the break-even CV becomes 0.55 (Table 3-5).

Looking at break-even costs another way, for every $1/ha/yr increase in the cost of technology, paddock variation needs to increase by approximately 0.03 CV units. Hence if the technology cost $10/ha, paddock CV would need to be 0.47 to break-even.

Consider a year with median GSR of 246mm (soil evap 110mm), in a paddock with WUE of 16.7kg/ha/mm (farm average). In this year, the average expected yield would be 2.3t/ha. There would have to be just over 0.75t/ha difference between the top third of the paddock and the bottom yielding third of the paddock for Zone Management to produce a greater gross margin than Uniform Management, before the costs of technology are considered. Considering only the costs of Zone Management technology[3], this breakeven tonnage/ha rises to 1.5t/ha difference. If the cost of RTK guidance is considered as well, this becomes 2.5t/ha. If the technology cost is assumed as $10/ha, the breakeven difference between the top third and the bottom third would be in the order of 2.1t/ha.

[3] Consider the cost of the GPS guidance required to undertake Zone Management as a sunk cost

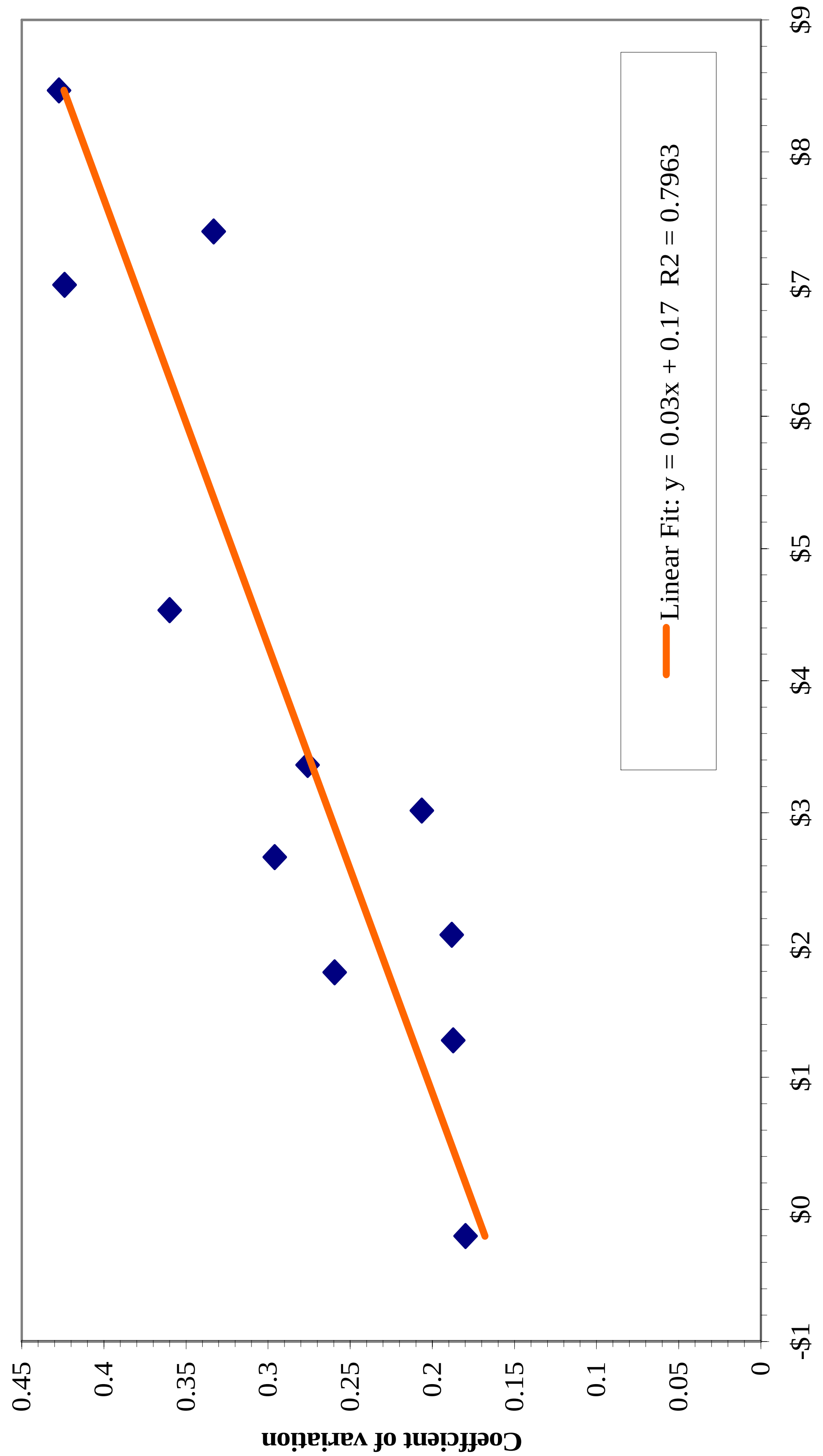

Figure 3-3. **Break-even paddock variation: Coefficient of Variation of Paddock Mean WUE vs. the Benefit of Zone Management with RTK guidance over a uniform approach with no GPS**

3.4 GPS Guidance

There are a number of reported benefits from GPS guidance in the literature. The main benefit is reduced overlap. The Sub-Metre GPS guidance being analysed allows accuracy to 10cm, whilst the RTK system analysed is accurate to 2cm (Table 2-5). In this study, reduced overlap because of GPS guidance saves cost. It is assumed that without any guidance system, there is significant overlap that is not automatically accounted for in assumptions about input costs used in generating GM details (Table 2-3 and 2-5). As a result, under each scenario, the cost of production increases according to the level of overlap assumed.

Expected minimum input cost savings for Sub-Metre guidance is $8.29/ha/yr and the maximum is $12.98/ha/yr (Figure 3-4). The median minimum for RTK guidance is $9.74/ha/yr and the maximum is $14.54/ha/yr (Figure 3-2). That is, under the same assumptions, RTK guidance is likely to have a slightly larger benefit than Sub-Metre guidance. This is expected because RTK is a more precise technology. Figure 3-4 helps demonstrate the variation in simulated benefits according to different states of nature (Crystal Ball assumptions). In Table 3-7 is shown the variation in gross returns from different Sub-Metre GPS receivers, demonstrating the large effect of receiver precision on potential returns from GPS guidance investment.

The cost savings from GPS guidance are subject to seasonal variability that affects the amount of inputs applied, as shown in Figure 3-5. In each of the 8 years in the analysis, RTK guidance provided a greater input cost saving than Sub-Metre guidance, of $1 - $1.50/ha/yr. Note that the Sub-Metre overlap is 10cm, which is at the upper end of the accuracy available in a Sub-Metre guidance system.

Under the assumptions of this model, Sub-Metre guidance only demonstrated benefits from reduced overlap. Real-Time Kinetic (RTK) Guidance may also enable an Inter-Row Sowing yield and gross margin benefit as well.

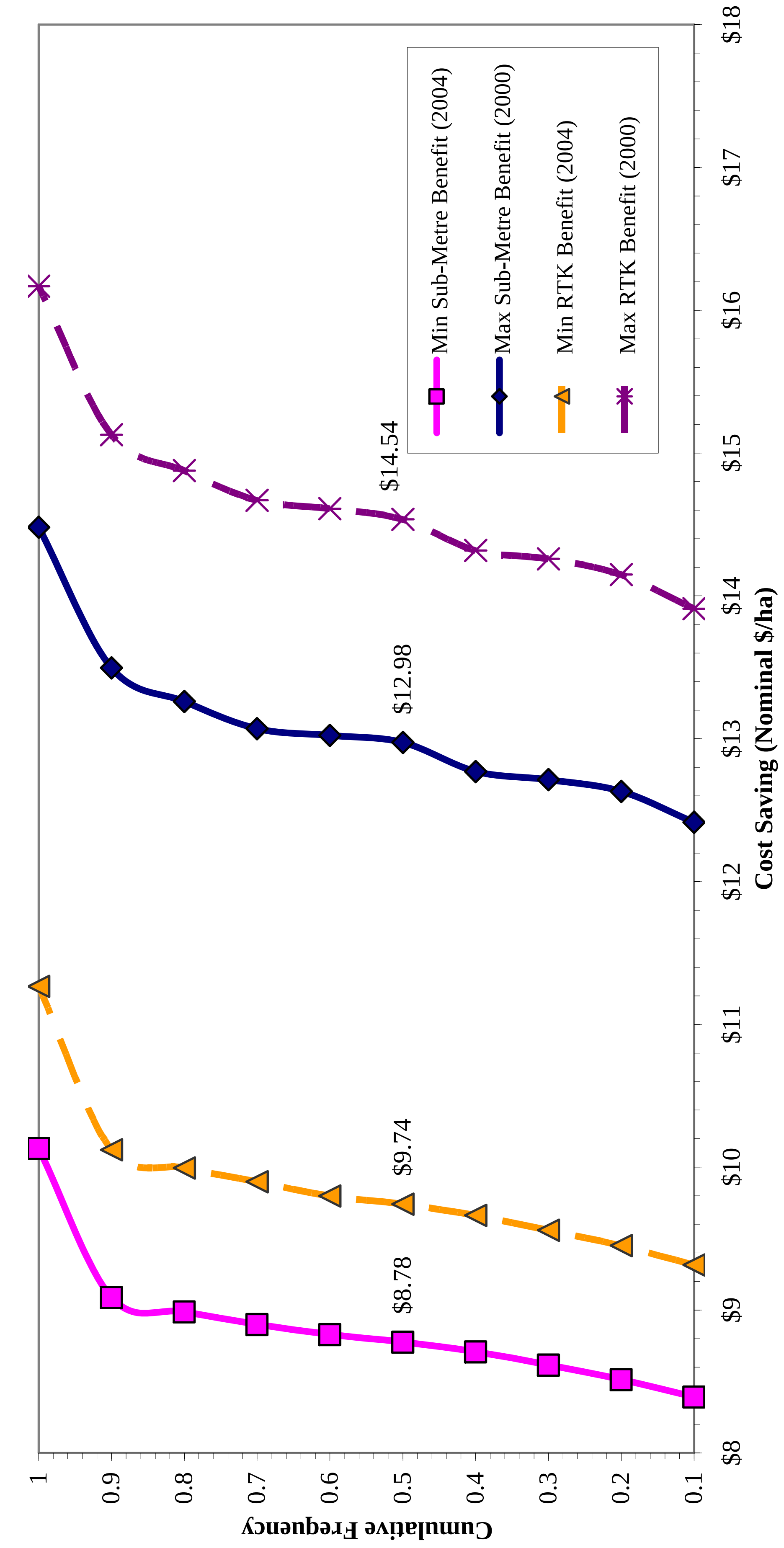

Figure 3-4 **Overlap Cost Savings Attributable to GPS Guidance - Minimum and Maximum benefit over simulated period 1998 – 2005**

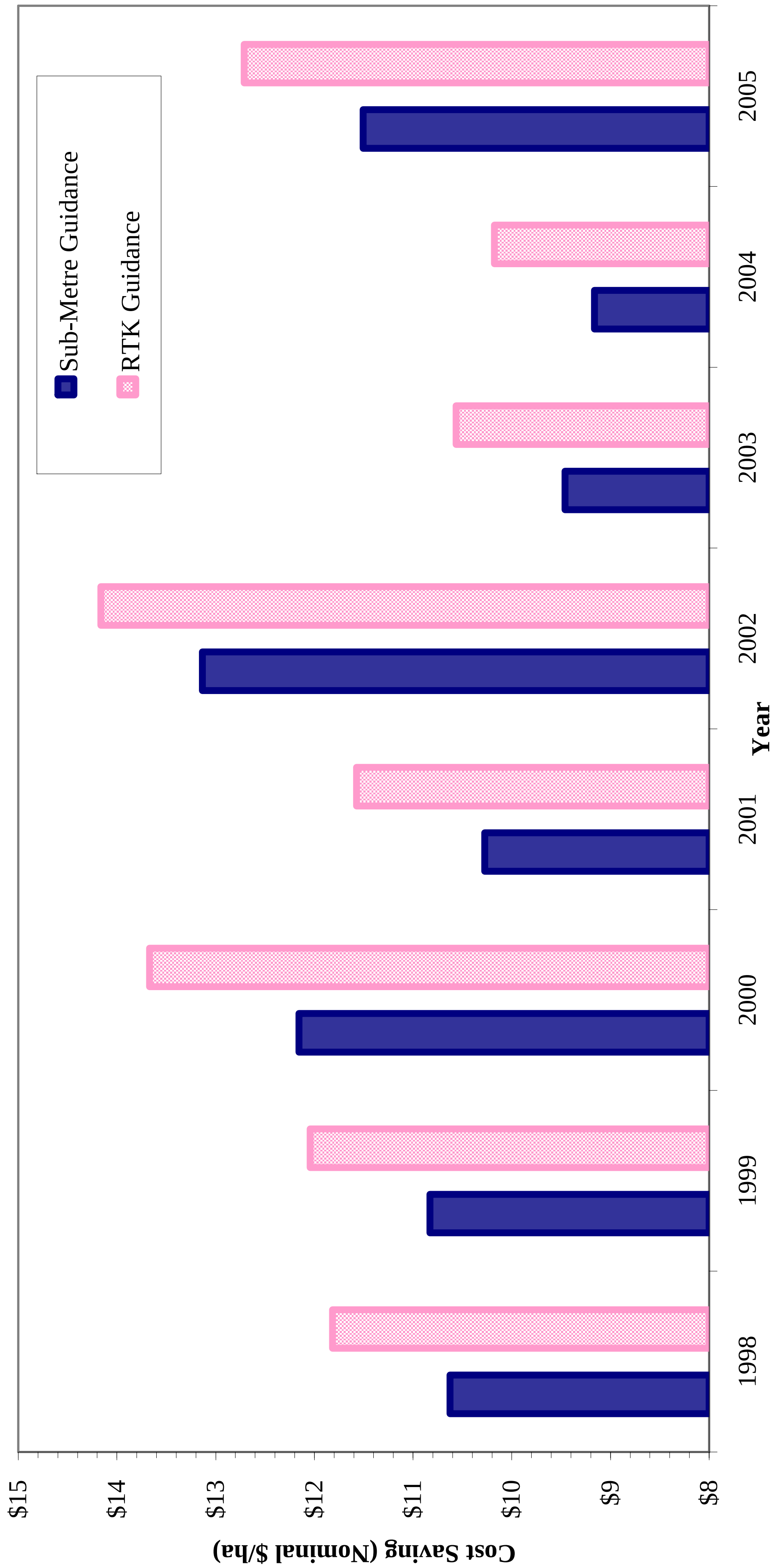

Figure 3-5 Overlap Cost Savings Attributable to GPS Guidance - Minimum and Maximum benefit over simulated period 1998 – 2005

Table 3-7 Comparison of costs savings due to reduced overlap for different guidance brands over simulated period 1998 to 2005

DGPS Signal	Receiver 1	Receiver 2	Receiver 3	Receiver 4	Receiver 5	Receiver 6	Receiver 7
Average	$10.92	$7.92	$6.46	$9.39	$10.91	$7.86	$1.77
Minimum	$9.11	$6.57	$5.29	$7.84	$9.11	$6.52	$0.34
Maximum	$13.90	$11.33	$10.07	$12.40	$13.83	$11.27	$5.58

Table 3-8 Increase in Gross Margin Attributable to Yield Benefits from RTK Guidance for the simulated period 1998 to 2005 (Perfect Knowledge)

Year	1998	1999	2000	2001	2002	2003	2004	2005
Total Available Moisture (mm)	172.15	272.2	265.3	226.8	110.65	229.2	158.88	234.9
Minimum	$15.42	$35.40	$37.74	$25.57	$2.37	$27.66	$15.42	$34.24
Mean	$23.55	$50.90	$55.42	$38.14	$4.62	$38.40	$21.69	$45.43
Maximum	$39.80	$82.20	$89.60	$61.78	$9.52	$59.46	$31.12	$62.33

Mean simulated savings from reduced overlap are not influenced by seasonal knowledge (assuming crop is sown every year, even under Perfect Seasonal Knowledge). Another benefit, yield benefits, show a significant sensitivity to seasonal forecasts (Figure 3-6). Over the seven years, seasonal uncertainty reduced the mean annual benefits of RTK guidance consistently by 20-22% (Figure 3-6).

3.5 Net Investment Benefits of GPS Guidance

The net benefits, when the costs of GPS guidance technology are considered in an investment analysis framework, are presented in the following section. Unless otherwise stated, all discounted cash flow analysis is carried out over an 8 year planning horizon (1998 – 2005), at a discount real rate of 8%, and no salvage value for technology. Results are given in real dollars. For the purpose of the investment analysis, the costs of enabling technology are allocated to their various income generating abilities. For example, the technology cost and returns to Zone Management are considered separately to those for RTK and Sub-Metre guidance (Tables 3-3, 3-6, 3-7 and 3-8). The assumption is that investment in the guidance technology is a sunk cost in terms of Zone Management, and that the same level of Zone Management is possible under both Sub-Metre and RTK guidance.

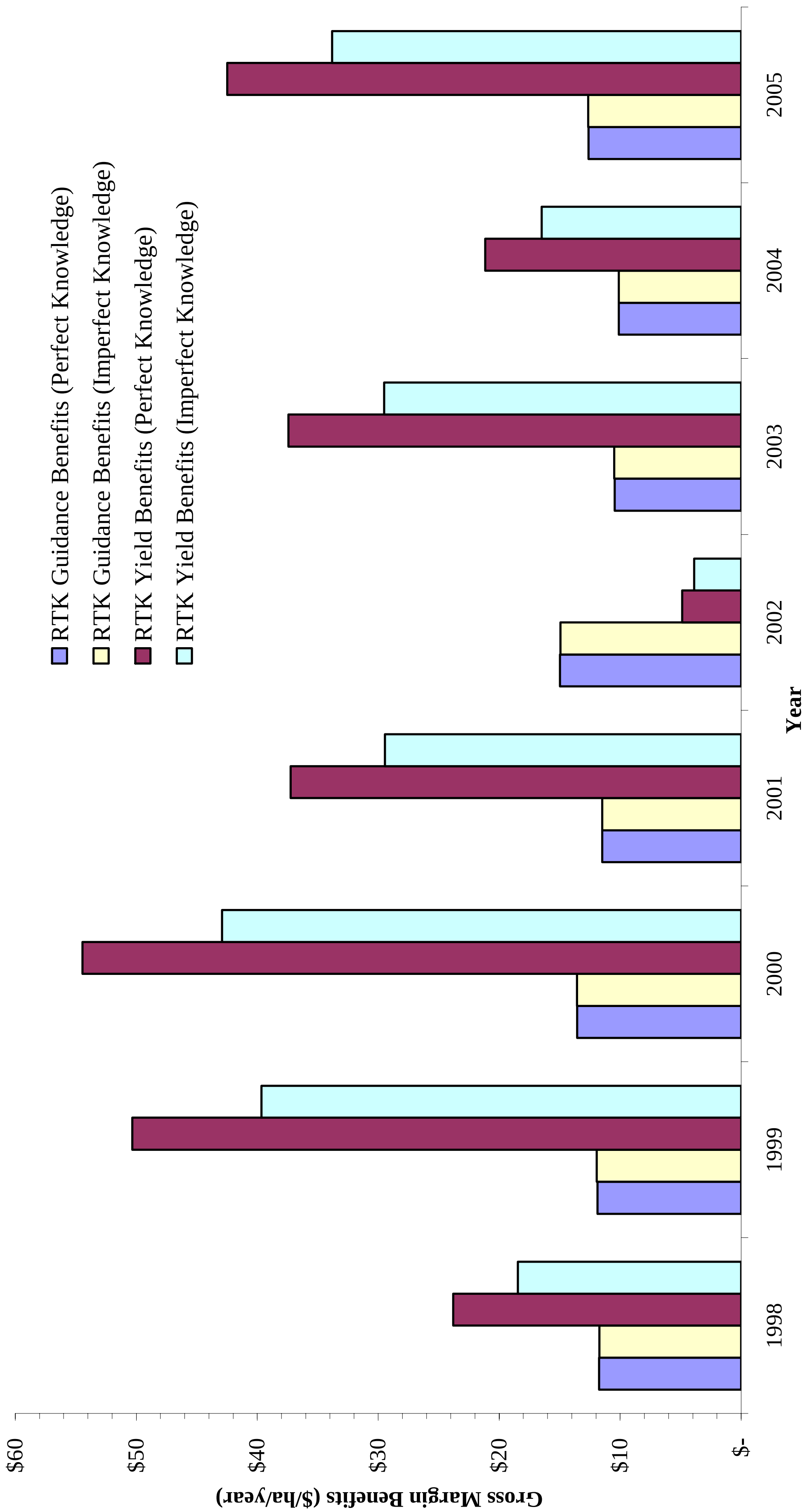

Figure 3-6. RTK Yield Benefits vs Guidance Benefits: Comparing the impact of imperfect seasonal knowledge on benefits

In Table 2-3 is shown the details of the various types of Sub-Metre guidance analysed (Kondinin 2003). The figures especially of interest are the R50 precision information, which is the observed pass-to-pass (15minute) precision[4] of the GPS receiver in question as tested by the Kondinin Group (2003).

Simulated net benefit diminishes quickly for various types of DGPS receiver as the precision of the receiver declines (Figure 3-7). Whilst the cost of the receiver will partly determine the net benefit of the technology, in this case, the precision of the receiver influences profitability the most (Figure 3-7).

Receiver 1, with 10cm accuracy and a cost of $14,500 (annualised cost of $22/ha/yr) returns in the simulation a minimum net benefit of $29/ha, a median of $33/ha and up to a maximum of $99/ha in total over the 8 years (Table 2-3 and 3-9). This is compared to the Receiver 2 that only costs $8,700 (annualised cost of $15/ha) for an R50 precision of 30cm, which has a median simulated total net benefit of $23/ha (Table 3-8 and 3-9). Figure 3-8 shows the comparison between all types of Sub-Metre technologies analysed.

The preceding analysis was carried out on the average area sown to cereals of 884ha per year (out of the 1400ha in the analysis). The zero NPV break-even number of hectares managed using the PA technology increases exponentially as the precision of the receiver declines (Figure 3-7).

[4] The R50 measure refers to the distance at which there is a 50% level of confidence that the receiver position is actually within that distance (i.e. 10cm for Receiver 1 DGPS signal). The distance increases for increasing levels of confidence (i.e. the R95 for Receiver 1 is 20cm).

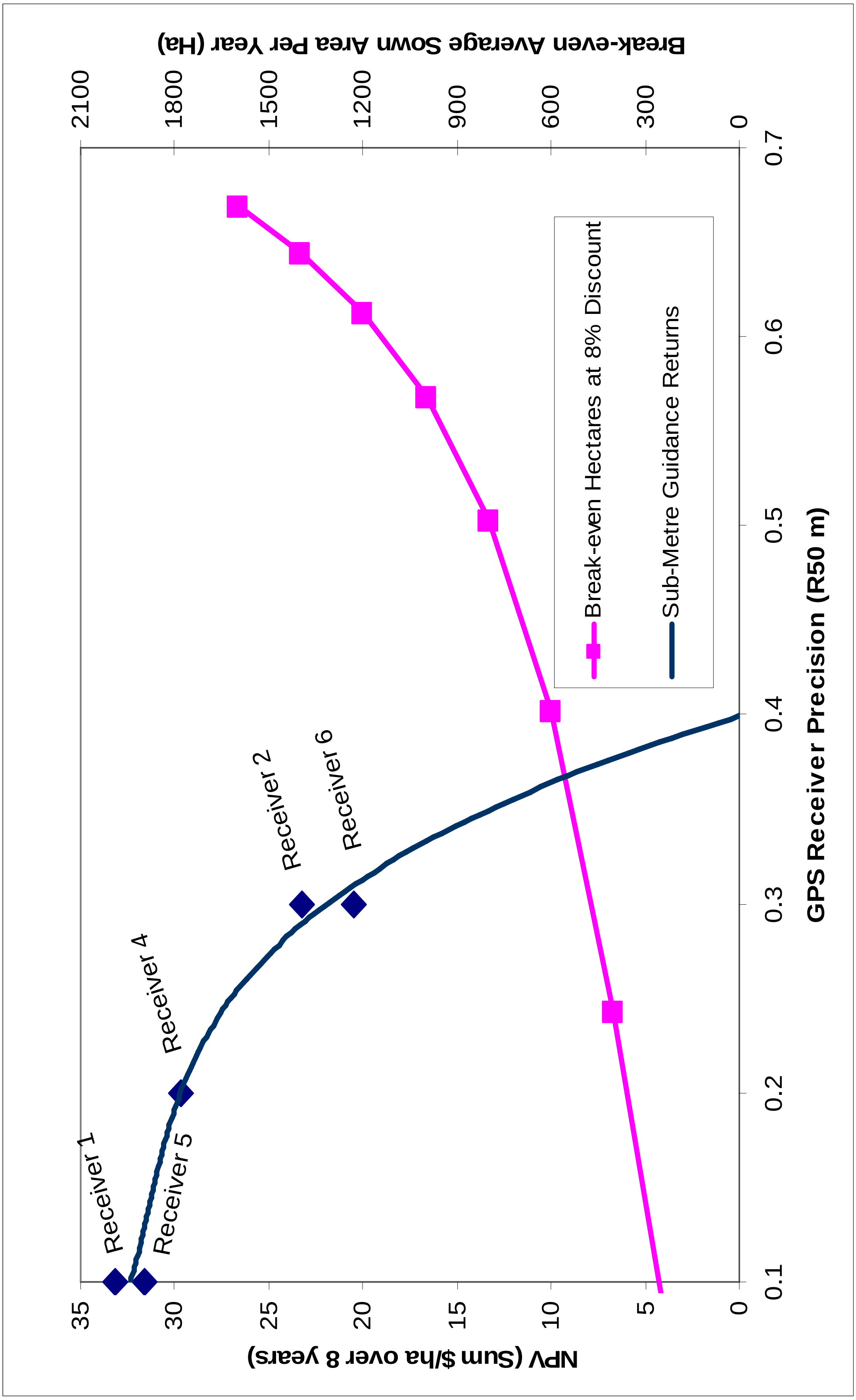

Figure 3-7. **Net Present Value of various Sub-Metre Guidance technologies and the break-even area sown versus the precision of the Sub-Metre GPS receiver**

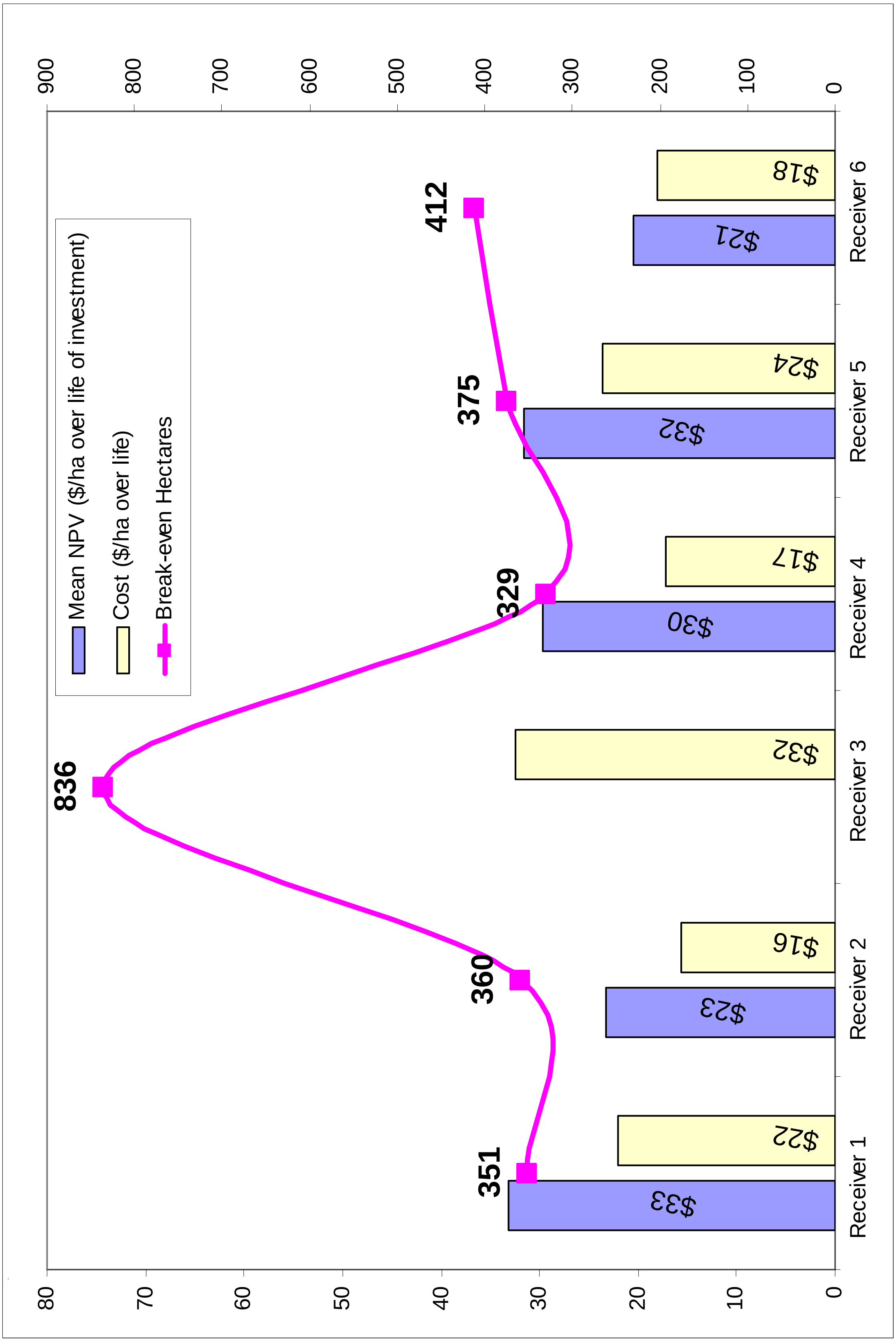

Figure 3-8. Net Present Value ($/ha) of various Sub-Metre Guidance technologies and the break-even area sown metre GPS receiver

Table 3-9. NPV ($/ha) of guidance at 8% Discount rate (1998 Dollars)

DGPS Signal	Receiver 1	Receiver 2	Receiver 3	Receiver 4	Receiver 5	Receiver 6	Receiver 7
Minimum	$29.91	$19.83	-$3.75	$26.24	$28.49	$17.32	
Median	$33.16	$23.26	-$0.14	$29.71	$31.59	$20.51	
Maximum	$99.66	$89.72	$67.23	$96.12	$98.14	$86.61	
Break-even[5]	351	360	836	329	375	412	1675
Cost ($/ha)	$21.99	$15.53	$32.39	$17.16	$23.69	$18.08	$17.16

Under the assumption of no added gross margin benefits changes to the cropping system as a result of adopting RTK guidance, Sub-Metre guidance (10cm precision) returns a higher NPV over the life of the project by $4.50/ha/yr versus $1.76/ha/yr for the RTK guidance system and is less risky (CV of 0.23 vs. 0.6) (Table 3-5). These figures are quite small when broken down to per hectare per year. At a farm level the gains equate to an NPV of $12,500 for RTK compared to the NPV for Sub-Metre guidance of $32,000 (Table 3-5). Considering that Sub-Metre guidance, in this analysis, requires a lower start up cost as well ($19,500 compared to $49,500), it is a better investment in economic terms.

In terms of break-even levels to key parameters, most of the analysed Sub-Metre guidance products have quite low break-even average hectares to be sown each year, between 329 – 412 hectares (Figure 3-9). One receiver, Receiver 3 with an R50 precision of 40cm, has a much higher break-even sown area of 836ha (Figure 3-9). Further, Receiver 7, which uses a beacon receiver with a precision of 70cm, has a simulated break-even sown area of 1675ha. These results demonstrate how small decreases in precision have dramatic effects on profitability of a system compared to the no guidance case.

The larger investment in RTK Guidance (including yield benefits from related system changes) has a considerably larger break-even sown area of 707ha. Under this model, there is a linear relationship between the break-even hectares and the cost of technology (Figure 3-2). On the case study farm, to be indifferent between a the Receiver 1 Sub-Metre and RTK guidance choice, then the cost of the RTK technology would need to be around $25,000, not $49,500 (Figure 3-2).

When the break-even analysis is conducted assuming Perfect Seasonal Knowledge, the results demonstrate the negative impact that seasonal uncertainty has on input decisions and the ability to maximise returns on investment. Both Zone Management and RTK guidance benefit considerably from Perfect Seasonal Knowledge, with the Zone Management break-even area to manage reduced from 1670ha to 382ha, whilst RTK guidance breakeven is reduced from 707ha to 184ha.

[5] Area (hectares) to earn 8% required rate of return

3.6 Yield and gross margin benefits from changes to the cropping precision as a result of adopting RTK Guidance

A yield and gross margin benefit under the RTK Guidance was built into the model to account for the other possible benefits available from this technology, with extra growing costs and harvesting costs included to derive gross margin benefits.

The Monte Carlo risk analysis of benefits from the enabling technology shows that the minimum benefit is $34.24/ha while the maximum benefit is $62.33/ha (Table 3-8). There is significant seasonal variability also, with simulated mean yield benefits of only $4.62/ha in 2002 because of low yields and as high as $55.42/ha in 2000, a year with high evapotranspiration (Table 3-8). Yield benefits from RTK guidance show a strong positive relationship to total plant available water, with an average yield benefit from RTK guidance of $45/ha over the period 1998 – 2005 (Table 3-8).

Including yield and gross margin benefits from greater precision made possible under RTK guidance, in addition to the savings from reduced overlap, significantly affects the net investment results. The mean NPV for RTK guidance with no yield benefits is much lower than if yield benefits are included. One further research area that is imperative to future analyses like this study is the estimation of yield benefits from inter-row sowing made possible through RTK guidance. The NPV ($/ha/yr) for RTK guidance with no yield benefits ranges between $1.00 - $9.00/ha/yr, averaging $1.70/ha/yr. This compares to NPV in a range of $14.00-$26.00/ha/yr and an average of $18/ha/yr if yield benefits are possible (Table 3-5).

If the assumptions are valid, this demonstrates that it is vital that if producers invest in RTK guidance they also undertake supporting management changes that allow maximum use of the technology, such as inter-row sowing and or controlled traffic to increase yield. Further, the simulated net benefits under RTK with yield benefits exhibit less variation than the case without yield benefits (CV of 0.1 versus 0.6).

When the managed area is taken to 2000 ha per year, the mean NPV ($/ha/yr) increases to $24.50 under RTK with yield benefits included, with a small reduction in the variability of return (Table 3-6).

4 - Summary of Findings and Conclusion

Precision Agriculture technologies enable site-specific management. Detailed investigation of the economics of spatial land management strategies is warranted. The aim of this study was to analyse whole-farm profitability and risks of precision agriculture and site specific crop management systems. To answer the research questions, a model for predicting yield under PA management was developed to simulate paddock and activity gross margins. The profitability of PA technologies and also the risk was analysed.

The main findings are:

- On this case study farm over the 8 year period, an investment in Zone Management technologies to crop 1400 hectares (886 ha on average annually under cereals) would not make the required return of 8% and in addition is risky. The minimum average cereal crop area sown annually to achieve the minimum return on capital for a full SSCM system (RTK guidance and Zone Management) was 1670 hectares for this type of farm system. There was considerable variation in potential profitability.

- In this study a paddock had to exhibit at least a 2.5t/ha difference between the top yielding third of the paddock and the bottom yielding third of the paddock for RTK Guidance with Zone Management (a full SSCM system) to meet the required rate of return. If the costs of RTK guidance technology are considered sunk, the difference is reduced to 1.5t/ha.

- Seasonal variation has a much bigger impact on profitability than spatial variation. On the case study farm, in five of the eight years of the analysis, seasonal variation had at least a two-fold or greater impact on nitrogen limitation and gross margins than did spatial variation.

- On this case study farm over the 8 year period, when the costs of technology were considered along with the gross benefits, the expected NPV at 8% real discount rate for RTK guidance with additional yield benefit as well as cost savings from reduced overlap was $18/ha/yr compared to $1.70/ha/yr without RTK guidance, and with lower variability. This demonstrates the need to maximise potential benefits from the technology by adopting complementary management practices

- Sub-Metre guidance returns exceeded the required 8% real return, with the break-even crop area required for GPS receivers with precision less than 30 cm being between 350 – 400ha.

In sum: investment in GPS guidance technology can be a worthwhile investment - a conclusion endorsed by many Australian farmers who have implemented GPS guidance systems (Kondinin 2006). Investment in variable rate technology for more precise nitrogen applications did not earn a competitive rate of return in the case study analysed.

4.1 Model and Analysis restrictions

Only a part of potential PA benefits on a particular case study farm is investigated in this study; there are other potential tangible and intangible benefits. Further, the analysis was conducted for a farm of a particular size, using only wheat and barley paddocks in the rotation, in the relatively dry period 1998 – 2005. Further enhancement of the model such as the use of a more sophisticated crop modelling tool would allow further investigation of farm management systems and the impact of PA technology.

The use of empirical WUE does not account fully for the spatial variability in crop growing conditions or the effect of temporal variability (within season and between seasons) on spatial variability. Rodriquez *et al.* (2006) suggest that simulation exercises in the Victorian Mallee should account for the presence of subsoil constraints specifically. Sophisticated crop models, such as APSIM, could be used in the model to predict yields more closely, and allow for assumptions about tillage and stubble retention.

Benefits from inter-row sowing and controlled traffic may take several years to accumulate, as would the benefits from improved nutrition of less mobile nutrients like phosphorus. Consideration of these may help.

It is important to remember that this research explores only a small part of potential PA/SSCM benefits. It does not consider the non-financial benefits of GPS guidance and only considers the variable rate treatment of one crop input, nitrogen. As a result, the figures presented in this study could be considered the minimum possible from PA/SSCM because the same technology can be used for spatial management of other crop inputs. The analysis, and model, could be extended to consider variable rate chemical application for weed management, other fertilisers such as phosphorus and soil ameliorants, such as lime and gypsum. Additional technology could be analysed, such as variable rate spraying and spreading of fertilizer.

5 - Acknowledgements

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6 - Bibliography

Ancev, T., Whelan, B. M., and McBratney, A. B. (2004), '*On the economics of precision agriculture: technical, informational and environmental aspects'*, Proceedings of the 2004 Annual Conference of the Australian Agricultural and Resource Economics Society, Melbourne, Victoria, Australia, 11-13 February 2004.

Ancev, T., Whelan, B. M. and McBratney, A. B. (2005). '*Evaluating the benefits from precision agriculture: the economics of meeting traceability requirements and environmental targets*', Proceedings of the 5th European Conference on Precision Agriculture, Uppsala, Sweden, 9-12 June 2005, Netherlands: Wageningen Academic, 2005.

Anderson, J. R., Dillon, J. L. and Hardaker, J. B. (1977), *Agricultural decision analysis*, 1st edn, Ames, Iowa State University Press, USA.

Anderson, W. K. and Hoyle, F. C. (1999), 'Nitrogen efficiency of wheat cultivars in a Mediterranean environment', *Australian Journal of Experimental Agriculture*, vol. 39, pp 957 – 965.

Angus, J. F., Nix, H. A., Russell, J. S. and Kruizinga, J. G. (1980), 'Water use, growth and yield of wheat in a sub-tropical environment', *Australian Journal of Agricultural Research*, vol. 31, pp 873 – 886.

Angus, J. F., Stapper, M. and Donnelly, J. R. (1993), 'Simulation models for strategic and tactical management of crops and pasture', *Journal of Agricultural Meteorology*, vol. 48, pp 775–778.

Angus, J. F. and van Herwaarden, A. F. (2001), 'Increasing Water Use and Water Use Efficiency in Dryland Wheat', *Agronomy Journal*, vol. 93(2), pp 290 – 298.

Asseng, S., Turner, N. C. and Keating, B. A. (2001), 'Analysis of water and nitrogen use efficiency of wheat in a Mediterranean climate', *Plant and Soil*, vol, 233, pp 127 – 143.

Babcock, B. A. and Shogren, J. F. (1995), 'The cost of agricultural production risk', *Agricultural Economics*, vol. 12, pp 141 – 150.

Blake, J., Forrester, D., Knell, G., McConnell, G., Patabendige, D., Rossere, T., Shepherd, D. and Burt, E. (2004). 'Evaluating the impact of farming systems change using precision agriculture within innovative farmer groups.' Australian Farming Systems Association Conference Papers 10th August 2006 (http://afsa.asn.au/pdfs/blakejohn.pdf)

Bongiovanni, R. and Lowenberg-DeBoer, J. (2000), 'Economics of Variable Rate Lime in Indiana', *Precision Agriculture*, vol. 2, pp 55 – 70.

Bongiovanni, R. and Lowenberg-DeBoer, J. (2004). 'Precision Agriculture and Sustainability', *Precision Agriculture*, vol. 5, pp 359 – 387

Caviglia, O. P. and Sadras, V. O. (2001), 'Effect of nitrogen supply on crop conductance, water- and radiation-use efficiency of wheat', *Field Crops Research*, vol. 69, pp 259 – 266.

Cook, S. E. and Bramley, R. G. V. (1998), 'Precision agriculture - opportunities, benefits and pitfalls of site-specific crop management in Australia', *Australian Journal of Experimental Agriculture*, vol. 38, pp 753 – 763.

Cook, S. E., Corner, R. J., Riethmuller, G., Mussel, G. and Maitland, M. D. (1996), 'Precision Agriculture and risk analysis: An Australian Example', in *Precision Agriculture: Proceedings of the 3rd International Conference on Precision Agriculture*, ed. P. C. Robert, R. H. Rust and W. F. Larson, pp 1123 – 1132.

Cooper, P. J. M., Gregory, P. J., Keatinge, J. D. H. and Brown, S. C. (1987), 'Effects of fertilizer, variety and location on barley production under rainfed conditions in northern Syria. 2. Soil water dynamics and crop water use', *Field Crops Research*, vol. 16, pp 67 – 84.

Crosthwaite, J., MacLeod, N. and Malcolm, B. (1997), *Case Studies: Theory and Practice in Natural Resource Management*, Proceedings of the Australian Association for Social Research Conference, Charles Sturt University, Wagga Wagga February 1997.

Cupitt, J. and Whelan, B. M. (2001), *Determining potential within-field crop management zones*, in ECPA 2001, eds G. Grenier and S. Blackmore, Proceedings of the 3rd European Conference on Precision Agriculture, Montpellier, France, 18-20 June 2001

Daberkow, S. G. and McBride, W. D. (2003), 'Farm and Operator characteristics affecting the awareness and adoption of precision agriculture technologies in the US', *Precision Agriculture*, vol. 4, pp 163 – 177.

Ehlert, D. and Adamek, R. (2005), *Crop variability and resulting management effects*. Proceedings of the 5th European Conference on Precision Agriculture, Uppsala, Sweden, 9-12 June 2005, Netherlands : Wageningen Academic, 2005.

Feder, G. (1980), 'Farm Size, Risk Aversion and the Adoption of New Technology Under Uncertainty', *Oxford Economic Papers*, vol. 32(2), pp. 263 – 283.

Fisher, P. and Abuzar, M. (2005), 'Precision agriculture - common sense with a dash of technology', GRDC Ground Cover Issue 58, October/November 2005 14th July 2006 (http://www.grdc.com.au/growers/gc/gc58/supplement/zoning.htm)

Fleming, K. L., Westfall, D. G., Wiens, D. W. and Brodahl, M. C. (2000), 'Evaluating Farmer Defined Management Zone Maps for Variable Rate Fertilizer Application', *Precision Agriculture*, vol. 2, pp 201 – 215.

Freebairn, D. M., Wockner, G. H., Lawrence, D., Cawley, S. and Hamilton, A. N. (2004), 'A framework for extending principles of conservation cropping' The Australian Society of Agronomy 21st July 2006 (http://www.regional.org.au/au/asa/1998/7/118freebairn.htm)

French, R. J. and Schultz, J. E. (1984), 'Water Use Efficiency of Wheat Production in a Mediterranean-type Environment. I: The Relation Between Yield, Water use and Climate', *Australian Journal of Agricultural Research*, vol. 35, pp 743 – 64.

French, R. J. and Schultz, J. E. (1984), 'Water Use Efficiency of Wheat in a Mediterranean-type Environment. II: Some Limitations to Efficiency." *Australian Journal of Agricultural Research*, vol. 35, pp 765 – 775.

Godwin, R. J., Wood, G. A., Taylor, J. C., Knight, S. M. and Welsh, J. P. (2003). 'Precision Farming of Cereal Crops: a Review of a Six Year Experiment to develop Management Guidelines', *Biosystems Engineering*, vol. 84(4), pp 375 – 391.

Hammer, G. L., Holzworth, D. P. and Stone, R. (1996), 'The value of skill in seasonal climate forecasting to wheat crop management in a region with high climatic variability', *Australian Journal of Agricultural Research*, vol. 47, pp 717 – 737.

James, I. T. and Godwin, R. J. (2003), 'Soil, Water and Yield Relationships in developing Strategies for the Precision Application of Nitrogen Fertiliser to Winter Barley', *Biosystems Engineering*, vol. 84(4), pp 467 – 480.

Kelly, R., Strong, W., Jensen, T., Butler, D., Norng, S., Cook, S., Town, B. (n.d.) 'Integrating yield and protein spatial information: a framework for analysis and interpretation', The Australian Society of Agronomy (http://www.regional.org.au/au/gia/16/528kelly.htm)

Kondinin (2003), 'Tests put GPS units on level playing field', *Farming Ahead*, no. 142, November 2003, The Kondinin Group

Kondinin (2006), 'Research Report - GPS Guidance Equipment', *Farming Ahead*, no. 171, April 2006, The Kondinin Group

Lilley, J., Kirkegaard, J., Robertson, M., Probert, M., Angus, J., Howe, G. (2003), 'Simulating crop and soil processes in crop sequences in southern NSW', Australian Society of Agronomy (www.regional.org.au/au/asa/2003/c/12/lilley.htm)

Lopez-Bellido, L., Lopez-Bellido, R. J. and Redondo, R. (2005), 'Nitrogen efficiency in wheat under rainfed Mediterranean conditions as affected by split nitrogen application', *Field Crops Research*, vol. 94, pp 86 – 97.

Lowenberg-DeBoer, J. (1996), 'Precision Farming and the New Information Technology: Implications for Farm Management, Policy, and Research: Discussion', *American Journal of Agricultural Economics*, vol. 78(5), pp 1281 – 1284.

Lowenberg-DeBoer, J. (1996), 'Economics of precision farming: payoff in the future' February 1996 (http://pasture.ecn.purdue.edu/~mmorgan/PFI/pfiecon.html)

Lowenberg-DeBoer, J. (2003), 'Precision farming or convenience agriculture?', *in Proceedings of the 11th Australian Agronomy Conference*,The Regional Institute Ltd. 21st July 2006 (http://www.regional.org.au/au/asa/2003/i/6/lowenberg.htm)

Lowenberg-DeBoer, J. and Boehlje, M. (1996), 'Revolution, evolution or dead-end: Economic perspectives on precision agriculture', in *Precision Agriculture: Proceedings of the 3rd International Conference on Precision Agriculture*, ed. P. C. Robert, R. H. Rust and W. F. Larson, pp 923 – 944.

Malcolm, B. (2004), 'Where's the economics? The core discipline of farm management has gone missing!', *Australian Journal of Agricultural and Resource Economics*, vol 48(3), pp 395 – 417.

Malcolm, B., Makeham, J., and Wright, V. (2005), 'The farming game: agricultural management and marketing', Cambridge University Press, Port Melbourne 2005.

McBratney, A. B., Bouma, J., Whelan, B. M. and Ancev, T. (2005), 'Future directions of Precision Agriculture', *Precision Agriculture*, vol. 6(1), pp 7 – 23.

McBratney, A.B., and Whelan, B.M. (1999), '*The 'null hypothesis' of precision agriculture'*, in Precision Agriculture '99 (Part 2), ed J.V. Stafford, Proceedings of the 2nd European Conference on Precision Agriculture, Odense Congress Centre, Denmark, 11-15 July 1999 pp 947 – 957.

McDonough, C. (2004) '"Reducing risk and reaching potential" - Getting nitrogen right in the Mallee', GRDC Research Update, 2nd June 2006 (http://www.grdc.com.au/growers/res_upd/south/s04s/mcdonough.htm)

Mosse, J. (1990), 'Nitrogen to Protein Conversion Factor for Ten Cereals and Six Legumes or Oilseeds', *Journal of Agricultural Food Chemistry*, vol. 38, pp 18 – 24.

Murat, I. and Madhu, K. (2003), 'Stochastic Technology, Risk Preferences, and Adoption of Site-Specific Technologies', *American Journal of Agricultural Economics*, vol. 85(2), pp 305 – 317.

Nemenyi, M., Mesterhazi, P., Pecze, Z. and Stepan, Z. (2003), 'The role of GIS and GPS in precision farming', *Computers and Electronics in Agriculture*, vol. 40, pp 45 – 55.

Noulas, C., Stamp, P., Soldati, A. and Liedgens, M. (2004), 'Nitrogen Use Efficiency of Spring Wheat Genotypes under Field and Lysimeter Conditions', *Journal of Agronomy & Crop Science*, vol. 190, pp 111 – 118.

Pannell, D. J. (2006), 'Flat Earth Economics: The Far-reaching Consequences of Flat Payoff Functions in Economic Decision Making', Review of Agricultural Economics, vol. 28, no. 4, pp 553 – 566.

Palta, J. A. and Fillery, I. R. P. (1995), 'N Application Enhances Remobilization and Reduces Losses of Pre-anthesis N in Wheat Grown on a Duplex Soil', *Australian Journal of Agricultural Research*, vol. 46, pp 519 – 531.

Rainbow, R. (2004), 'Getting into Precision Agriculture - The Basics', Precision AgNews Winter 2003, Southern Precision Agriculture Association. 2nd June 2006. (http://www.spaa.com.au/downloads/SPAAwinter2003.pdf)

Rodriguez, D., Nuttall, J., Sadras, V. O., van Rees, H. and Armstrong, R. (2006), 'Impact of subsoil constraints on wheat yield and gross margin on fine-textured soils of the southern Victorian Mallee', *Australian Journal of Agricultural Research*, vol. 57, pp 355 – 365.

Seelan, S. K., Laguette, S., Casady, G. M. and Seielstad, G. A. (2003), 'Remote sensing applications for precision agriculture: A learning community approach', *Remote Sensing of Environment*, vol. 88(1), pp 157 – 169.

Siddique, K. H. M., Tennant, D., Perry, M. W. and Belford, R. K. (1990), 'Water use and water use efficiency of old and modern wheat cultivars in a Mediterranean-type environment', *Australian Journal of Agricultural Research*, vol. 41, pp 431 – 447.

Stafford, J. V. (2000), 'Implementing Precision Agriculture in the 21st Century', *Journal of Agricultural Engineering Research*, vol. 76(3), pp 267 – 275.

Swinton, S. M. and Ahmad, M. (1996), 'Returns to Farmer Investment in Precision Agriculture Equipment and Services', in Precision Agriculture, in *Precision Agriculture: Proceedings of the 3rd International Conference on Precision Agriculture*, ed. P. C. Robert, R. H. Rust and W. F. Larson, pp 1009 – 1018.

Van Meirvenne, M. (2003), 'Is the Soil Variability within the Small Fields of Flanders Structured Enough to Allow Precision Agriculture?', *Precision Agriculture*, vol. 4(2), pp 193 – 201.

Weiss, M. (1996), 'Precision farming and spatial economic analysis: Research challenges and opportunities', *American Journal of Agricultural and Applied Economics*, vol. 78, pp 1275 – 1280.

Welsh, J. P., Wood, G. A., Godwin, R. J., Taylor, J. C., Earl, R., Blackmore, S. and Knight, S. M. (2003), 'Developing Strategies for Spatially Variable Nitrogen Application in Cereals, Part I: Winter Barley', *Biosystems Engineering*, vol. 84(4), pp 481 – 494.

Whelan, B.M. (1998), Reconciling continuous soil variation and crop yield - a study of some implications for within-field variability for site-specific crop management, PhD Thesis, University of Sydney, Sydney

Whelan, B. M. and McBratney, A. B. (2000). "The ‘‘Null Hypothesis’’ of Precision Agriculture Management." Precision Agriculture 2(3): 265-279(15).

Whelan, B.M., and McBratney, A.B. (2001), 'Precision Ag - Oz Style', in *Leading Edge (included in Australian Grain)*, vol. 11(4), pp 46 – 48.

Whelan , B. M., and McBratney, A. B. (2003) ‘Definition and interpretation of potential management zones in Australia’, Australian Centre for Precision Agriculture (ACPA), (http://www.regional.org.au/au/asa/2003/i/6/whelan.htm)

Whelan, B., and Taylor, J. (2005), ‘A Process for Implementing Site-Specific Crop Management’, Australian Centre for Precision Agriculture, 21st July 2006 (www.usyd.edu.au/su/agric/acpa/GRDC/SSCMprocess.pdf)

Wong, M. T. F., and Asseng, S. (2004), ‘Fluctuations in spatial variability of wheat yield’, 4th International Crop Science Congress, 2nd June 2006 (www.cropscience.org.au/icsc2004/poster/1/4/1158_wongmt.htm)

Zhang, N., Wang, M. and Wang, N. (2002), ‘Precision agriculture-a worldwide overview’, *Computers and Electronics in Agriculture*, vol. 36(2), pp. 113 – 132.