THE UNIVERSITY OF ADELAIDE

"I can't be green if I'm in the red":

Combining precision agriculture and remote sensing technologies for sub field and regional decision making

Thesis presented for the degree of

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Chapter 1: Introduction

1.1 Motivation for the research

The Australian grains industry has huge viability and sustainability challenges in the future. There is increasing evidence that the industry faces potentially adverse effects of climate change on agricultural production, with large regional differences occurring in specific agricultural regions around Australia (Howden and Jones, 2001; Luo *et al.*, 2003; Van Ittersum *et al.*, 2003; Luo *et al.*, 2005a; Luo *et al.*, 2005b; Ludwig and Asseng, 2006; Anwar *et al.*, 2007). Studies show that higher rainfall regions will become more suitable for cropping (Howden and Jones, 2001; Ludwig and Asseng, 2006) and wheat yields in the drier regions will be greatly reduced (Luo et al., 2005a; Luo et al., 2005b; Ludwig and Asseng, 2006; Anwar et al., 2007), both with significant economic repercussions. Outside Australia, further evidence through regional impact assessments have identified agricultural land with a Mediterranean climate as the most vulnerable to reductions in grain yield (Harrison and Butterfield, 1999; Olesen and Bindi, 2002; Ewert et al., 2005), land abandonment (Ewert et al., 2005; Berry et al., 2006) and lack of capacity to adapt to the impacts of climate change (Metzger and Schröter, 2006). These studies have specific relevance to the grain regions of Australia which are typified by a Mediterranean climate.

Next to climate change, prevention of environmental degradation is also a major issue worldwide. In Australia, salinity has been a major cause of environmental degradation and loss of biodiversity with eradication of plant species and invertebrates in low lying parts of the agricultural landscape (George et al., 1997; George et al., 1999;Beresford et al., 2001). The clearing of native woodland or perennial grassland for production based annual cropping has led to an increase in the proportion of rainfall unused by vegetation and has resulted in larger rates of infiltration and recharge to groundwater aquifers. This increased recharge has caused saline aquifers to rise, causing secondary salinisation and reducing water quality (George et al., 1997; Clarke et al., 1999, Clarke et al., 2002; Hatton et al., 2003). Large impacts on agricultural areas have been predicted, in particular for the western region of Australia, where an estimated 8.8 million hectares will be lost due to salinity by 2050 (National Land and Water Resources Audit, 2001). The most promising option for mitigation is the re-introduction of deep rooted perennial plants (trees and shrubs) to large proportions of the landscape (Clarke et al., 2002; Barrett-Lennard et al., 2005; Lefroy et al., 2005; Ridley and Pannell, 2005). Hydrological studies to assess the magnitude of area required suggest that mass plantings could range between 30 to 80% of the rural landscape to achieve significant salinity reductions (Stirzaker et al., 1999, Clarke et al., 1999; George et al., 1999; Pracilio et al., 2003 Hodgson et al., 2004). The enormity of this estimated area suggests that substantial reductions to farm and regional agricultural income will occur if no financial offset is received for this land use change.

Presently in Australia, a stalemate exists in the economic decision of who will pay for environmental benefits in the rural landscape. In European and American agricultural landscapes, direct price support or area based incentives are paid to growers to meet environmental objectives (Parks and Schorr, 1997; Bills and Gross, 2005; Otte *et al.*, 2007; Baylis *et al.*, 2008). In comparison, very little financial compensation is paid to Australian growers for environmental actions with much of the cost of on-farm conservation expected to be borne by the landholder. This situation has been reflected in the aims of many research studies which have investigated the likely economic viability of various alternative agricultural land uses such as perennial pastures (Kingwell *et al.*, 2003; John *et al.*, 2005; O'Connell *et al.*, 2006) and woody perennials (Abadi *et al.*, 2006; Bennell *et al.*, 2007; Hobbs *et al.*, 2007; Dorrough *et al.*, 2008; House *et al.*, 2008). Some options also offer further potential financial benefits from both carbon sequestration as an abatement to climate change and green house gas emissions (Venn, 2005; Flugge and Abadi, 2006; Harper *et al.*, 2007; Hunt, 2008) and biomass production as an energy alternative (Varela *et al.*, 2001; Bryan *et al.*, 2008). These opportunities provide some ways to offset the potential loss in income.

The attractiveness of these alternative land uses will be based on their profitability with respect to the overall financial position of the farm business (Pannell, 2001; Bathgate and Pannell, 2002; John *et al.*, 2005; O'Connell *et al.*, 2006) as well as the magnitude of the economic opportunity cost associated with the replacement of traditional cropping practices (Cary and Wilkinson, 1997; Curtis and Lockwood, 2000). However, current research into the application of economic opportunity cost for agricultural land use trade offs has major limitations. Previous studies have been non-spatial and fail to distribute the economic opportunity costs over different agricultural enterprises within a region. Where spatial datasets does exist, the spatial resolution is too broad for any on ground decisions to be made. In cases where high resolution data exists, its currency provides only an annual snapshot of land use and assigns production figures reported at a regional, farm or field level. This assignment potentially blurs the spatial yield variability that is apparent within a region due to rainfall, soil fertility and agronomic factors.

Precision agriculture technology provides one opportunity of high resolution data collection. The technology is used to quantify the spatial variability of crop production at a sub-field level through crop yield mapping. Yield mapping is the process in which the grain harvester is fitted with a global positioning system and a grain flow measuring device to collect yield estimates and their corresponding position at per second intervals. Mapping of this data over a variety of seasons for individual fields and for the farm as a whole identifies areas that exhibit both spatial and temporal yield variability. The high spatial resolution of these mapped estimates over time allows growers to make input management decisions to match infield crop yield potential. This resolution also enables the grower to identify areas of profit variability and income consistency on farm by applying financial estimates which define the costs and returns of crop production (Massey *et al.*, 2008). This spatial and temporal quantification of income generation therefore provides the basis for the calculation of economic opportunity cost at a high resolution sub-field scale. However, with any automated method of data collection, measurement error does occur. We must be sure that the data used for long term management decisions is accurate and represents the true yield variation. Previous overseas studies have highlighted various forms of yield mapping errors but these papers have focussed on only a few possible sources of error in fields substantially smaller than those that occur in Australia (Blackmore and Marshall, 1996; Blackmore and Moore, 1999; Beck *et al.*, 1999; Thylen *et al.*, 2000; Beck *et al.*, 2001; Simbahan *et al.*, 2004a; Ping and Dobermann, 2005; Robinson and Metternicht, 2005; Shearer *et al.*, 2005; Drummond and Sudduth, 2005a; Sudduth and Drummond, 2007). A movement towards a common set of procedures to identify and remove yield mapping errors and a greater understanding of the error types inherent in Australian yield data is needed.

High resolution yield mapping of Australian farms whose size often exceed 2,000 hectares over several seasons provides vast amounts of data. Removing yield errors by hand is extremely time intensive. Although software has been created to remove a variety of error sources (Rands, 1995; Thylen *et al.*, 2000; Beck *et al.*, 2001; Kleinjan *et al.*, 2002; Reese *et al.*, 2002; Simbahan and Dobermann, 2004b; Drummond, 2005b; Sudduth and Drummond, 2007), none are comprehensive and often require each field to be investigated individually. A batch processing error removal system is required if numerous farms over a substantial time period are needed to create robust estimates of spatial and temporal yield variability.

While some growers in Australia have been collecting crop yield data for over a decade, there has not been a full adoption of the technology (Jochinke et al., 2007) at the broader scale. One way to circumvent this problem is to draw on historical yield mapping data from early adopters and relate this spatial dataset to vegetation indices from archived remotely sensed imagery. Several studies have shown good relationships between these indices and actual crop yield, with the explanation of 50-91% of yield variation (Boissard and Pointel, 1993; Quarmby et al., 1993; Labus et al., 2002; Wendrotha et al., 2003; Dobermann and Ping, 2004; Enclona et al., 2004; Weissteiner and Kühbauch, 2005; Liu et al., 2006). However, the reliability of the relationships developed between wheat yield and satellite derived spectral measurements are primarily governed by the choice of satellite sensor. Previous predictions of wheat yield from remotely sensed imagery have used coarse resolution sensors because of their low cost, easy availability, extensive areal coverage and frequent acquisition dates. However, the choice of resolution limits the applicability of the results to the farm scale and below because the imagery does not adequately characterise crop productivity at this scale (Garrigues *et al.*, 2006; González-Sanpedro *et al.*, 2008) and can include other crop types or riparian vegetation (Labus *et al.*, 2002; Doraiswamy *et al.*, 2004).

Another limitation of these studies is the scale at which the wheat yield data is collected. Data is acquired from regional, farm, field or geo-referenced hand-sampled estimates (Rudorff and Batista, 1991; Singh *et al.*, 1992; Hamar *et al.*, 1996; Lobell and Asner, 2003; Ferencz *et al.*, 2004; Liu *et al.*, 2006). The mixing of resolutions at which both the satellite imagery and yield data are collected will minimise landscape heterogeneity and can over inflate the strength of the resultant relationships (Benedetti and Rossini, 1993; Doraiswamy and Cook, 1995; Reeves *et al.*, 2005).

The use of yield mapping technology provides a perfect opportunity to collect data at a high resolution to relate to imagery of a similar resolution. Studies relating higher resolution imagery and yield mapping datasets have been conducted (Thenkabail, 2003; Dobermann and Ping, 2004; Enclona *et al.*, 2004; Reyniers and Vrindts, 2006b) but these yield prediction models are confined to specific fields and are rarely validated against other field datasets. For these studies, the high spatial resolution of data collection is traded off with a small measurement extent meaning that regional coverage is minimal. The acquisition of this type of imagery is costly and means a once off annual snapshot approach has been favoured (Lobell *et al.*, 2003). While previous research has identified a broad window for image acquisition (Dawbin *et al.*, 1980; Smith *et al.*, 1995), further research is needed into the robustness of the empirical relationships derived both during and between seasons.

For on ground decision making, mid to high resolution imagery with a large regional coverage and relatively frequent acquisition dates is needed. The Landsat sensors provide a data source that satisfies these criterions, with 30 metre spatial resolution, a 185km by 185km regional coverage and an image acquired every 16 days. Given that yield mapping data can be aggregated to the spatial resolution of the senspor without considerable loss in grain yield variation, empirical relationships between these two independent datasets can be developed. This development and its subsequent extrapolation, provide a means to create high resolution estimates of yield variability over the broad extent of the imagery.

The creation of this type of information over a regional scale will provide numerous benefits. The creation of a pattern of past yield performance may enable non or recent adopters of yield mapping technology to leap frog technology adoption hurdles. Access to this information would provide the equivalent of long term yield map archives so that management and land use decisions can be made sooner. The ability to apply financial estimates associated with production spatially identifies areas that consistently generate marginal income. These areas may have the potential for higher financial and environmental returns from the adoption of alternative land uses. Alternatively, areas of high profitability are also highlighted and hence suggest where land use change should not occur. This information is created at an extent where environmental planning or policy decisions are made by catchment managers or government authorities. This will allow for a greater understanding of the economic viability of adoption and adaptation of alternative land uses in specific regions. Such information can act as a critical sounding board between the land holder and the catchment manager where conflicting objectives of economic and environmental outcomes can be compared.

In summary, the occurrence of climate change and environmental degradation will severely hamper current agricultural production. In these areas, indicators of yield and economic performance of current cropping systems are required to evaluate the potential for and financial repercussion of land use change. Economic analysis to evaluate the likelihood of adopting a structural change in land use has traditionally used data at the regional level, neglecting the paradigm of spatially and temporally variable crop yield. High resolution data is collected at the sub-field but only at the farm scale. Remote sensing imagery is collected at a high resolution at the regional scale but its vegetation indices need auxiliary yield data for empirical relationships to be developed. Therefore, there is a clear need to examine the potential for yield mapping and remote sensing to create high resolution estimates of economic performance to help facilitate and inform both infield and regional land use decision making.

1.2 Thesis aims, objectives and structure

This research has the overarching goal of developing a framework to create high resolution broad scale estimates of economic opportunity cost in grain growing regions. Existing wheat yield data mapped through precision agriculture technology and remotely sensed imagery was recognised as being crucial to achieve this goal.

The first aim of thesis dealt with the identification and removal of yield mapping errors. This aim comprises of three objectives.

This first objective involved reviewing the existing published literature on the nature of errors inherit in yield mapping, the types of methods used to remove these errors and the benefits of applying them to estimate spatially variable yield. A logical structure of common error removal processes was constructed and subsequent gaps in the literature addressing other specific error sources were filled.

The cataloguing of the previously developed methods and their benefits led to the second objective of this aim: the development of a comprehensive error removal computer program based on previous cited methodologies and new cleaning routines proposed by the author.

The third objective of the first aim was to test the effectiveness of these routines to remove yield mapping errors. The program algorithms were implemented on 183 yield mapped fields and the results compared against two less targeted methods of error removal. Each individual algorithm's effectiveness for error removal was assessed and further statistical and visual assessment was undertaken with a randomly selected field to evaluate the change in local yield variation.

Having robust estimates of wheat yield will allow the second aim of the thesis to be addressed. This second aim focused on the identification of areas that show spatial and temporal consistency of financial returns across a farm. Methods were developed to incorporate the spatial and temporal variability of income which will help inform both the magnitude of economic opportunity cost and the amount of area available in the land use reassignment decision making process.

The third aim of the thesis assessed the possibility of creating high resolution estimates of wheat yield and economic performance at a broad scale. This aim utilised the historical archive of both yield mapping data and remotely sensed imagery. Creation of these estimates overcame the lack of adoption of yield mapping technology by grain growers and provided regional yield information so that grain growers, catchment planners and government agencies can determine the financial trade-offs for regional environmental strategies.

The final aim of the thesis was to test the strength of the wheat yield prediction models developed from historical yield mapping and remote sensing data over six different growing seasons. This aim examined the robustness of the empirical relationships that can be expected over different timings and distributions of growing season rainfall and the yield prediction error involved when they are extrapolated to a regional extent.

This thesis is structured with eight chapters, each written as articles for publication in peer-reviewed journals.

The thesis begins with a general introduction and overview of the need for and motivation behind this research and an outline of the structure of the thesis (Chapter 1 - this chapter).

Chapter 2 begins with a review of the background literature relating to the value of agriculture to the Australian economy and the effects of climate change on dry land agriculture. The chapter introduces salinity as the major environmental problem in grain growing regions of Australia, brings together the published estimated costs of this problem to Australian society and highlights the proposed options and opportunities of environmental remediation. Chapter 2 also highlights the need for a sustainable agricultural sector and highlights the drivers and determinants of Natural Resource Management (NRM) adoption. A brief introduction into the use of precision agriculture and its application within an NRM context is then presented. In addition to this chapter, a detailed review of literature is also presented at the start of each individual chapter.

The major conclusions from Chapter 2 were presented as a conference paper titled: “Drivers and determinants of natural resource management adoption at the farm scale” at MODSIM 2005 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2005, Melbourne.

Chapter 3 examines the literature around the nature of yield mapping errors and the types of error removal methods used to remove them and the benefits of applying them in order to estimate spatial varying grain yield. This chapter has been submitted as a paper to *Precision Agriculture* as at 28th November 2009, titled “Comparison of post processing methods to eliminate erroneous yield measurements in grain yield mapping data: A review”.

Having assessed the published methods of error removal, Chapter 4 highlights the incorporation of published and proposed methods to remove yield errors present in the harvesting of Australian fields. A logical structure of implementation is proposed and the effectiveness of the new software developed to remove erroneous yield errors is assessed. This chapter has been submitted as a paper to *Precision Agriculture* as at 17th Aprily 2010, titled “The effectiveness of post processing routines to remove erroneous yield mapping errors”.

With erroneous data removed, robust spatial estimates of wheat yield were used for analysis presented in Chapter 5. We used three farm datasets over a variety of years to test the spatial variability of the income to area relationships. For one farm with 8 years of data we illustrated the use of the z-score standardisation to highlight the spatial and temporal consistency of income. The magnitude of area and the associated financial returns from the production areas identified as spatially and temporally consistent were then used to derive spatial estimates of economic opportunity costs for land use reassignment. This chapter has been submitted as a paper to *Agriculture, Ecosystems and Environment* as at 23rd February 2010, titled “Identifying the spatial and temporal variability of economic opportunity cost in Mediterranean grain growing regions”.

Chapter 6 assesses the usefulness in combining yield mapping estimates and plant growth surrogates derived from remotely sensed imagery. This chapter evaluates the spatial and temporal accuracy of crop type image discrimination and correlations between yield mapped wheat estimates and NDVI taken at specific times in a particular growing season. This article has been accepted on 12th May 2009 to *Ecological Indicators*, as Lyle G.M. and Ostendorf, B., titled “A high-resolution spatial indicator of economic performance in the grain growing regions of Australia”.

Chapter 6 acted as a pilot study to assess the magnitude of error associated with both crop type discrimination and wheat grain yield simulated from NDVI wheat yield relationships. Chapter 7 furthers the validation process and tests the accuracy of the yield mapped wheat yield estimates NDVI relationships over imagery collected in low (>200mm and <230mm), medium (> 230 and < 330 mm) and high (> 330mm) in-season rainfall growing conditions. This chapter has been submitted as a paper to *Remote Sensing of Environment* as at 24th February 2010, titled “Estimating wheat yield from Landsat TM imagery and precision agriculture technology”.

Chapter 8 reviews the findings of the research and the extent to which the aims have been met. The thesis ends with a summary of important areas for future research.

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Chapter 2: Literature review

2.1 Introduction

This literature review addresses the published background knowledge which surrounds this thesis and places the reader into the context of current issues and opportunities within the Australian grain industry. More detailed literature reviews at the start of each chapter are presented to provide additional information relevant to specific chapters.

The initial focus is on the value of agriculture in Australia and in particular the Australian grains industry on which this thesis is based. The potential impacts of a changing climate and the salinisation of the Australian agricultural landscape are discussed in terms of their affects on the agricultural landscape and the grains industry.

To address these problems, I turn the spotlight onto the likelihood and possible implementation of a revegetation strategy. Here, I review the literature to report how much areas should be revegetated, where and how it should be arranged and the possible financial opportunities available to growers from a revegetation strategy.

The chapter then discusses the main drivers and determinants for Australian grain growers to adopt natural resource management (NRM) practices at a farm scale. I then use a sustainable development conceptual model developed by Gallopín (2002, pp. 361-392 in: Gunderson, L.H. and Holling, C.S. (eds), *Panarchy: Understanding Transformations in Human and Natural Systems*, Island Press, Washington) to characterise the current NRM adoption situation.

Finally, I introduce the concept of using Precision Agriculture technology in particular grain yield mapping for potential use in understanding the degree and capacity to which the Australian grain growers can adopt natural NRM practices.

A summary of this chapter was published as a conference paper titled: "Drivers and determinants of natural resource management adoption at the farm scale" at MODSIM 2005 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2005, Melbourne.

2.1 The value of agriculture to the Australian economy

With Australia's growing economy and the growth of other industries, the relative rate of growth of agriculture means that the sector now represents just 3% of Gross Domestic Product (GDP) measured on the basis of farm gate value of production (Econotech, 2005). Is it then worthwhile to continue investment to keep the industry viable given it is only a small proportion of GDP? Considering this question, what is interesting is the observation that a major drought impacting on the farm sector can have a very significant effect on the national economy, stripping as much as 1.6% from national GDP (Econotech, 2005). This then poses the question of how much the agricultural sector is actually worth to the Australian economy both pre and post farm gate. Econotech, 2005 examined the Australian Agricultural Sector in terms of its contribution to supplying and consuming goods and services in the Australian economy. As a supplier, the agricultural sector provides raw inputs to a range of different Australian economic sectors, termed Farm-Output Sector. As a consumer, the agricultural sector also purchases inputs from various other sectors of the Australian economy, termed Farm-Input Sector. Figure 1 shows the structure of Australia's 'Farm Dependent Economy' (FDE) and its interactions with three sectors, (1) the combination of the Agricultural Sector, (2) the Farm-Output Sector and (3) the Farm–Input Sector. By giving a clearer estimate of the value of agriculture in Australia, the authors gained a better understanding of the interactions and potential impacts of both natural and policy shocks on the agriculture industry and the Australian economy as a whole. Results of the study showed that in 2003-04, the agricultural sector accounted for 3.1% of Australia's GDP with average GDP of the sector contributing 3.2% of GDP over the past six years. In terms of where goods and services are produced, 88% of Agricultural sector is produced by regional Australia. For Farm Input and Output Sectors 69% and 63% of output was provided by the six state capitals. The total FDE saw around a 50:50 split between regional and state capitals based on ABS statistical regions. Using ABS data to identify the size of Australia's FDE, the contribution of Agriculture was estimated at an average of 12.1% of the national GDP for the six year up to and including 2003-04. Of this, the Agriculture Sector contributed on average 3.2 % of GDP, the farm input sector contributed 0.8% and the farm–output sector contributed 8.1% of GDP. The sector therefore contributes an additional 8.9% of GDP. The study concluded that in value terms, for every dollar of agricultural sector GDP, there is an additional $3 worth of GDP in the economy through Farm-Input and Farm-Output Sectors. In terms of employment, for every million dollars of the agricultural sector GDP, there are 22 jobs in the agricultural sector and an additional 65 jobs in the rest of the FDE. For each dollar earned from agricultural exports, there was created an additional $1.07 of output in the domestic economy (Econotech, 2005).

NOTE:
This figure is included on page 20 of the print copy of the thesis held in the University of Adelaide Library.

Figure 1 Australia's farm dependent economy (Econotech, 2005)

2.2 The value of the Australian grains industry

The Grains Research and Development Corporation (GRDC) highlight that there are currently some 40,000 grain producers in Australia, with 39% of them classed as "grains only", 38% as "mixed farming" and the remaining 23% spread across a range of industries, such as cotton, beef and sheep, where grain production is a minor part of their activities (Grains Research and Development Corporation and Grains Council of Australia, 2004). Specifically, for the Australian Grains Industry, in 1998-99, the share of Agriculture Sector Production has been estimated at 19% or $6.3 billion out of an estimated $34 billion (Econotech, 2005).

Analysis into the triple bottom line of different industries in the Australian economy (Foran *et al.*, 2005) provides a numerated approach of generalized input – output analysis to generate a triple bottom line account of the Australian economy. One of the sectors measured was the contribution of "Wheat and Other Grains" to the Australian economy. Although this sector does not entirely represent the Australian grains industry it can be used as a constricted surrogate of the relative performance of the industry. The study estimated that the industry provides 34 million tonnes (Mt) of grain per year comprising of wheat (22 Mt), oats and grain sorghum (4.5 Mt), oil seeds such as canola (3 Mt), pulses (2.4 Mt) and cottonseed (1 Mt). The study estimated that the farm gate value was approximately $9 billion of which wheat makes up $6 billion. In terms of world production, Australia is a relatively small grain producer with approximately 3% of annual world production although it contributes around 10-15% of world grain trade behind the United States, Canada and the European Union.

In terms of the contribution of the grains industry to the Australian economy, the analysis ranks the industry as 61st out of a possible 135 industries and with a value-adding component to the economy estimated at 0.28% of GDP. This can be compared to the rice industry, which contributes 0.02%, commercial fishing 0.18%, dairy products 0.29%, residential building 2.54% and retail trading 4.26%. The study showed that the industry has moderate employment creation and contributes to employment in industries such as flour milling and animal feeds, although the study mentions that activities within the sector produces average stimuli for the associated upstream and downstream sectors. The sector has moderate resource requirements with over 1% of national water use and less than 1% of energy use and greenhouse emissions. This is suggested to be an average rating compared to other industries. Conversely, the study highlights that the industry is a major contributor to landscape disturbance with over 2% of the national land disturbance with five to eight times the average for water use and land disturbance. The study suggested that this land disturbance indicator reflects the physical reality of Australia's variable climate and relatively poor soils (in a world context).

In financial terms, the grains sector has strong financial indicators and has great importance to Australia's national accounts in terms of exports and imports. The industry has an export propensity more than three times the average while import propensity to the industry were 55% below the average. The study highlights that operating surplus was estimated at 30% above the economy wide average, with two thirds due to direct effects of the industry. Social indicators showed strong employment generation, 30% greater than average; of which two thirds is a direct effect. However, weaker indicators for income and government revenue were highlighted, with estimates 50% and 40% lower than the average, respectively. Weak income returns were also supported by one study (Grains Research and Development Corporation and Grains Council of Australia, 2004) which highlighted that household incomes vary widely between farms with 19% of farmers classed as "very well-off" and 22% "very low income", with a wide spread of incomes between these two groups. One important feature of the grains industry is that employment and profits are generated locally and do not dissipate to city activities and firms (Foran *et al.*, 2005). The industry therefore contributes to the sustainability of regional centres since all profits that are generated locally are spent locally.

2.3 Climate change effect on dry land agriculture

Of further significance to the sustainability of the world's agricultural industry is the effect of climate change on agricultural production. Although different agricultural regions of the world will have varying risks of vulnerability to climate change, research suggests that there will be a mixed response on crop yields from rising CO_2 levels, higher temperatures, altered patterns of rainfall and the increased occurrence of extreme weather events

(Tubiello and Ewert, 2002; Easterling and Apps, 2005; Rounsevell *et al.*, 2005; Berry *et al.*, 2006; Reilly *et al.*, 2007; Wu *et al.*, 2007).

For the world's dryland grain industry, computer simulation predictions have attempted to assess the impact of climate change on wheat crop yields. In the United States of America prediction have ranged from a 31% increase to a 76% decline in wheat grain yield (Lobell and Asner, 2003; Antle *et al.*, 2004; Thomson *et al.*, 2005; Isik and Devados, 2006). Similar results are apparent in the wheat growing regions of Europe (Olesen and Bindi, 2002; Ewert *et al.*, 2005; Porter and Semenov, 2005; Rounsevell *et al.*, 2005) and Australia (Howden and Jones, 2001; Luo *et al.*, 2003; Van Ittersum *et al.*, 2003; Luo *et al.*, 2005a; Luo *et al.*, 2005b; Ludwig and Asseng, 2006; Anwar *et al.*, 2007). These studies suggest that of the current areas for dryland wheat production, the areas that will be most affected by climate change are where production is on the margins (Thomson *et al.*, 2005), or have the poorest resource endowments (IPCC, 2001; Antle *et al.*, 2004; IPCC, 2007).

In Europe, regional impact assessments identified agricultural land with a Mediterranean climate as the most vulnerable to reductions in grain yield (Harrison and Butterfield, 1999; Olesen and Bindi, 2002; Ewert *et al.*, 2005), land abandonment (Ewert *et al.*, 2005; Berry *et al.*, 2006) and lack of capacity to adapt with the impacts of climate change (Metzger and Schröter, 2006). These studies have specific relevance to the grain regions of Australia which are typified by a Mediterranean climate.

Regional analyses to understand of the impacts of CO_2 and climate change on wheat grown under Australian conditions suggest that large regional differences will occur. Higher rainfall regions will become more suitable for cropping (Howden and Jones, 2001; Ludwig and Asseng, 2006) and wheat yields in the drier regions will be greatly reduced (Luo *et al.*, 2005a; Luo *et al.*, 2005b; Ludwig and Asseng, 2006; Anwar *et al.*, 2007) with significant economic repercussions. However, a recent wheat yield simulation study in the Western Australian cropping region (Ludwig *et al.*, 2009) suggest that the resulting wheat yield declines are dependent on when rainfall reductions occurred. For example, the study showed that rainfall decreases particularly in the months of June to July did not result in a reduction in simulated yield while reductions in May or August caused wheat yield to decline. The study concluded that previous analyses which attempted to estimate the impact of a drying climate by applying proportional reductions in rainfall across whole seasons are too crude and probably overestimate the impact of climate change on yield and farm productivity.

2.4 Salinisation

Australia as an ancient landscape has land exhibiting primary or naturally occurring salinity. Salinity refers to the discharge of dissolved salts to either the soil or water systems predominately affecting plant growth in an agricultural production sense. This natural salinity has been estimated at 29 million hectares (Haw *et al.*, 2000). However, excessive land clearing and the replacement of perennial vegetation with annual cash cropping within the Australian rural landscape have been increasingly recognised as the major cause of 'secondary' salinity (Hatton and Nulsen, 1999; Clarke *et al.*, 2002; Hatton *et al.*, 2003). Secondary salinity can be seen as a human induced hydrological process. The clearing of native vegetation has led to higher rates of water recharge increasing the level of saline ground water tables into plant root zones and consequently impacting on agricultural potential (George *et al.*, 1997; Haw *et al.*, 2000). The replacement of native vegetation has been extreme across Australia. In New South Wales, it has been estimated that the south west slopes and the central Lachlan region now have less than 4% and 1% woody vegetation cover (Williams, 2000) respectively. In Western Australia, 90% of the agricultural region (20Mha) has been replaced with annual production based vegetation (George *et al.*, 1999) and within the Murray-Darling Basin, it has been estimated that 12-20 billion trees were removed without replacement (Walker *et al.*, 1993).

2.4.1 Cost of salinity

There is abundant literature on the estimation of the cost of salinity to the Australian society (Williams, 2000; National Land and Water Resources Audit, 2001; Short and McConnell, 2001; Cullen *et al.*, 2003; Kington and Pannell, 2003). Of all the Australian states, the National Land and Water Resources Audit has predicted that Western Australia has by the far the greatest risk, with 80% of the current national total and 50% of the 2050 forecasted area that will be affected (National Land and Water Resources Audit, 2001). Within Western Australia, several studies have tried to estimate the costs and risks of salinity. In 1996, it was estimated that dryland salinity had affected 1.8 Mha and in terms of future hectares lost, predicted 3 times this magnitude (Ferdowsian, 1996). In 2001, this estimate was re-evaluated with the current area of production lost due to salinity estimated at 4.4 million hectares and the estimated area affected by 2050 calculated at 8.8 million hectares (National Land and Water Resources Audit, 2001). Two studies (Short and McConnell, 2001; McFarlane *et al.*, 2004) provided yet another estimate with 30% of agricultural land expected to be lost within the next 50-100 years.

In terms of monetary loss, several studies into the estimates of the cost of dryland salinity to farmers and the wider Western Australian community have been reviewed (Clarke *et al.*, 2002). The author highlights estimates varying from nearly $1 billion a year to as little as $60 million a year based on the direct, on-farm loss to farmers only. This study also highlighted the results of the most recent Western Australian State Salinity Strategy (State Salinity Strategy, 2000) that estimated the value of lost agricultural production in 2050 to be $300–400 million and the lost capital value of farmland at $3-4 billion.

Higher rates of water recharge are highly correlated with annual rainfall (Asseng *et al.*, 2001). With the reduction in rainfall caused by a changing climate, recent studies have suggested that the spread of dry land salinity and the rise groundwater levels could be less than initially predicted (McFarlane *et al.*, 2004; Ludwig *et al.*, 2009). George *et al.*, 2008 reports that since 2000 surveillance bores established by the WA Department of Agriculture and Food has shown falling ground water levels in the northern areas of the state in response to reduced rainfall. However, the authors suggest that trends driving the spatial assessment of salinisation cannot be reliably assessed by time series data alone.

Clearly no matter what the specific cost, the amount of agricultural land lost or the type of environmental degradation, there will be a great cost to society. It will not only have a long-term impact on agricultural production and rural incomes but salinity will also affect downstream water quality and the welfare and livelihoods of communities in a broader sense as well as ecosystem biodiversity, town infrastructure and terrestrial ecosystems (Hall *et al.*, 2004; Pannell, 2005; Ridley and Pannell, 2005; Lyons *et al.*, 2007; Seddon *et al.*, 2007).

2.5 Salinity management options

A strategy of manipulating current annual crops and pastures to increase water use will not provide the outcomes needed to address salinity issues (Clarke *et al.*, 2002). Benefits will have to come from changing the structural components of the agricultural landscape. This means the replacement of annuals by plants with deeper roots and higher water use over a much longer period than just a year. This requirement has been acknowledged in the Salinity Strategy for Western Australia (State Salinity Strategy, 2000), which states that 'reducing recharge will not be achieved by manipulating existing farming systems, but by developing new systems that include a considerable area of deep-rooted perennial species.

Research into management options (Stirzaker *et al.*, 1999; Ali *et al.*, 2004; Pannell and Ewing, 2006; Dear and Ewing, 2008; Roberts *et al.*, 2009; Robertson *et al.*, 2009) for combating dry land salinity on cropping land include:

- the improvement of agronomy to increase annual crop water use,
- the introduction of perennial pastures, grasses or shrubs into cropping rotations,
- the introduction of woody perennials,
- the reintroduction of trees,
- engineering solutions to manage excess surface or ground water.

Several authors consider whether the adoption of a revegetation strategy (a mixture of mainly deep rooted and perennial plants) could improve the management of dryland salinity and reduce groundwater tables in Western Australia. Several studies (Clarke *et al.*, 1998a; 1998b; George *et al.*, 1999; Clarke *et al.*, 2002) illustrate that specifically placed revegetation strategies lowers ground water tables locally but needs to be widespread for regional effects. Hatton *et al.*, 2003 suggest an alternative view, that restoring the landscape solely with revegetation, in terms of rates and balances is not feasible or even possible, with only certain aspects of the original balance being restored in specific landscape positions. The study does mention that at the local level, the re-introduction of perennials with summer activity has significant benefits in reducing run-off and groundwater recharge, however, it was less clear as to whether landscape position matters over the actual proportion of the catchment planted for recharge control (Hatton and Nulsen, 1999).

Several studies (Lefroy and Stirzaker, 1999; Lefroy *et al.*, 2005) took an economic approach to determining the feasibility of a revegetation strategy, suggesting that if profit was to be the primary driver of adoption, then it appeared that the available revegetation options will fall short of existing hydrological targets with the exception of areas within higher rainfall zones. Both studies concluded that revegetation options are only likely to be an effective solution to water management where options can compete directly on commercial terms with conventional agriculture. This comparison of profitability, particularly by the earlier study, has led to a major research focus into adoption of perennial based farming systems (Price and Hacker, 2009).

Various economic studies have assessed the viability of mixed cropping-perennial farming systems. With the reintroduction of perennial systems, hydrological modelling suggests that the most responsive local groundwater flow systems may take 10-20 years to re-equilibrate while intermediate systems are expected to take 50 years or longer (Barr and Wilkinson, 2005). This means that future benefits and costs within feasibility and profitability studies must be discounted so that valid comparisons are made of the economic impacts occurring at different times. Given the large time lag, discounting causes the significance of these off-site benefits in present day terms to be small relative to the direct and indirect costs of establishment (Pannell, 2001; Bathgate and Pannell, 2002). Therefore, in order to assess the potential for widespread adoption of perennials by land holders, it is essential to consider their economic costs and benefits other than those of salinity prevention (Frost *et al.*, 2001).

Economic analysis of revegetation trials (Kingwell *et al.*, 2003; Barr and Wilkinson, 2005) demonstrated only a few examples where the economic evidence favoured high levels of adoption. Besides the profit advantages there has still been very widespread but small scale adoption of some unprofitable conservation practices among many landholders, triggered in part by government programs (Pannell *et al.*, 2006). A recent Western Australia study also supports the claim of small scale adoption, with 4.6% (1,750 hectares) of two neighbouring catchments being replanted to woody perennial vegetation from the 1920's to 2006. However, most revegetation areas (77%) had been privately funded (Smith, 2008).

The economic costs and benefits of available salinity management can be based on two scales.

At the farm level, where the attractiveness of each management option is based on the overall economic incentive and profitability derived from the overall financial position of the farm business (Greiner, 1997; Mueller *et al.*, 1999; Pannell, 2001; Bathgate and Pannell, 2002; John *et al.*, 2005; Masters *et al.*, 2006). The introduction of perennial plants, such as lucerne and saltbush as feed sources for livestock, have proved profitable up to a certain level of planting beyond which the marginal return from planting a greater area to perennials becomes negative (Bathgate and Pannell, 2002; O'Connell *et al.*, 2006). This ceiling lies between 10-30 % of farm size depending on rainfall while the introduction of alley farming systems (for example the introduction of oil mallees) could increase this ceiling by 10-15% (Lefroy *et al.*, 2005). Targeting specific species to specific farm defined land management units has also been proposed Bathgate *et al.*, 2009. Whole farm economic modelling suggested that the targeted introduction could raise profit be 26%, with an additional 12% of farm land switched to plants with better water use efficiency.

At the regional level, where economic scenario based modelling integrates socio-economic data collected at the national or farm scale level to understand the influence and likely responses to different policy approaches (Greiner, 1998; Cacho *et al.*, 2001; Curtis *et al.*, 2003; Kington and Pannell, 2003; Hall *et al.*, 2004). One particular study (Hajkowicz and Young, 2002) showed through economic modelling that the feasibility of a revegetation strategy in the Lower Eyre Peninsula located within South Australia, had a significantly small benefit-cost ratio, 0.68. Hajkowicz and Young, 2002 and Hajkowicz and Young, 2005 cite Herbert, 1999 who also indicates similar low benefit:cost ratios. Of the nine salinity management strategies proposed, only two received ratios above one (1.64 and 1.37) while the remaining had ratios ranging from 0.15-0.45. Unfortunately, the types of strategies proposed by Herbert were never explained. Based on these low benefit-cost ratios, a revegetation strategy within this agricultural area was unlikely due to their economic feasibility. Hajkowicz and Young, 2002 did suggest that a targeted, as opposed to a broad scale, revegetation strategy could be achievable. Specifically, they suggest targeting land:

- that does not currently provide large financial returns
- in catchments with hydro-geologically or hydro-ecological significant areas
- in areas of high biodiversity value
- in areas which contain or impact on valuable human infrastructure.

Recent research compares economic performance of revegetation scenarios on grazing farm businesses (Crosthwaite *et al.*, 2008), mixed cropping systems (House *et al.*, 2008) as well as defining grazing economic opportunity cost (Dorrough *et al.*, 2008). Conclusions from these studies and in particular the study by Dorrough *et al.*, 2008 demonstrate that incentive schemes for land retirement would be cheaper in low productivity areas than those on higher productivity areas. These studies confirm the conclusions made by Hajkowicz and Young, 2002.

Therefore, if revegetation of the landscape is to be implemented, the questions raised are how much area should be revegetated and where and how should it be arranged?

2.5.1 How much area should be revegetated?

Authors have used various methods to understand the amount of revegetation needed to provide environmental benefits, such as a hydrological approach (George *et al.*, 1997; Clarke *et al.*, 1999; Hatton and Nulsen, 1999; Stirzaker *et al.*, 1999), a deep drainage geographical system approach, (Pracilio *et al.*, 2003), a numerical modelling approach (Dawes *et al.*, 2001) and a spatial modelling approach (Hodgson *et al.*, 2004). All approaches suggest that substantial portions of the landscape need to be returned to native vegetation for beneficial environmental outcomes. In fact, under the current understanding of the environmental problems, some catchments need to allocate up to 30% of the catchment to native vegetation to avoid serious ecological damage and the loss of ecosystem services (Williams, 2000). These studies mentioned above suggest that this estimate may be conservative and a greater amount may be needed. A study within the

Western Australian wheatbelt (Clarke *et al.*, 1999) examining a revegetation strategy for low rainfall areas showed that the water level could be lowered by 0.2 m/year by a 50% increase in canopy cover on 32% of the land, or by 100% canopy cover on 16% of the land. However, a different conclusions (George *et al.*, 1999) suggested that generally only extensive plantings, perhaps influencing as much as 70–80% of the catchment will lead to significant catchment scale reductions in water tables.

An important conclusion to this research area was that the proposed concept of changing the hydrological imbalance through the reassignment of land use to other vegetation will be difficult, indeed perhaps impossible. This is because of the irreversible changes that have already been inflicted to the system, without major geologic or climatic upheaval. Nevertheless, many researchers and the community see an ethical compulsion to bring to our agricultural landscape as much of the original hydrologic function as possible (Hatton and Nulsen, 1999).

2.5.2 Where and how should it be arranged?

Development of effective salinity management strategies requires groundwater and salinity management targets to be made at a regional level. However, these targets do not take into account where to adopt salinity management options on ground. Rather than a random placement of revegetation options, a targeted approach has also been proposed by hydrological and environmental studies in order to maximise environmental benefits.

Several hydrological studies (Hatton and Nulsen, 1999; Clarke *et al.*, 2002) have highlighted that a targeted placement of trees or similarly deep-rooted vegetation in landscape positions can not only access local rainfall but also shallow, fresh groundwater from upslope areas. Several studies (George *et al.*, 1999; Barrett-Lennard *et al.*, 2005) suggest a targeting of revegetation for salinity abatement in valley floors of low surface relief. In their review (Clarke *et al.*, 2002) on the positioning of revegetation, the authors highlighted two studies on reforestation. Several planting strategies were illustrated, but little benefit was given by the strategy of planting strip type structure concluding that there was insufficient area of trees planted and that there was a need for extensive plantations in order to control groundwater flows. In terms of the positioning of revegetation, trees must be planted in arrangements that minimise competition for water with crops, for it is common for crops to experience water deficits even in years when drainage occurs (Stirzaker *et al.*, 1999; Oliver *et al.*, 2005). In determining where to place revegetation, the hydrological aspects of the landscape must be taken into account. These determine the appropriate scale for which decisions can be made on the number and distribution of trees required to manage rising water tables. Therefore, at the regional scale, some knowledge of the hydrogeology of a catchment is necessary in order to resolve questions on how regional and local aquifers interface and where salt is stored in the landscape. When establishing the right position for revegetation there is a need for a focus on a catchment-scale perspective taking into account local catchment and field scale determinants in order to identify functional mimicry so that the actions can be shifted towards the minimisation of saline discharge (Hatton and Nulsen, 1999).

At the local catchment scale, a targeting approach to identify the optimal locations for plantations in mid slope or convergent zones where fresh water flows from upslope areas occurred may be relevant (Clarke *et al.*, 2002). Additional landscape features such as dykes, changes in slope or soil type may give revegetation strategies access to groundwater before it gets either too deep or too salty to be useful (Hatton and Nulsen, 1999). However, targeted planting of tree belts to manage perched water tables may be of limited value unless slope exceeds five degrees (Stirzaker *et al.*, 1999). Research also suggests (George *et al.*, 1999) that a targeted approach where trees are planted in areas of recharge, rather than discharge areas could be more beneficial for local catchment initiatives. The premise of targeting revegetation has been highlighted by other studies (Clarke *et al.*, 1999; Pracilio *et al.*, 2003; Verboom and Pate, 2003; Harper *et al.*, 2005). These studies have used airborne geophysical data or regional soil mapping to characterise hydraulic conductivities so as to identify the most drainage prone soil types. This acquisition and use of this spatial data has helped to understand and predict the effectiveness of revegetation treatments throughout individual catchments.

At a farm level, targeting specific land management units (Flugge and Abadi, 2006; Bathgate *et al.*, 2009) or the farm's landscape shape (Kingwell and John, 2007) have also been shown to affect the impacts and spread of dryland salinity. Other options at the farm scale for spatial structures of revegetation have also been proposed. Several studies have attempted to quantify the response of water tables with tree belts in alley way alignment

(Ellis *et al.*, 2005; Crosbie *et al.*, 2008; Noorduijn *et al.*, 2009). Here, deep rooted perennial vegetation is planted in alternation with traditional cropping.

Targeted revegetation strategies have also boded well within the ecology discipline for managing salinity, wind erosion and biodiversity. Numerous studies have mentioned the protection of biodiversity and enhanced ecological function with the reassignment of agricultural areas to perennial pastures, plants or trees (Cocks, 2003; Dorrough and Moxham, 2005; Vesk and Mac Nally, 2006; Dorrough *et al.*, 2007; Bryan and Crossman, 2008; Crosthwaite *et al.*, 2008; Thomson *et al.*, 2009). Advances in remote sensing and geographic information systems mean that high resolution spatial ecological datasets are available for spatial prioritisation and optimisation approaches (Vermaat *et al.*, 2005). Several studies have used spatial methods such as focal species, systematic regional planning and conservation planning tools to identify geographic priorities for large scale restoration planning (Freudenberger and Brooker, 2004; Crossman and Bryan, 2006; Westphal *et al.*, 2007; Crossman and Bryan, 2009; Thomson *et al.*, 2009). These methods account for multiple species objectives and connectivity requirements at a spatial extent relevant to ecosystem management. The major conclusions gleamed from these studies is that generally; priority areas are clustered around existing vegetation. However, areas in richer soils and with higher rainfall were more highly ranked, reflecting the potential to support high quality habitats (Thomson *et al.*, 2009).

2.6 Conclusion of targeted strategies

Review of the literature has shown that revegetation has the potential to lead to significant long term economic and environmental benefits, for example, ecological and salinity benefits as well as increases in capital value of the asset. However, for individual landholders these longer term benefits are likely to be small and provide limited incentive (Dorrough *et al.*, 2008) given the likely economic opportunity cost from loss of production income. Adoption is more likely to occur in areas where profit from traditional cropping practices is comparative (Frost *et al.*, 2001; Lefroy *et al.*, 2005; Abadi *et al.*, 2006). This may occur in areas where the whole agricultural practice can be identified as marginal (Dorrough and Moxham, 2005; Maraseni and Dargusch, 2008), or where farms have diminishing financial returns to farm area (Groeneveld, 2005) caused by either unproductive soil types (John et al., 2005; House et al., 2008) or land where production has been affected by environmental degradation (O'Connell et al., 2006). Of significance is a study by Lawes and Dodd, 2009a who use high resolution wheat yield estimates from precision agriculture technology to identify poor performing areas for revegetation. Their analysis found that poor performing patches were rare and occupied 11% to 23% of farmland across three farms. Assessment of the ecological value through spatial techniques (landscape metrics) found that the revegetation of the areas identified as poor performing provided little ecological benefit. However, no consideration was given to the short term financial opportunities that may exist from a revegetation strategy.

2.7 Short term opportunities for financial offsets of revegetation

The integration of perennial plants into Australian farming systems provide potential commercially viable opportunities from carbon sequestration, woody biomass crops and fodder crops which will be able to improve risk management and both short and long term economic sustainability and resilience of agricultural landscapes (Bennell *et al.*, 2007; Hobbs *et al.*, 2007; Hobbs, 2009).

Studies into the adoption of woody crops in Southern Australia (Bennell *et al.*, 2007; Hobbs *et al.*, 2007; Hobbs, 2009) suggest two existing and potential revegetation industries for low rainfall agricultural areas. The first encompasses forestry and woody crop systems for extractive use (e.g. sawlogs, pulp logs, oil mallees, bio-energy and fodder shrub systems). The second relates to permanent revegetation for environmental plantings or carbon crops (e.g. habitat plantings for biodiversity, natural resource protection plantings, and dedicated long term monocultures for carbon sequestration). A range of adaptable woody species and systems are suggested based on thorough species surveys which provide robust and reliable crop options in landscapes with variable soils and climates. These options are intended to produce large scale commodity products from highly productive species and agroforestry systems, and utilise large scale industrial approaches to harvest and handling of the products. Conclusions from these studies suggest that the highest priority industries appropriate to lower rainfall regions include: wood fibre industries; bioenergy (electricity generation); Eucalyptus oil; integrated wood processing (oil/charcoal/bioenergy); and fodder shrubs for livestock industries. They also identify a number of emerging industry types including: carbon sequestration; industrial carbon (carbonised wood and charcoal); liquid fuels from woody biomass; and other plant extractives. Furthermore, studies have shown that woody crops can be used as a renewable energy resource (Varela *et al.*, 2001; Fung *et al.*, 2002; Cannell, 2003; Raison, 2006; Bryan *et al.*, 2008; Perez-Verdin *et al.*, 2008; Abdullah and Wu, 2009; McHenry, 2009; Talbot and Ackerman, 2009).

Besides these opportunities and planting for salinity benefits, woody crops can sequester carbon in (1) the form of plant biomass both above ground and below ground, (2) within the soil organic carbon stock and (3) in wood products (Burrows *et al.*, 2002; Turner *et al.*, 2005; Roxburgh *et al.*, 2006; Paul *et al.*, 2008; Quinkenstein *et al.*, 2009). The amount of carbon sequestered is dependent on plant species and growth traits, the location and local weather conditions, the structure of planting such as the planting density and the plantation management such as fertiliser and rotation period (Quinkenstein *et al.*, 2009).

Spatial models of plantation productivity, existing and potential industry infrastructure and expected landholder economic returns have been used to identify regions and industries with the greatest potential for new agroforestry expansion or development (Hobbs *et al.*, 2007). Spatial estimates of expected productivity and potential carbon sequestration from revegetation are developed from either plantation productivity (allometric) observations within a region coupled with soil-climate models (Hobbs, 2009) and process based models that simulate growth process to estimate growth rates (Landsberg and Waring, 1997; Battaglia *et al.*, 2004).

Economic returns depend on the calculation of above ground carbon stocks measured as tonnage of carbon per hectare per year and the market price paid for carbon. While the potential carbon stock can be reliably measured, the major limitation for payment for carbon is that currently no global market exists. Current prices are available for only a few national or regional markets with each having constraints to access. In Europe, carbon market prices have ranged from 8-30 €/tCO_2-e (Carraro and Favero, 2009) with a mean carbon price of 20 €/tCO_2-e (Chevallier, 2009). In Australia, carbon prices in the New South Wales market ranged between in 3-8 AUS$/t$CO_2$ in 2008 (Carraro and Favero, 2009). Given this unknown and volatile price situation, several studies have looked at the financial returns of carbon sequestration through changing carbon price scenarios to identify potential areas of carbon sequestration (Flugge and Abadi, 2006; Harper *et al.*, 2007; Hunt, 2008). Regional analysis of potential industries for woody biomass crops (Hobbs, 2009) show average financial returns for carbon sequestration from bioenergy species at $370/ha/yr while carbon sequestration with oil mallee and habitat species were significantly lower ranging between $10-$12/ha/yr. Current estimates of potential income derived across the South Australian wheat-sheep zone are suggested to be around $264/ha/year with a standard deviation of $110ha/yr (pers. com. Trevor Hobbs, Department of Water Land Biodiversity, October 2009). This estimate was derived on unharvested woodlots of the most productive species (including Sugargum *Eucalyptus cladocalyx*, Redgum *E. camaldulensis*, Swamp Yate *E. occidentalis*, Tasmanian Bluegum *E. globulus*, Tuart *E. gomphocephala*, Mallee Box *E. porosa*). Analysis of areas in South Australia suggested that these returns vary spatially. The study by Polglase *et al.*, 2008 suggests similar returns for carbon plantings ($200 /ha/yr). Both studies suggest regional variations in financial returns and more targeted studies have been carried out to identify region specific income generation from carbon sequestration and spin-off industries (Bryan *et al.*, 2007; Bryan *et al.*, 2008).

2.8 The need for an environmentally sustainable agricultural sector

Growers, land managers and agricultural industries are increasingly realising that environmentally sound production offers benefits in terms of business liability and profit, while having a beneficial effects on the environment (Cullen *et al.*, 2003; Gunningham, 2007). The community, including rural landholders, has a high expectation that natural resources will be better managed. Consumer awareness has also increased with a sharper consumer focus on food safety and environmental performance in agricultural production (Selfa *et al.*, 2008). Industries themselves are progressively moving towards establishing codes of practice that promote quality assurance and delivery of safe food and fibre products to the marketplace for access to higher niche market prices (National Land and Water Resources Audit, 2001; Ridley, 2007; Higgins *et al.*, 2008). These situations highlight a need for a sustainable agricultural industry. From current government policies, industry visions and the literature, several drivers and determinants for growers to adopt NRM practices at farm scale can be highlighted.

2.8.1 Government and regional catchment management authorities

Moving into the new millennium, the Australian federal government, in agreement with its States and Territories, have identified investment strategies for NRM to facilitate the integrated delivery of NRM priority issues. The assessment for prioritising objectives was based on the National Land and Water Resource Audit that identified areas significantly affected by environmental degradation and the potential for cost effective preventative action (National Land and Water Resources Audit, 2003). A total of fifty six regions were created with each region creating its own targets and priorities in the form of a regional environmental action plan. This redistribution of power from state and federal policy makers to the regions was aimed at empowering the community by identifying local community issues. In order to develop targets Catchment Management Authorities (CMA) or other regional groups were to consult with all members of their community so as to develop a single vision for the region. The plans would identify the shaping forces and threats to the asset base as well as priorities, goals and opportunities for the region. With this as a basis, the CMA would also identify the regions investment strategies and framework as well as the monitoring, reporting and evaluation frameworks. The plans must be consistent with state and federal policies and strategies, and once accredited, are the basis for the distribution of regional investment from both the Natural Heritage Trust and the National Action Plan for Salinity and Water Quality.

In its regional NRM strategy for the Northern Agricultural region of Western Australia, the Northern Agricultural Catchments Council (Northern Agricultural Catchments Council, 2005) highlighted the broadness of the approach taken. NRM problems are complex and occur on various spatial and temporal scales. They are also likely to involve difficult trade-offs between alternative land uses and different community aspirations and values – at local, regional, state and national level.

2.8.2 The Australian grains industry

In 2004, the Grains Research and Development Corporation (GRDC) developed its single vision framework for the Australian grains industry (Grains Research and Development Corporation and Grains Council of Australia, 2004). The strategy highlighted key themes which emerged from grower interviews and the 2003 National Grains Industry Search conference. These consultations identified that the future focus of the grains industry should be on a commitment to the triple bottom line. That is, the need for economic, environmental and social sustainability. The GRDC envisions that this approach embraces good farming practice as well as good environmental stewardship as the key to regional and industry prosperity. One major outcome of this approach is sustaining the industry's image of clean and green production ("the Green Continent" global branding) to allow for product differentiation in the global market. The document highlights a pathway from 2005 to 2025 where current production systems will use water more efficiently and the farming systems will be redesigned in terms of restoration of land and natural vegetation capabilities. By 2020, GRDC expects that the industry will be seen to have a shared responsibility as a partner for natural resource management and regional community development.

2.8.3 Farming federation groups

The triple bottom line objectives above are further supported by the National Farmers Federation and their comparative state based affiliates. The South Australian Farmer Federation in 2004 reported that a triple bottom line approach was needed out of necessity to stabilise declining rural populations. In its report, the Federation addressed the emerging triple bottom line objectives that are essential ingredients in modern day thinking about life in Australia. Their initiative builds on the identification of increased opportunities for providing environmental and community services in rural areas that the whole South Australian community can value and reward (South Australian Farmers Federation, 2004).

2.8.4 Regional farming system groups

Ridley, 2005 identifies the progress of larger high profile farming system groups towards sustainable farming in Australia. The creation of these groups has been in response to regional issues and provides growers with an avenue to discuss local issues and act on options and opportunities which work locally in their region. Actions are firstly undertaken at the plot scale and if applicable are expanded to field or farm scale. Research from these groups focuses mainly on profitability and economic viability. Focus on environmental issues has been in response to the urgency and visibility of a problem or to a particular environmental 'champion' who raises awareness amongst the group (Ridley, 2005). A major obstacle for research into environmental issues by these farming groups has been the lack of funding from research and development agencies which growers' identify with (Ridley, 2005) rather than the group's appreciation for environmental outcomes. The establishment of these groups has led to a common vision, ownership of environmental problems and they should be now more ready to tackle environmentally sustainable issues in a more meaningful way (Ridley, 2005).

Wilkinson and Barr, 1993 identifies the effects of peer pressure within communities dealing with complex environmental problems. They suggest that voluntary solutions were more palatable than compulsory solutions. But compulsory solutions could work where the community engagement and leadership was strong, and the problem was seen as urgent leading to local community pressure.

2.8.5 Actions by the grower

With this increased focus on NRM to improve environmental outcomes the problem exists that the objectives of the grower are not those of the greater community. Adoption of NRM in Australia therefore has been limited. In order to understand the adoption of NRM at the grower scale, research has focused on the economic, sociological and psychological attributes of landholders. Table 1 summaries the research into the determinants and factors that effect uptake of NRM and the adoption of specific NRM practices by the grower (Cary *et al.*, 2002; Herr *et al.*, 2003; Nelson, 2004; 2004; Ridley, 2005). These determinants can be classed into four main areas (1) economic, (2) individual grower and social characteristics, (3) institutional issues and (4) adoption of a particular NRM practice. The literature suggests that understanding these factors and capacity for individual landholder to make NRM decisions will ensure more realistic and more effective catchment and regional plans. Unfortunately, studies using survey research into these grower attributes provided very few statistically significant explanatory variables (Cary *et al.*, 2002; Herr *et al.*, 2003; Nelson, 2004). The majority of farmers adopting sustainable farming practices were members of Landcare or production groups. Economic factors including farm size, off farm income and level of farm equity also influenced the likelihood of adoption of NRM practices (Nelson, 2004).

Table 1 Determinants of NRM Adoption in Australia taken from Cary et al., 2002; Herr et al., 2003; Nelson, 2004; 2004; Ridley, 2005.

Economic	Level of farm income, business characteristics, farm size, equity, income needs, property management planning, off farm income, labour available, type and access to consultant
Individual grower and social characteristics	Values, goals, culture, peer group, cultural expectations of farming, motivation , adaptation, attitudes to NRM and NRM organisations, altruism, risk perception, education, skills, age, family, succession, participation in groups, demographics and socio-political structure in the community or catchment where the grower lives, ability to uptake specialist, strategic or organisational knowledge, local knowledge within catchment
Institution	Regulatory environment, government agency support structures, incentive schemes and taxation arrangements, adoption of Environmental Management Systems
Adoption of a particular NRM practice	Cost, relative advantage, complexity, risk characteristics, compatibility, trialability, observability, local information and effectiveness, neighbourhood uptake

Of greatest significance were two studies (Cary *et al.*, 2002; Herr *et al.*, 2003) which found a negative link between equity (the degree to which a farm is debt-free) and adoption. Two plausible solutions have been offered for this negative correlation. The first study (Cary *et al.*, 2002) suggested that managers with high equity ratios could be more risk adverse and thus less inclined to adopt what they might see as risky resource management technologies. The second study (Herr *et al.*, 2003) offers an alternative insight with the quantification of the equity measurement. Equity can be seen as an absolute term and therefore growers with low value properties could have a low value of equity while growers with a high value property may have less equity. These results and views are contrary to the suggested theories that higher equity indicates better financial capacity to undertake NRM changes and therefore provide higher adoption rates.

Figure 2 provides further abstraction of Table 1 and was adapted from a study into the decision making process in sustainable development (Gallopín, 2002). The study highlighted three major obstacles and their interactions (Table 2), willingness (W), understanding (U) and capacity (C). The author suggests that a lack of political willingness, a deficiency in the understanding of the behavioural and complexities of environmental problems and the insufficient adaptive capacity (both financial and social) to act on the changes needed limit sustainable development. Figure 2 also shows the interaction between physical feasibility and the decision process by including the variable physical possible (P). By definition the capacity to do what is physically impossible cannot exist. Understanding and willingness allows for the acceptance of what is and is not physically possible. The decision domain highlighted in this study (Gallopín, 2002) can help understand the situation of NRM adoption by landholders in Australia. Both economic and social capacities have been found to increase the likelihood of adoption, although two studies (Cary *et al.*, 2002; Herr *et al.*, 2003) indicated that adoption of NRM may not be purely based on the financial situation of the farm business. In terms of understanding, the concept and introduction of the Landcare organisation has provided 10 years of information exchange into the understanding and identification of NRM degradation and strategies. A survey of broad acre and dairy farmers (Nelson, 2004) reported that more than half of growers surveyed reported signs of degradation while 23% reported a significant degradation problem. It was further reported that only 7% of farmers faced with significant degradation felt that they were unable to effectively manage the problem, mostly because effective management options were either unavailable or beyond their resources.

NOTE:
This figure is included on page 41
of the print copy of the thesis held in
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Figure 2 Intersections between physically feasible and decision processes (Gallopín, 2002) where W = Willingness, U = Understanding, C =Capacity and P = Physically Possible.

This increase in understanding of the environmental degradation and strategies for amelioration indicates that very few farmers need further skills or information to help them address degradation issues (Nelson, 2004). In terms of willingness, focus has been on incentives rather than regulatory policy to influence NRM by institutional organisations. Incentive such as tax write offs, auctions, bush tenders have been developed in order for growers to change farm management practices. Willingness to adopt has been limited due to uncertainty of the longer term benefits of NRM alternatives. The focus for government NRM programs in the future is to create new technologies for addressing recognised degradation issues and enhancing economic incentives for their adoption.

Table 2 identifies the interactions between all three areas of NRM adoption. The drivers that have been highlighted will specifically target willingness and understanding and the conceptual intersection between the two. What limits appropriate adoption of NRM is that capacity is based on each individual grower's position. If growers believe that they have the capacity, are willing and have the understanding of how to adopt NRM, adoption may still not be beneficial to the grower. The decision for adoption still will be based in an environment of uncertainty and ignorance of the resulting consequences. What is needed is information on the physical and production characteristics at the sub-field, field and farm scale, as well as how these scales interact at the greater landscape scale. Information at these scales will provide an understanding of the farms ability to provide environmental benefits as well as the financial implications to the grower. Unfortunately, local information, impacts and knowledge needed for tackling land and water degradation is often deficient (Cary *et al.*, 2002). The capacity to make decisions at this scale is further pointed out by catchment groups when dealing with the issue of salinity. Gaining advice at a field scale is essential for landholders to make informed management decisions. At this point in time there is clear market failure in providing this "on farm" advice (Northern Agricultural Catchments Council, 2005).

Table 2 Actions taken from NRM adoption (Gallopín, 2002)

NOTE:
This table is included on page 42
of the print copy of the thesis held in
the University of Adelaide Library.

Research into the area of NRM adoption has been limited in terms of farms physical capacity for adoption. Focus should be firstly on the actual farms capacity to adopt NRM rather than growers' capacity. The emphasis on the latter, may explain the lack of significant uptake of NRM by growers in terms of their already good understanding of environmental problems and strategies. Understanding the degree to which the farm can uptake NRM options based on the trade-offs between production and the actual environmental benefit will influence the growers' willingness to adopt. Being able to quantify the costs and benefits of the proposed situation will help reduce grower uncertainty to the short term consequences of the longer term change. This in term will help the grower understand its effect on the future capacity of the farm business.

2.9 The application of precision agriculture to natural resource management

Precision agriculture (PA) can be defined as a set of crop management methods which recognise and manage within field spatial and temporal variations in the soil-plant-atmosphere system (Cook and Bramley, 1998). The PA concept can be viewed as an application of information technology in agriculture (Lowenberg-DeBoer and Boehlje, 1996) and aims to improve the management of agricultural production by matching resource application and agronomic practices with soils and crop requirements as they vary in space and time (Whelan and McBratney, 2000). This represents a movement in management practice from uniform input applications to either the use of variable rate technology or zone management strategies to provide more profitable cropping outcomes (Cook and Bramley, 1998; Bullock and Bullock, 2000; Whelan and McBratney, 2000).

A range of technologies, such as yield mapping or proximal and remote sensing, are used to identify and explain the spatial variation of yield across a field or farm. Yield mapping technology, in particular, has become more prevalent in Australian dry-land agriculture and the process requires the combine harvester to be fitted with a global positioning system and a grain flow measuring device. The fitting of these devices enables infield measurements to be collected so that grain yield and the current harvester position can be calculated continuously while the combine moves through the field. The accuracy of this technology has been reported to be range from 95% to 99.5% (Murphy *et al.*, 1995; Birrell *et al.*, 1996; Missotten *et al.*, 1996; Reitz and Kutzbach, 1996; Jasa, 2000; Arslan and Colvin, 2002a). After harvest, the grower can map this data in two dimensions to identify the magnitude of spatial variability in grain yield within the field. This collection and visualisation process is illustrated in Figure 3.

Figure 3 The yield mapping process: As the combine harvester harvests (a) data is collected to determine yield and the position of the harvester by the yield monitor (b). This process enables the two dimensional mapping of yield to identify its spatial variation within a field.

Yield maps have been used for numerous agronomic and economic applications. Yield maps have been used to assess the spatial and temporal persistence of crop production (Stafford *et al.*, 1996; Lark and Stafford, 1997; Blackmore, 2000; Blackmore *et al.*, 2003; Joernsgaard and Halmoe, 2003; Sadler *et al.*, 2005; Lawes *et al.*, 2009b). This recognition of spatial and temporal variability has seen yield maps being used to inform precise crop management based on yield differences (Ping and Dobermann, 2003; Brock *et al.*, 2005; Cox and Gerard, 2007; Xiang *et al.*, 2007) or as ancillary data with other proximal or remotely sensed soil, plant or topographic variables (Adams *et al.*, 2000; Wong *et al.*, 2001; Anderson-Cook *et al.*, 2002; Flowers *et al.*, 2005; King *et al.*, 2005; Li *et al.*, 2007; Taylor *et al.*, 2007; Armstrong *et al.*, 2009). Yield maps have been used to test the apparent economic benefits that can be expected when changing from uniform to zone or variable fertilizer applications (Bullock and Bullock, 2000; Koch *et al.*, 2004; Bongiovanni *et al.*, 2007; Brennan *et al.*, 2007; Khosla *et al.*, 2008; Robertson *et al.*, 2008; Robertson *et al.*, 2009) as well as the profitability of individual fields (Massey *et al.*, 2008). Predictive relationships between yield maps have also been developed with variables such as protein (Skerritt *et al.*, 2002; Norng *et al.*, 2005), soil water holding capacity (Timlin *et al.*, 2001) and remotely sensed biomass indexes (Yang and Everitt, 2002; Chang *et al.*, 2003; Dobermann and Ping, 2004; Fisher *et al.*, 2009). Furthermore, yield maps have been used to assess the accuracy and validation of their predictive power of crop models to interpret and manage crop yield variability (Basso *et al.*, 2001; Batchelor *et al.*, 2002 Wong and Asseng, 2006; Basso *et al.*, 2007; Anwar *et al.*, 2009; Basso *et al.*, 2009).

Several studies which have utilised yield mapping have shown that yield and gross margins vary considerably across individual fields and growing seasons (Blackmore, 2000; Cook and Bramley, 2000; Blackmore *et al.*, 2003). Studies into grain yield over time in Western Australia routinely show yields of between 0.5 tonnes per hectare and greater than 4 tonnes per hectare within a single field (Cook and Bramley, 2000; Wong and Lyle, 2003; Wong and Asseng, 2006; Robertson *et al.*, 2008). However, some studies suggest that the magnitude of temporal variation is large compared with the spatial variation meaning that temporal variability will greatly influence how spatial variability is expressed in a given field (Eghball and Varvel, 1997; Florin *et al.*, 2009).

Studies into the temporal stability of yield within a field have showed mixed results. International studies have shown temporal instability can occur and is dependent on the type of management, diversity of field topography, crop type and more specifically in low or high rainfall years (Lamb *et al.*, 1997; Blackmore *et al.*, 2003; Joernsgaard and Halmoe, 2003; Kravchenko *et al.*, 2003; Kaspar *et al.*, 2004; Schepers *et al.*, 2004). Analysis of the temporal stability of cropping financial returns also suggested a reversing of the spatial pattern over time (Liu *et al.*, 2006; Massey *et al.*, 2008). However, several studies (Dobermann *et al.*, 2003; Jaynes *et al.*, 2003; Perez-Quezada *et al.*, 2003; Ping and Dobermann, 2003; Jaynes *et al.*, 2005; Sadler *et al.*, 2005; Bakhsh *et al.*, 2007; Cox and Gerard, 2007; Casa and Castrignano, 2008) have used cluster, discriminate or geostatistical analysis to successfully highlight spatially and temporally stable yield trends. Perez-Quezada *et al.*, 2003 suggests that yield from one crop was a poor predictor of another crop grown in another year but after yield standardisation, areas with the same average performance tended to be clustered. Recently, a Bayesian analysis of corn yield (Jiang *et al.*, 2009) demonstrated similar results of temporally consistent spatial yield patterns when soil water was limited.

A major constraint of these studies is the amount of yield data, either in the form of yield maps or experimental plots, that are available to gain a thorough understanding of spatial and temporal interaction. A small number of crop simulation studies (Basso *et al.*, 2007; Basso *et al.*, 2009) which utilise yield maps to develop yield zones and historical meteorological datasets to understand soil-climate interactions based crop outcomes have shown spatial and temporally consistency relating to primarily to soil water content.

In Australia, a mix of spatial and simulation modelling analysis has been conducted to assess the spatial pattern of yield over time. For dry-land agriculture in Western Australia, a field based study showed areas of low yield that consistently lost money independent of seasonal variation (Wong and Lyle, 2003) and fertiliser management (Wong and Asseng, 2006). The 2006 study determined the potential yield and possible yield zoning of the field by using soil electrical conductivity measured by proximal sensing and crop yield simulation modelling. The degree of plant available soil water storage capacity (PAWc) was suggested to be the major cause of variation in the sandy soil types. This meant that that soil types with low PAWc yielded poorly. This method of yield zoning was seen to be more beneficial to creating yield zones than current zoning techniques based on a limited number of yield maps and therefore seasons. Florin *et al.*, 2009 in a geostatistical based study on two fields over four years in southern Australia, suggested some spatial and temporal structure was evident but suggested these conclusions were limited because they were based on only a few years of yield data. This lack of data issue is similar to the above study and others (Lamb *et al.*, 1997; Joernsgaard and Halmoe, 2003) with long term monitoring greater than six years needed (Jaynes and Colvin, 1997).

Another Western Australian based study (Lawes *et al.*, 2009b) using a statistical approach to identify the temporal stability of yield showed stability in certain soil types. However, these results were consistent only when the field yielded less than 1 t/ha or greater than 3.5 t/ha. Here, changes in the stability of yield over different growing seasons only occurred in one soil type. Further analysis of the study area was carried out using crop yield simulation modelling by the same authors (Lawes *et al.*, 2009). Yield simulations derived on 106 years of historical rainfall and PAWc measurements taken across two fields showed that in seasons with different temporal rainfall episodes, temporal yield variability on soils with different PAWc held relatively constant (62%). Around 20% of the modelled seasons were low yielding (growing season rainfall = 119mm) and in these situations, soil types with high PAWc (>60-80 mm) produced lower yields than those with lower PAWc (< 60mm).

Rab *et al.*, 2009 in their study on one field in the south-eastern region of Australia (Victoria Mallee and Wimmera) found similar relationships to Lawes *et al.*, 2009 but contrary to Wong and Asseng, 2006. In this study where yield zones were defined from four years of yield maps and remote sensing data and a different measurement of PAWc, the authors demonstrated that zones with the largest values of PAWc were found on areas that generally corresponded to the low yield. A complementary study by Anwar *et al.*, 2009, on the same field showed some contradicting results. This study by Anwar *et al.*, 2009 which used crop yield simulation modelling over 119 years of historical rainfall showed that the delineated yield zones for two (low rainfall years) seasons from which the zoning were based were correct . However, long term simulation modelling showed low yielding zones had the greatest median yield. This occurred in 80-90% of the years modelled. Anwar *et al.*, 2009 suggested that these differences were because the yield zones were delineated from data that exhibited a limited range of seasons. Armstrong *et al.*, 2009 explains that within this region, soil types regarded as fertile with high yield potential in normal seasons, such as Vertosols, have consistently performed poorer compared to the sandier soil types in low rainfall years.

Within this short summary of the use of precision agriculture technology I have shown that within dryland cropping areas of Australia, significant spatial variability in yield exists within a field. Lesser evidence of this spatial variability holding over time is apparent but this may be due to the study design such as the number of yield maps used and the mixing of crop types rather than its actual spatial existence. However, if spatial and temporal consistency is apparent then the use of yield mapping will play an important part in helping the grower quantify the specific monetary loss to the farming enterprise if land uses are changed. Currently for growers, any on ground decision making is usually done within a whole farm planning process (Landcare, 2009). This process allows the grower to plan and design management strategies based on ecological and economic factors. For on-ground decision making, the creation of a farm map based on aerial photography (Figure 4 is a hypothetical example) is proposed as one way to guide farm works and form a co-ordinated approach to maintain a sustainable and profitable farm business.

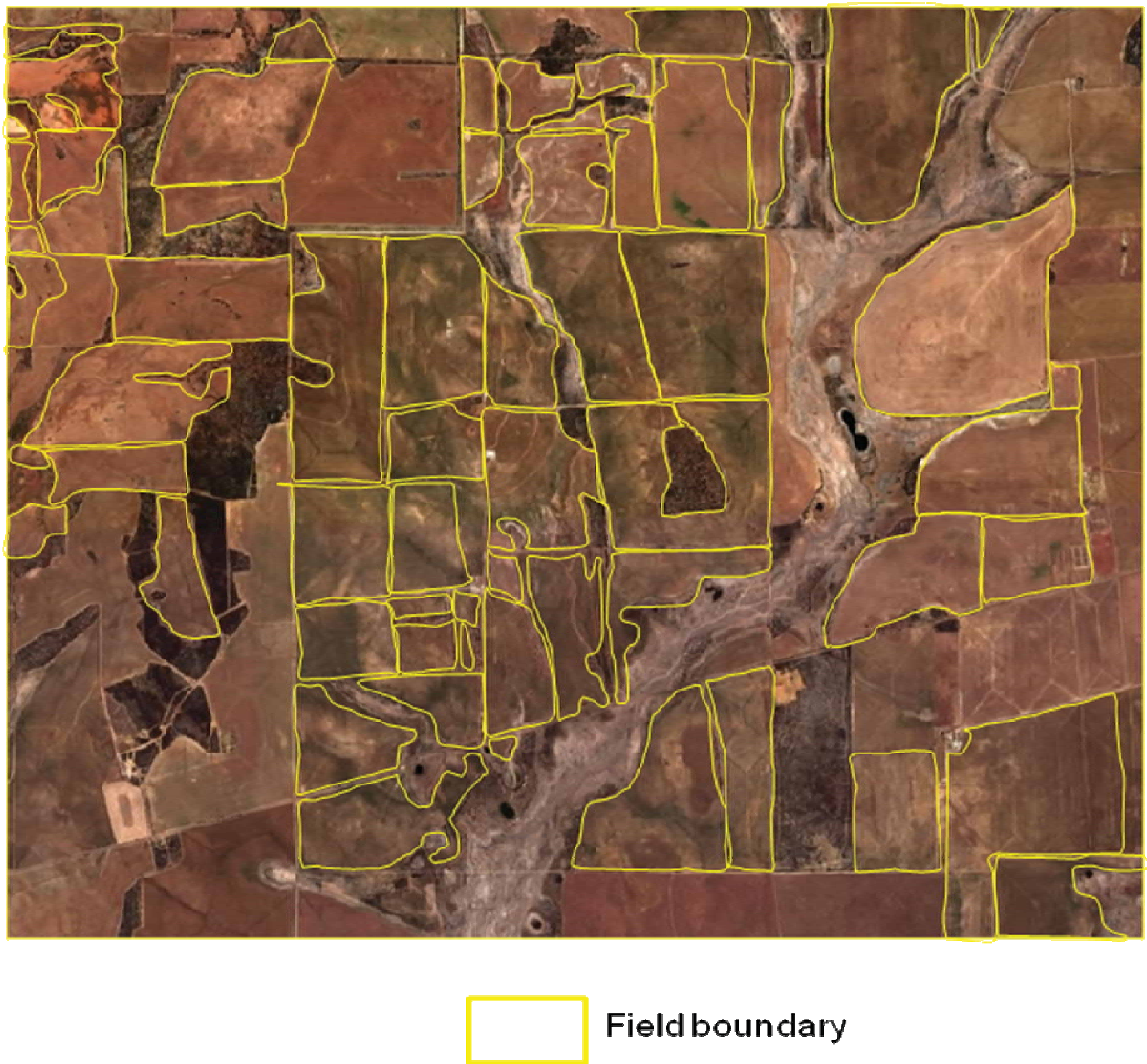

Figure 4 Example of an aerial photograph of a hypothetical farm which is used to identify a farm map (field boundaries in yellow) proposed for a whole farm planning analysis.

This information can then be coupled with business and production information, usually estimated average field yields however, most plans are based on minimal datasets. With access to only minimal datasets, decision making is severely limited and is based at the field scale. Recently, studies into a variety of medium to high resolution geospatial information has been investigated to provide targeted information on soil or environmental properties within a landscape to inform land management decisions (George and Woodgate, 2002; Abbott *et al.*, 2007). The broad spatial extents allows for the identification of trends throughout a region while the high resolution allows growers greater insight into making in field decisions. For example, radiometric datasets enable the identification of soil impediments and landforms that influence woody crop growth (Dorrough and Moxham, 2005; Pracilio *et al.*, 2006) while others have used it for soil characterisation (Cook *et al.*, 1996; Pracilio *et al.*, 2003; Pracilio *et al.*, 2006; Wong and Asseng, 2006; Wong *et al.*, 2009). These datasets are then used in decision analysis to assess the spatial extent of dryland salinity through the use of fuzzy modelling (Malins and Metternicht, 2006), catchment condition from multi criteria decision analysis (Hill *et al.*, 2005) or systematic regional planning (Bryan *et al.*, 2005). Therefore, a gap still exists between the spatial resolution at which this environmental data is collected and that of currently collected economic data. Here, yield mapping can inform the grower of the expected profit that the grower will have to forgo (economic opportunity cost) in transferring these areas out of cropping to other land use alternatives. Providing financial estimates at the sub-field scale for the whole farm provides the grower with information at a scale from which a compromised trade off between economic environmental objectives can be achieved. One study (Lyle and Wong, 2003) attempted to understand these compromises using a spatial modelling approach in Western Australia. At the farm scale, the reassignment of land based on a compromise between two differing but individually important outcomes showed the loss to grower in terms of profits foregone in order to gain environmental benefits in the longer term. Although this study was an introductory insight into the way PA technology could help NRM decision-making, it still shows a possible approach through quantification of both yield and identification of areas where there were imminent environmental problems.

The use of PA technology especially yield mapping can help understand the degree and capacity to which the farm can change on ground and identify the risks of impact on the farm business from adoption of NRM practices (Figure 5).

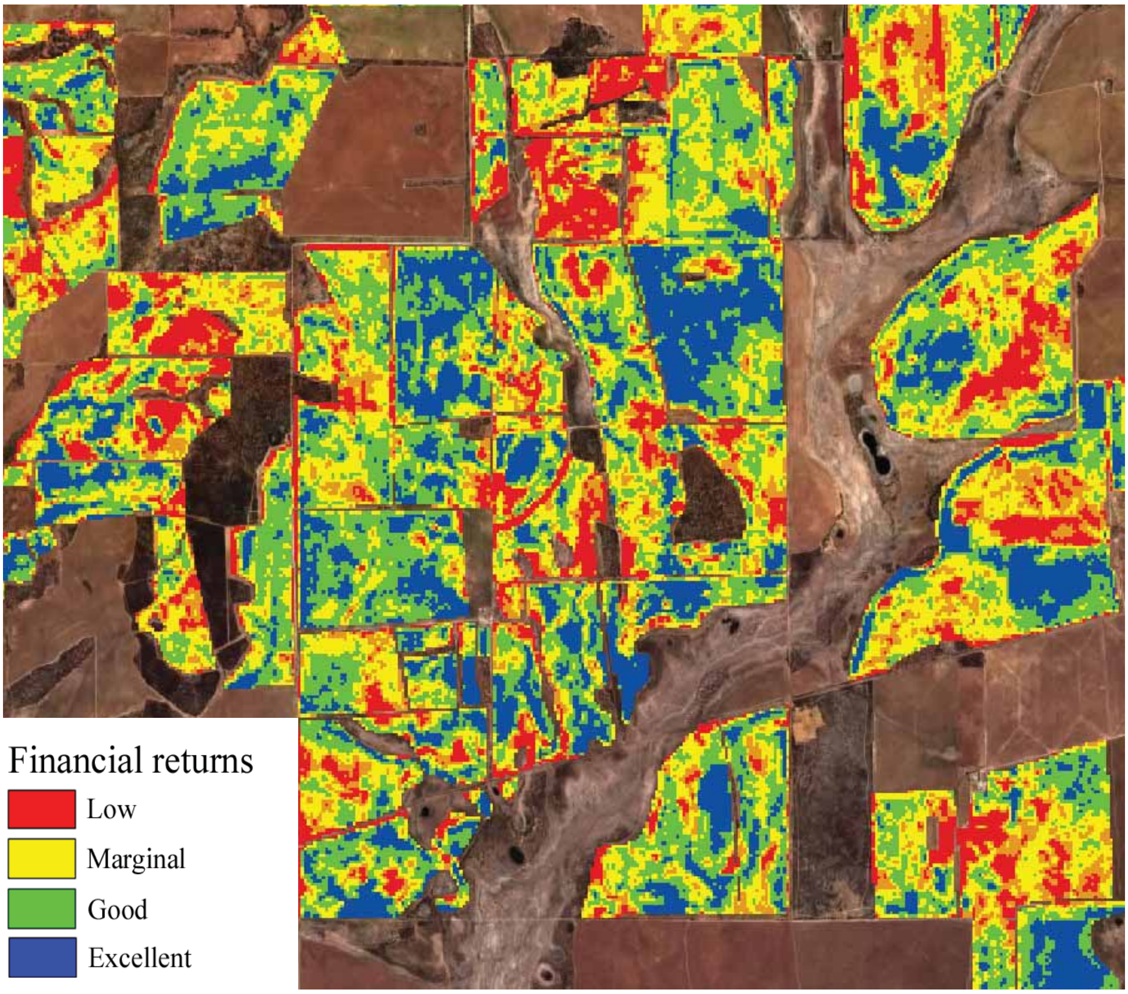

Figure 5 Example of yield mapping highlighting the spatial variability of yield across a hypothetical farm. Red and yellow areas highlight where areas of reassignment to an alternative land use may occur depending on the alternative's potential income generation. Green and blue areas highlight where cropping may be more profitable.

This figure shows the grain yield variability for wheat for a hypothetical farm in Western Australia. Most fields have a mixture of financial returns categories with a clustering of areas with like values. Only a few fields as a whole consistently lose money. Areas that have been highlighted from the yield mapping as "Low" and "Marginal" financial returns categories (red and yellow areas) could be possibly reassigned to an alternative land use depending on the alternative's potential income generation in those areas. Areas categorised as "Good" and "Excellent" financial returns (green and blue areas) highlight where cropping may be more profitable. The clustering of high and low values means that traditional broad scale agricultural cropping can still be undertaken fairly easily, in terms of the placement of alternatives land uses and management of traditional cropping enterprises within specific fields. If these areas are seen as temporally consistent then more inform decisions can be made than with current datasets used for on farm decision making (Figure 4). The high spatial resolution at which yield mapping is collected can therefore quantify the infield monetary repercussions that will be sustained due to any potential land use change.

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Chapter 3: Comparison of post processing methods to eliminate erroneous yield measurements in grain yield mapping data: A review

***Keywords**: yield mapping, errors, post processing methods, software.*

3.1 Abstract

Yield mapping is becoming a more prevalent tool in agricultural management. The measurement accuracy has been reported to range from 95% to 99.5% based on certain types of harvest situations. Straying from these conditions will produce erroneous yield measurements. Numerous studies have highlighted the existence of these errors, their sources and have proposed post processing methods to remove these outliers. A thorough cataloging of the types of errors that are possible is needed for new users. This highlights the types of errors inherit in yield mapping, identify the methods used to remove them and emphasize the benefits of applying them.

We were able to characterise four types of yield mapping errors associated with yield monitoring from the literature. These reflected issues associated with combine harvester dynamics, the continuous measurement of grain yield and moisture, the position of the harvester, and the harvester operator. Methods to remove these errors have ranged from simple thresholds to complex routines that incorporate harvest position and local yield variation. Benefits of applying these filters have shown reductions in the statistics of yield variation and the prediction variance estimated from interpolation techniques. Using Western Australian examples, we highlight the statistical characteristics of raw yield files and propose extensions to current methods to remove errors associated with harvester speed, narrow finishes and harvester turns and overlaps. Also proposed is an extension to the current structure of routine implementation so that development of an automated post processing error removal system can be achieved.

3.2 Introduction

Grain yield mapping through the process of geo-referencing measurements taken from a combine-mounted grain yield monitor have become more prevalent in agriculture. The accuracy of continuous yield monitoring has been reported to be range from 95% to 99.5% (Murphy *et al.*, 1995; Birrell *et al.*, 1996; Missotten *et al.*, 1996; Reitz and Kutzbach, 1996; Jasa, 2000; Arslan and Colvin, 2002a) depending on the type and brand of yield monitor, calibration regime, flow rate and environmental conditions at harvest.

The two dimensional mapping of grain yield provides an insight into infield spatial variability. The acquisition of yield maps over a variety of seasons provides a means to temporally quantify yield variation and reduce uncertainty in estimating yield potential over climatically different growing seasons. From this information, confident crop management and input decisions can be made in a more site specific manner. It is therefore essential that growers have a high confidence in the accuracy of yield maps that are generated from data acquired during the yield monitoring process (Shearer *et al.*, 2005).

Achieving consistent and accurate grain yield measurements is a challenging process especially over the large dynamic range of flow rates that stem from spatial yield variability (Arslan and Colvin, 2002b). While the process of yield mapping can highlight naturally occurring yield variation within the landscape, the variation in the data also mask management induced yield variation as well as measurement errors caused by the yield monitoring process itself (Simbahan *et al.*, 2004a). The identification of management induced variability can be easily recognised through visual analysis and grower interaction. Error induced variability is much harder to identify and in certain circumstances cannot be distinguished visually. Many authors have highlighted the causes of this variability and provided methods to identify and either correct or remove erroneous data. However, much of the literature focuses on only a few of the possible sources of error (Simbahan *et al.*, 2004a). For a movement toward a common set of procedures to identify and remove yield mapping errors, a greater understanding of the error types inherent in yield data is needed. The objectives of this paper are therefore to review the published literature to highlight (i) a comprehensive list of the errors that are inherit in yield mapping, (ii) what methods have been used to reduce these errors, (iii) the affects of applying such methods.

3.3 Statistical characteristics of raw grain yield files

Histograms derived from yield mapped datasets are expected to be of a normal or Gaussian distribution. However, many datasets exhibit long low yielding tails that can often be attributed to combining errors (Blackmore, 2003). A way to check for normality is the calculation of the skewness and kurtosis statistics. Here, values less than or greater than zero indicate the departure from a normal distribution.

A total of 752 datsets were available over a ten year period for 183 fields. A single field year was randomly selected for each of the 183 locations covering differing crop types. To understand the extent of non-normality in raw yield datasets, the skewness and kurtosis statistics were calculated. For visualisation purposes, a subset of files with less extreme statistics with kurtosis plotted against skewness (Figure 6a) shows only 11% of files with normal distributions (Figure 6b).

Overall, the calculation of skewness showed a 56:44 split of positively and negatively skewed datasets indicating that files either had larger amounts of yield data distributed at either the lower or higher ends of the grain yield spectrum. Around 30% of positively skewed files had extreme kurtosis values (> 10) indicating a single peaked distribution and low yield variability at the low yield values. Conversely, files that had negative skewness also showed lower kurtosis values indicating larger frequencies of measurements at the higher end of the yield spectrum and greater yield variability. Examples of extreme distributions were also evident with extreme positive skewness and kurtosis (skewness = 67 and kurtosis= 7607) (Figure 6c), negative skewness and large positive kurtosis (skewness = -2.77 and kurtosis 12) (Figure 6d) and negative kurtosis illustrating a flat almost convex distribution (skewness = 0.4 and kurtosis = -1.1) (Figure 6e).

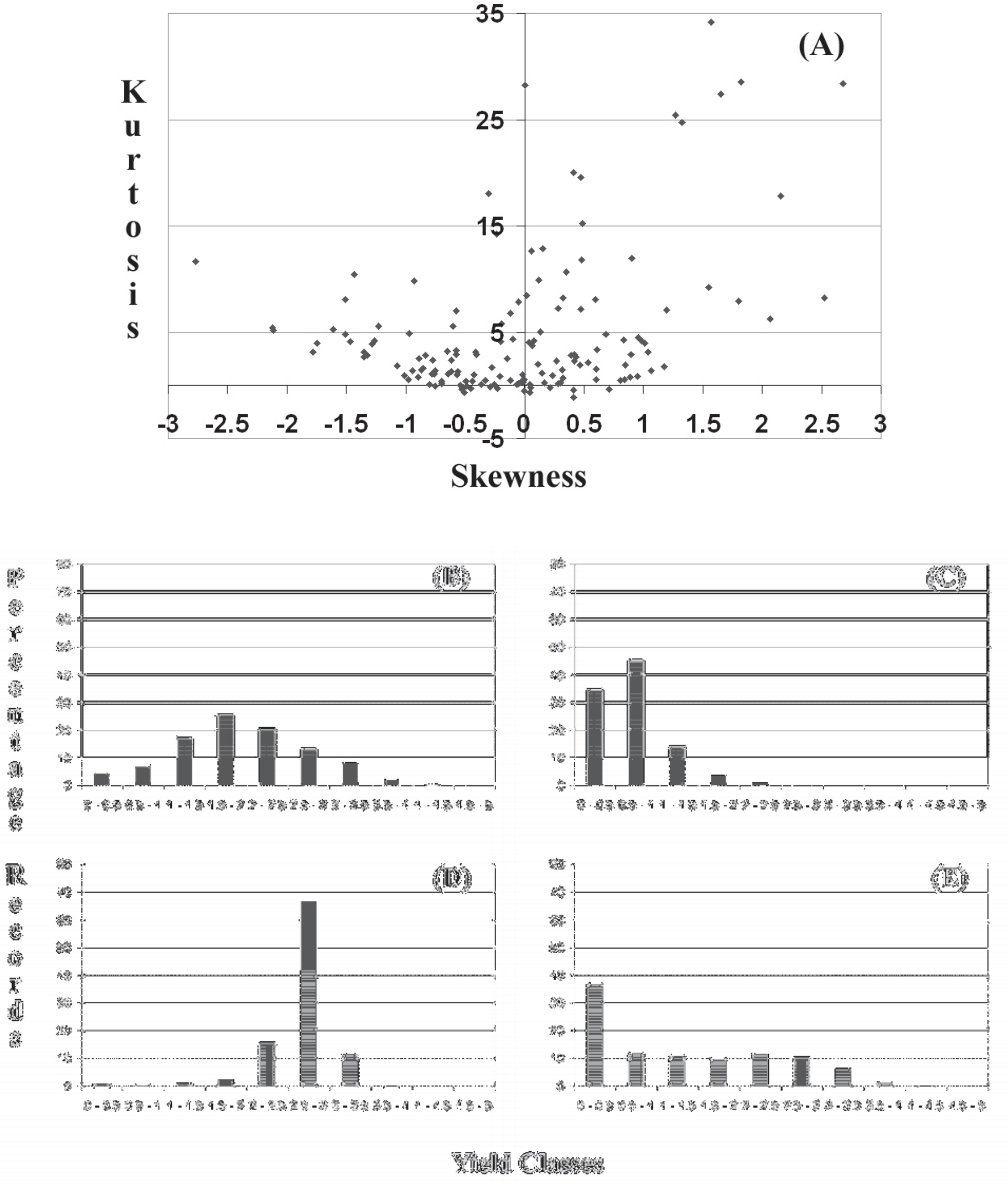

Figure 6 Kurtosis versus skewness values for raw yield mapped data (a) and the distributions created by yield mapping - a normal distribution (b), extreme positively skewed and peaked distribution (c), negatively skewed and peaked distribution (d), distribution with negative kurtosis (e)

Basing any infield management decisions on this raw yield data will be hazardous. The current information suggests that some fields have low yield variability and that uniform input management will suffice. While in others, yield variability is so large that it would be difficult to manage in a site specific manner. Although there may be cases where these distributions may not be normal caused by biophysical or soil property and rainfall interactions, it is more than likely that these distributions are the artifact of the collection of erroneous yield measurements. The use of post processing routines therefore provides one way to remove likely erroneous data to reflect this natural yield variation.

3.4 Post processing

Extensive research into the quality of yield monitored data has led to a general agreement on the contributing sources of error (Shearer *et al.*, 2005). Due to the magnitude of data recorded by yield monitor, the consensus within the research field suggests that errors should be removed rather than corrected.

Post processing methods have ranged from expert filters (Rands, 1995; Thylen *et al.*, 2000; Kleinjan *et al.*, 2002) to programmed spreadsheet macros (Reese *et al.*, 2002). Standalone programs have also been developed which have included the TAES filter (Beck *et al.*, 1999), TYME filter (Beck *et al.*, 2001), Yield Check (Simbahan and Dobermann, 2004b) and Yield Editor (Drummond, 2005b; Sudduth and Drummond, 2007). These yield cleaning tools have been trialed with varying degrees of success and their focus to remove certain types of errors can be classified into four areas.

3.5 The harvesting dynamics of the combine harvester

Previous research into the propagation of yield mapping error has dealt with the harvesting dynamics of commercial combine harvesters (Blackmore and Marshall, 1996; Nolan *et al.*, 1996; Thylen and Murphy, 1996; Whelan and McBratney, 1997; Moore, 1998; Blackmore and Moore, 1999; Arslan and Colvin, 2002a; Arslan and Colvin, 2002b). Here, three different types of time delays have been highlighted in the continuous measurement of yield.

3.6 Harvest lag time error

Several studies (Rands, 1995; Blackmore and Marshall, 1996; Moore, 1998; Blackmore and Moore, 1999; Arslan and Colvin, 2002b) highlight a travel time delay between the crop being cut and then measured at the yield monitor. These studies propose that a time offset be used so that yield flow and the actual GPS position measured at the monitor represent the actual harvest position within the field. These delay times vary between the make and model of harvester, the choice of yield monitor and GPS receiver (Nolan *et al.*, 1996; Beal and Tian, 2001; Chung *et al.*, 2002; Simbahan *et al.*, 2004a) and also vary within fields due to field and crop conditions (Chung *et al.*, 2002).

Several techniques have been used to estimate the magnitude of this time delay and they have ranged from (1) estimating a constant lag time derived from a visual inspection of the yield map (Birrell *et al.*, 1996; Chung *et al.*, 2002; Drummond and Sudduth, 2005a; Griffin *et al.*, 2007), (2) applying first order (Birrell *et al.*, 1996) and parametric modelling (Whelan and McBratney, 1997), (3) using a graphical method to identify the surface area ratio (Beal and Tian, 2001; Ping and Dobermann, 2005) and (4) geostatistical and data segmentation methods (Chung *et al.*, 2002). Currently, the visual inspection method seems the most practical, however, the inspection of each yield map is time-consuming and the criterion to estimate the delay is relatively subjective (Chung *et al.*, 2002).

Suggested harvest lag times (in seconds) have varied with delays of between 8-15 (Birrell *et al.*, 1996), 4-14 (Beal and Tian, 2001), 13-14 (Chung *et al.*, 2002), 6-18 (Simbahan *et al.*, 2004a; Ping and Dobermann, 2005), 8-24 (Griffin *et al.*, 2007) being proposed. These time ranges encompass the constant value (12 seconds) suggested to be applied by many monitor manufacturers to remove this problem. The total positional error that may be encountered can therefore be quantified by using the manufacturers proposed delay and the published maximum and minimum values (24 and 4 seconds). The per-second distance travelled by the harvester is estimated at 3m with the average speed at 10km/hr. This gives a maximum positional error of 36m in the most extreme cases. This suggests that positional error issues will only arise when small cell applications are targeted (Whelan and McBratney, 1997). To minimize this error, several studies have suggested that a more realistic resolution for yield interpolation would be 20 to 25 metres (Lark *et al.*, 1997;

Taylor *et al.*, 2007). This resolution approximates the scale over which a harvester mixes the grain before it reaches the sensor (Taylor *et al.*, 2007), smoothing the resultant variation caused by this error. Consequently, this resolution should also be used to inform the minimum area requirements for on-farm experimentation.

3.7 Harvester fill mode and finish mode error

Depending on the system used for continuous grain yield, the lowering and raising of the harvest cutter bar signals the start and end of a harvest run. This is indicated within the data file as an increment of a numerical counter. The harvester fill mode (also known as start-pass delay time) and finish mode (also known as end-pass delay time) time errors occur when the grain transport mechanism fills or empties at the start and end of a harvest pass. At this stage within the harvest run, low and unreliable measurements of yield are recorded. These delays can be variable because the timing with which the operator raises and lowers the cutter bar are often inconsistent for harvest pass to harvest pass (Drummond and Sudduth, 2005a).

Methods used to remove this type of error have focused on the visual interpretation of yield measurements graphed against the first and last 20 seconds of the corresponding harvest passes (Simbahan *et al.*, 2004a; Ping and Dobermann, 2005). Figure 7 shows the measured yield of the first and last 30 seconds of three randomly selected harvest passes for a yield mapped field in Western Australia. The first 10-15 seconds shows the recording of low yield values which rise rapidly to measure the actual yield variation. This recording situation is reversed in the last 10-15 seconds.

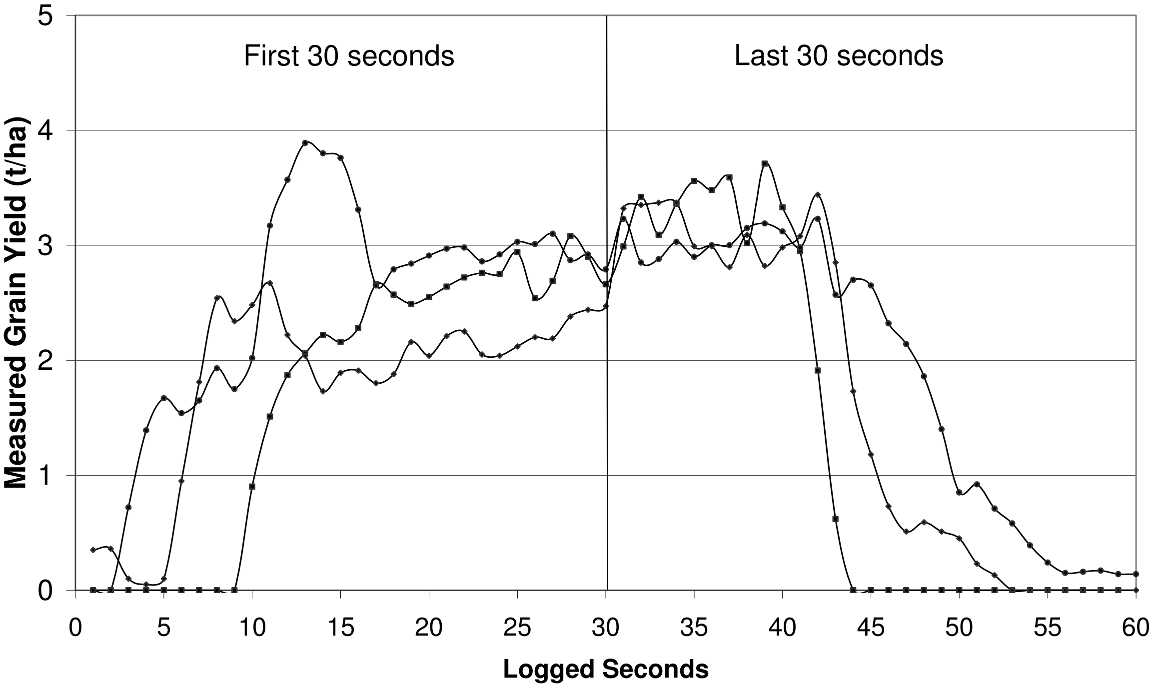

Figure 7 Grain yield in the first and last 30 seconds of continuous yield monitoring for three randomly selected harvest passes

This method allows for the quantification of the time lag delay by identifying the average time taken for consistent yield measurements to be reached at the start of a harvest pass or the point where inconsistent yield measurements are recorded at the end of a harvest pass.

Within an error removal process, yield data within these time periods can be deleted both at the start and end of each harvest pass. Identified delay times of between 10-40 seconds have been suggested (Nolan *et al.*, 1996; Thylen and Murphy, 1996; Moore, 1998; Blackmore and Moore, 1999; Robinson and Metternicht, 2005). Recent studies (Simbahan *et al.*, 2004a; Ping and Dobermann, 2005; Drummond and Sudduth, 2005a; Griffin *et al.*, 2007) have highlighted that start pass delay and end pass delay should be set between 0-10 and 0-16 seconds respectively, illustrating that the first 30m and last 72m should be removed from each harvest pass.

3.8 The continuous measurement of moisture and variables to calculate grain yield

The continuous recording of data within the by the yield monitoring process can influence the accuracy of grain moisture and grain yield measurements.

For the measurement of grain moisture, local harvest circumstances such as dry and dusty conditions can unduly effect their measurement (Beck *et al.*, 1999). Proposed methods to remove outliers focus on the setting of thresholds based on local conditions. For the United States, normal measurements are between 14% to 17% depending on what type of crop is being harvested while in Australia, grain tends to be harvested at a lower moisture content (<13%) to avoid post-harvest drying (Taylor *et al.*, 2005).

Yield measurements are expressed as the flow per logging time over a specified harvested area. The area is quantified as a function of the distance traveled and the length of the cutter bar. Within this calculation, flow and distance traveled are continuously measured while the length of the cutter bar and logging time are preset before harvesting and often presumed constant. Measurement of unrealistic yield values occur when ground speeds and distance traveled per cycle are low or where large mass flow rates combined with short distances are measured (Shearer *et al.*, 1997).

Several methods have been proposed to remove these yield outliers based on either the yield value themselves or the variables used to derive yield. Authors have used cut-off values based on expert knowledge of local biological limits (Blackmore and Marshall, 1996; Shearer *et al.*, 1997; Beck *et al.*, 1999; Kleinjan *et al.*, 2002; Ping and Dobermann, 2005; Shearer *et al.*, 2005) but in practice, only moisture limits can be viewed as being consistent from season to season (Beck *et al.*, 2001). Statistical thresholds such as ±3 standard deviations (Kleinjan *et al.*, 2002; Simbahan *et al.*, 2004a; Griffin *et al.*, 2007) or inter-quartile ranges (Robinson and Metternicht, 2005) have also been applied. This method however has little consideration of the spatial yield variation. To overcome these problems, more advanced and automated filtering techniques have been implemented. These procedures identify local yield extremes that occur in small patches or narrow strips which have little relationship to the values of their neighboring yield records. Deletions are made iteratively when a particular value is lower or greater than the average yield of a predefined local neighbourhood. This approach is consistent over many studies with only the definition and identification of the local neighbourhood changing. These range from the use of nearest neighbour and interpolation searches (Thylen *et al.*, 2000; Simbahan *et al.*, 2004a; Ping and Dobermann, 2005), the recognition of harvest tracks (Noack *et al.*, 2003; 2005) and the placement of paraboloid cones along the current harvest path (Bachmaier and Auernhammer, 2005) to define these search areas. Two problems exist with this technique, the first, is the reliance on commercial GPS receivers to identify harvest path which often have low positional accuracy. Secondly, the use of the search areas will have limited benefit where fields have yield zones with quite distinctive yield boundaries with large variations of grain yield between them such as in Australia (Wong and Asseng, 2006; Robertson *et al.*, 2008). In this case, threshold values calculated on bounding areas will be based on the average of yield values from different yield zones and may identify data exhibiting true yield variation as erroneous.

3.9 Post processing correction and methods associated with the Global Positioning System (GPS)

3.9.1 Post processing correction of locational data

Early studies (Birrell *et al.*, 1996; Stafford *et al.*, 1996) focusing on the relative positional accuracy associated with agricultural grade receivers ranged from 1-3m. Later studies (Arslan and Colvin, 2002a; Shearer *et al.*, 2005) suggested that the error of the current agricultural grade GPS receivers was ± 1m with a standard deviation of less than 6cm. Although these studies highlight that the relative accuracies of the newer systems are adequate for data collection, positional errors did occur. Two types of positional errors have been reported, those that affect the whole data set, which are effectively a whole of dataset positional offset and those that affect only a small number of geo-referenced data points within the field (Blackmore and Moore, 1999). The first error can be easily established with harvest points not contained within the field boundary. The second type of error where the harvest track is co-located or where the harvest track has veered off to generate a false representation of the actual harvester path (Blackmore and Moore, 1999) are more difficult to identify.

Current methods for identification of positional errors involve either the manual inspection of yield locations or the implementation of algorithms that interrogate each successive point's locational information within a harvest pass (Blackmore and Moore, 1999; Simbahan *et al.*, 2004a; Robinson and Metternicht, 2005). Further development of this method has involved the incorporation of simple linear geometrical adjustments to remove GPS variations (Shearer *et al.*, 2005). It is suggested that GPS accuracy problems should only resonated in older files with less problems in the future because of the falling cost of GPS receivers and the increasing accuracy of differential and RTK receivers (Blackmore and Moore, 1999; Arslan and Colvin, 2002b; Shearer *et al.*, 2005).

By applying these methods, GPS errors can be identified and removed so that further GPS based post processing routines can be employed. But before these are incorporated the correct trajectory of the harvester must be validated. While it has been reported that it is possible to straighten the GPS wander in harvest passes, this action requires an assumption that certain positional values are erroneous and others are correct (Beck *et al.*, 2001). Therefore careful consideration is needed to determine the appropriate selection of valid GPS locations and thresholds if any future algorithms under current GPS receiver accuracy are to be constructed.

3.9.2 Estimating constant harvesting cutter (swath) width or narrow finish errors

The setting of a constant length of harvester cutter bar provides another source of generating erroneous yield measurements. Incorrect measurements will be recorded when the full extent of the bar is not be fully utilized. This is especially the case at the end of harvest strips or when the combine operator cleans up areas that have been missed previously. These situations can be visually interpreted from yield maps as strips of low or high yield (Blackmore and Moore, 1999).

Two methods have been proposed to deal with this problem, (1) a real time engineering solution to measure the actual cutting width distance through the use of ultrasonic distance transducers (Reitz and Kutzbach, 1996) and (2) a post processing routine which incorporates GPS locations. For this routine, two authors (Blackmore and Marshall, 1996; Robinson and Metternicht, 2005) used Pythagoras' theorem to identify this error by highlighting individual yield values that exceeded a threshold based on the average yield values from neighbouring harvest segments. Further research made use of a Geographic Information Systems (GIS) environment. Two studies (Blackmore and Marshall, 1996; Blackmore and Moore, 1999) have suggested "Potential Mapping" which summed yield data over areas estimated from the GIS rather than from yield mapped measurements. Similar to this method was the Multi-Purpose Grid Mapping procedure (Kastens *et al.*, 2000; Taylor *et al.*, 2000) which determined yield for cells of a gridded area and then followed a rule based criteria to distinguish good and bad quality data. Two other studies (Drummond *et al.*, 1999; Shearer *et al.*, 2005) derived harvest area estimates from polygons created from sequential harvest co-ordinates. Overlapping polygons were then trimmed and yield values were recalculated to reflect the change in harvest area. This methodology was also undertaken by two other studies (Han *et al.*, 1997; Beck *et al.*, 2001) but these used grid representations to calculate actual harvest area to correct for swath width errors.

Although these methods have their limitations, they rely on a GIS to conduct the analysis and require a high GPS positional accuracy; they provided some important areas for future developments to occur to tackle the constant swath width problem.

The best practical way to limit these types of errors has been suggested to manually set the harvest swath width to 95% of the bar width before harvesting commences (Blackmore and Moore, 1999) or to avoid recording this type of data entirely (Beck *et al.*, 2001).

3.10 Harvest operator induced errors

The data acquired from yield monitors is no better than the abilities and dedication of the equipment operators who operate them (Beck *et al.*, 2001; Kleinjan *et al.*, 2002; Shearer *et al.*, 2005). The recording of erroneous measurements will occur because the operator must harvest fields as quickly as possible with minimal time to keep a careful note of changing circumstances (Blackmore and Moore, 1999). A variety of errors are possible, including the recording of stop and go and short segments, the inclusion of yield measurements derived from sudden speed changes and harvester overlaps and turns.

3.10.1 Short harvest segments

Arslan and Colvin, 2002a concluded that the accuracy of the yield measurements will decrease with harvested segment length. Variation in accuracy of measurements recorded by yield monitors and in field measurements ranged from 2-11% for harvested segments of 300 metres (m), 3-12% for 60m and 4-13% for 30m. Harvest lengths of around 15m were likely to cause the largest decrease in yield monitor accuracy (5-14%). Lamb *et al.*, 1995 estimated that accuracy degradation at this harvest length could be in the range of 25%. These measurements are seen as unreliable because they are affected by fill and finish mode errors. The removal of harvest runs with less than 12 logged points or less than 108 metres depending on travel speed and GPS recording cycle has been suggested (Blackmore and Moore, 1999; Simbahan *et al.*, 2004a; Ping and Dobermann, 2005).

3.10.2 Speed of the harvester

Speed of the harvester is a function of distance traveled and the recording time of the yield monitor. Large errors can occur when the combine's ground speed changes abruptly (Pierce *et al.*, 1997), stops altogether while logging or is not operating at the required design or grain flow calibration speed. Sudden changes in speed can cause either a large or small harvest area estimate which when accompanied by a relatively constant grain flow rate produces inaccurate yield measurements.

Arslan and Colvin, 2002a showed that varying speed between 8 to 11km/hr increased the average error to 5.2% while average error rates at a constant speed were 3%. The authors suggested that when combine speed was varied gradually, depending on yield variation, the error almost doubled. This suggests that maintaining a constant ground speed during harvest is essential for estimation of correct grain yield measurements.

Besides gradual variation in speed, sudden changes pose greater problems (Pierce *et al.*, 1997). Figure 8 illustrates the relationship between harvesting speed and the recorded yield measurements over a 36 second period. The grey area depicts a 15 second stage in the harvesting process where rapid speed changes occur. When harvester speed is dramatically reduced a higher value of yield is estimated (record number 15) while a low yield estimate is recorded when the harvest speed rapidly increases (record number 23).

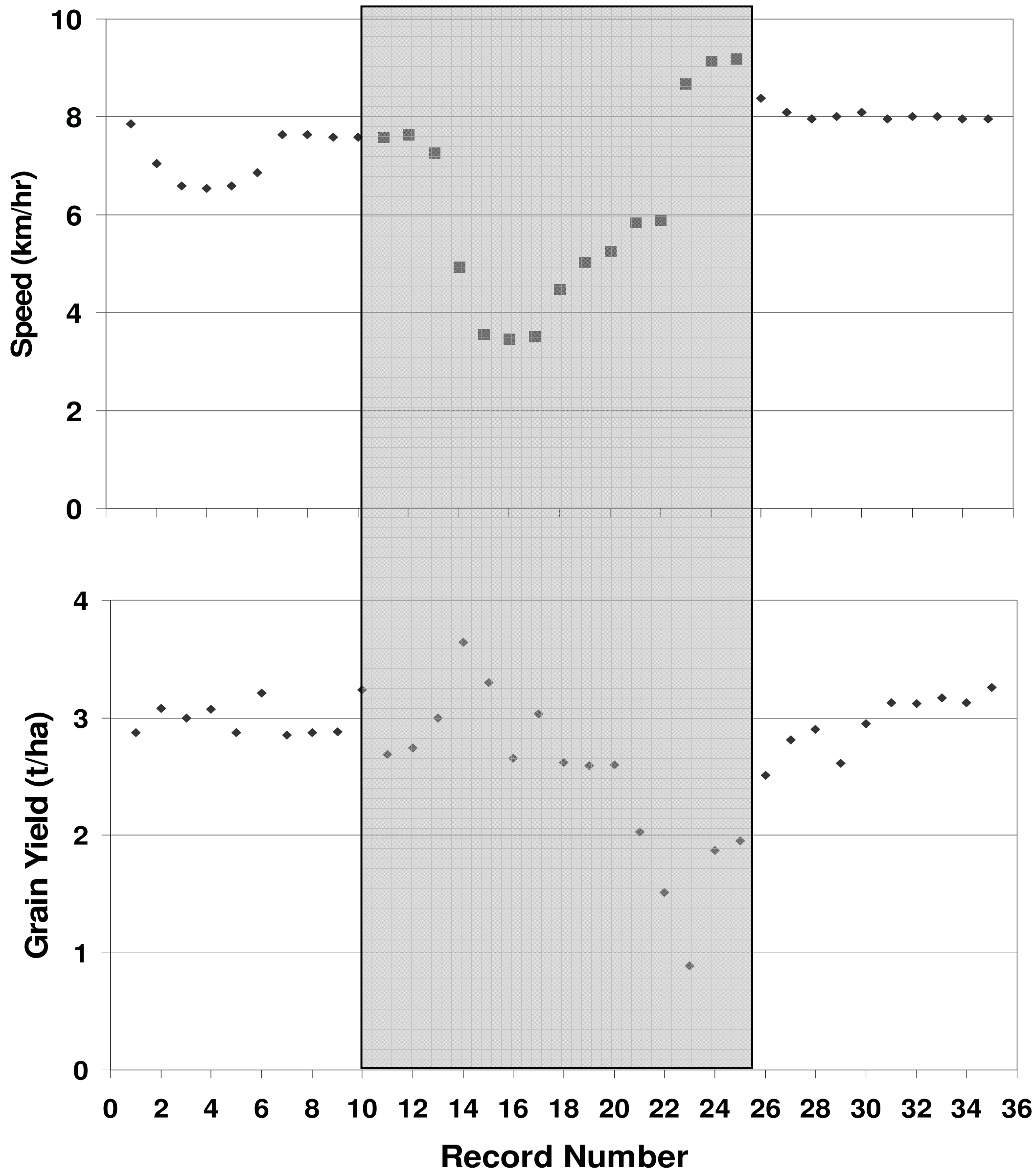

Figure 8 Changing harvester speed and the corresponding yield monitored grain yield measurements

To remove yield errors caused by speed changes, two studies (Beck *et al.*, 2001; Drummond and Sudduth, 2005a) proposed the establishment of speed thresholds which removed extremely high (> 10km/hr) and low harvester velocities (< 1km/hr). Another technique involved the pair wise comparison of sequential speed values. Outliers were highlighted when harvester velocity exceeded a user defined threshold (15%) based on the subsequent records initial velocity (Kleinjan *et al.*, 2002; Griffin *et al.*, 2007).

3.10.3 Overlaps and turns

The recording of yield measurements in previously harvested areas (overlaps) or when the combine is turning produces incorrect yield measurements. These errors are caused by the operator's reluctance to raise the cutter bar. When the cutter bar is raised the yield monitor either flags these records or recording is temporarily paused. On the commencement of harvesting, a new pass number is generated. Most yield mapping systems are designed to indicate a turn by changing a pass number recorded in the data file (Beck *et al.*, 2001). Measurement errors occur within turns when the combine harvests at an acute angle during the turn or when only a partial swath width is collected as the combine cuts to the end of a side and starts back onto the adjacent side (Beck *et al.*, 1999; Beck *et al.*, 2001). Rapid speed changes are also possible while traversing very acute turns. Within the yield data file, harvest overlap errors are characterised by either the same positional co-ordinates or the existence of low yield values. Figure 9 shows the recorded yield values for a harvested field with significantly lower yield measurements recorded where harvester overlaps and turns occur.

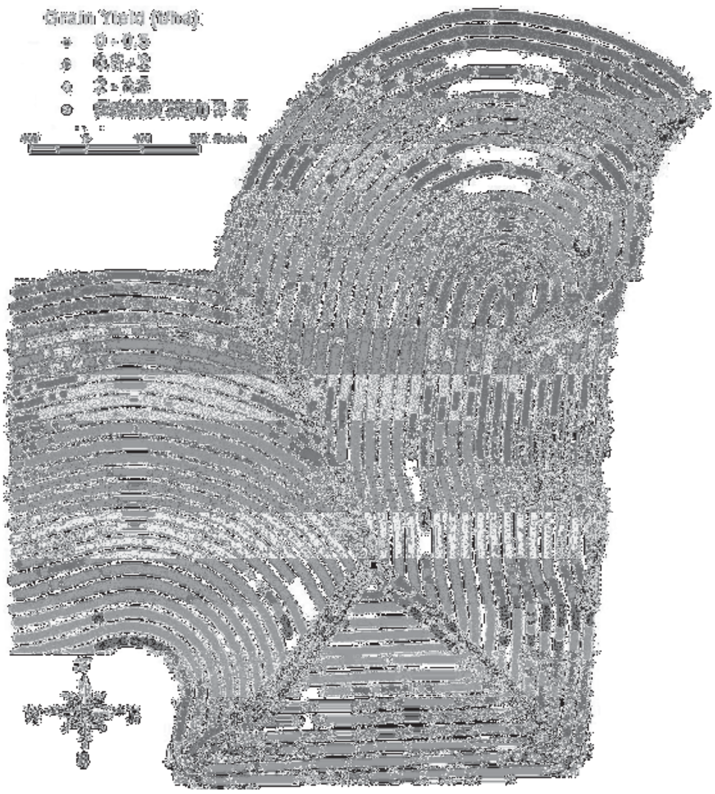

Figure 9 Harvest location and grain yield measurements for a specific part of a randomly selected field in WA. Black points represent low grain yield measurements associated with harvester overlaps and turns

In three studies (Simbahan *et al.*, 2004a; Ping and Dobermann, 2005; Robinson and Metternicht, 2005) co-located points were removed so as to avoid bias in the estimation of yield when interpolation processes were used. However, harvest overlaps that did not have the same positional location and combine harvester turns are harder to recognize. Two studies (Beck *et al.*, 1999; Beck *et al.*, 2001) proposed two filters to deal with these problems. The first method dealt with turns based on a specified number of point to point distances before and after a new pass number is incremented. Comparisons were based on a specified percentage of the swath width and points were eliminated that failed this threshold. This method dealt with turns in which operators were vigilant enough to raise the cutter bar. When this was not the case, the second filter, which also dealt with overlaps was used. This filter placed a bitmap grid over the entire field similar to harvest width identification proposed by another study (Han *et al.*, 1997). A user specified grid cell size was calculated as a percentage of the header swath width and each yield point was then assigned to a specific grid cell sequentially. Points that subsequently fell into already established "harvested" cells were then discarded.

A recent study (Ping and Dobermann, 2005) concluded that further improvements were needed in detecting errors due to the overlap of harvest passes. This review has highlighted the benefits of using positional information to identify erroneous data caused by harvester turns and overlaps. One further development of these algorithms could be the use of positional information to derive the harvester heading of the combine. Any abrupt change in the heading of the harvester along a harvest path will indicate the commencement of a harvester turn. The creation of "harvested cells" (Beck *et al.*, 1999; Beck *et al.*, 2001) through the direction of travel and the cutter bar width will also help identify areas that have already been harvested. Applying a spatial search through the dataset with these areas as bounding co-ordinates will identify harvested locations that fall within the bounded area.

3.11 Logical sequence of error processing

Identifying the appropriate sequence and criteria used for post processing datasets is difficult. Several studies suggest that the proposed methods examined above should be implemented in a logical, sequential and multilevel process, where specific criteria are established for error removal (Simbahan and Dobermann, 2004b; Shearer *et al.*, 2005; Drummond and Sudduth, 2005a; Sudduth and Drummond, 2007). A basic structure for yield error removal has been proposed which involves six steps of automated post processing (Simbahan *et al.*, 2004a; Ping and Dobermann, 2005; Sudduth and Drummond, 2007). Steps 1 and 2 remove technical errors associated with yield monitor operations. Steps 3 to 6 remove erroneous yield records caused by the combine operation and grain yield measurement. Rather a sequential approach, one study (Robinson and Metternicht, 2005) applied 4 post processing routines simultaneously. This study removed errors associated with unknown crop width, time lags associated with combine operation, yield surges and outliers and GPS signal.

Both studies provide a similar structure for post processing and it can be extended to incorporate other methods described in this literature review. Figure 10 shows a proposed sequential structure summarising the reviewed post processing methods with the last three methods identified by using GPS information. This structure will guide the program development in Chapter 4.

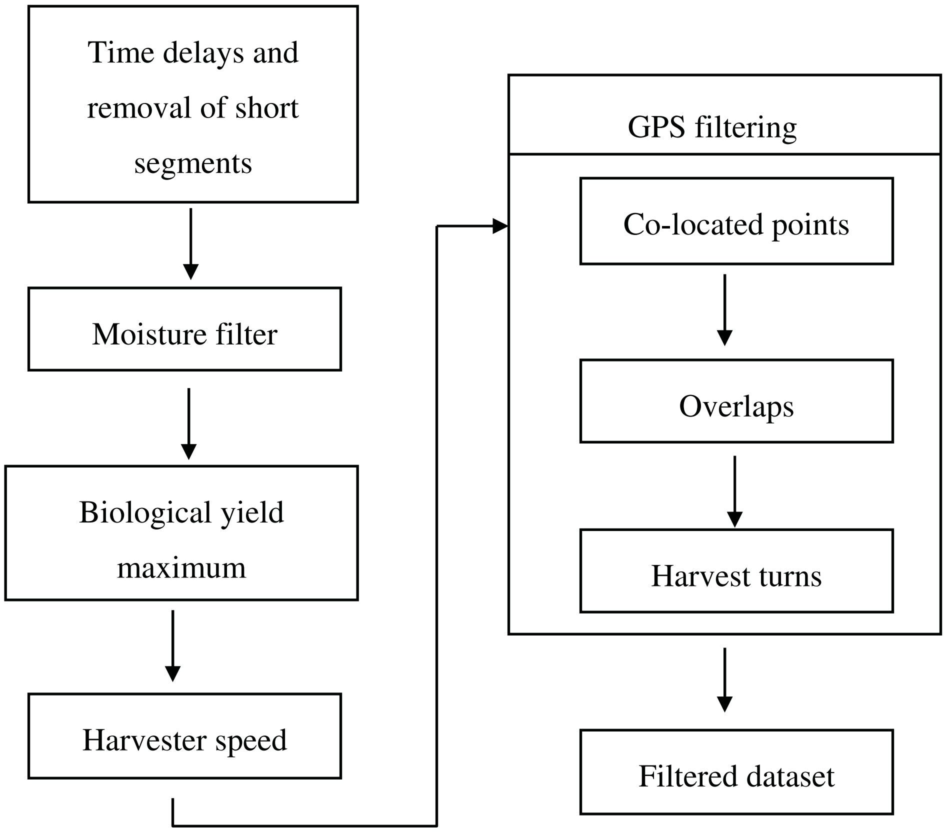

Figure 10 Flow chart summarising the proposed post processing error removal steps

3.12 Changes due to error checking

A major challenge for assessing the benefit of implementing post processing algorithms is the selection of accurate validation criteria (Ping and Dobermann, 2005). With the characteristics of the yield distributions being non-normal, validation criteria have focused on each algorithm's ability to remove data to generate more normal distributions. Filtered datasets are more likely to be representative of actual within field yield variability than raw files. Comparing the descriptive statistics derived from the original and filtered datasets has been one way of testing the efficiency of the proposed cleaning routines. Several studies have reported over 50% reduction in the coefficient of variation when post processing datasets are compared to raw files (Nolan *et al.*, 1996; Simbahan *et al.*, 2004a;

Sudduth and Drummond, 2007). These major reductions have corresponded to an increase in average yield of the dataset and a corresponding reduction in the standard deviation. Several studies have reported that the average yield of filtered datasets was consistently higher than that of the unprocessed dataset (Beck *et al.*, 1999; Beck *et al.*, 2001; Simbahan *et al.*, 2004a; Ping and Dobermann, 2005; Shearer *et al.*, 2005; Drummond and Sudduth, 2005a; Sudduth and Drummond, 2007). The magnitudes of change reported by these studies have ranged from between 6-15%. Several studies have reported declines in standard deviation in the magnitude of 22-64% (Thylen *et al.*, 2000; Simbahan *et al.*, 2004a; Ping and Dobermann, 2005; Drummond and Sudduth, 2005a; Sudduth and Drummond, 2007) demonstrating the need for and value of applying a cleaning procedure to raw yield datasets (Sudduth and Drummond, 2007). However, the application of cleaning routines has not always shown reductions in yield variation. One study (Shearer *et al.*, 2005) reported a standard deviation increase of 62.9%. Here, the author explained that this reverse trend may have been due to a greater yield variation within the field than first thought.

Reporting on the effects of post processing routines in terms of creating normality in yield distributions has been limited (Simbahan *et al.*, 2004a; Robinson and Metternicht, 2005). Simbahan *et al.*, 2004a who reported large negative skewness values in the raw yield distributions, showed reductions of 19% to 92% in the skewness statistic in three out of four fields investigated. Although significant reductions, these yield distributions still remained negative while one of the four fields analysed showed a greater negative skewness after error removal. This study highlights the limitations of using certain statistical methods for error removal. The application of a ± 2 or 3 standard deviation filter on large negatively skewed yield distributions will only remove yield measurements at the lower end of the yield spectrum while having only a limited effect on the higher end values. Actual removal of data will also be constrained to the 95th to 99th percentile of the yield distribution, which may have a little effect on the creation of a normal distribution. This was problem was foreseen by the author and percentile ranges were proposed as an alternative for dryland fields with very wide ranges of true yield variation (Simbahan *et al.*, 2004a).

The application of a set of comprehensive post processing routines which removes erroneous data has the effect of reducing the size of these yield datasets. Reduction of infield records has varied with conservative reductions ranging from 0.4% to 32% of the data recorded (Shearer *et al.*, 1997; Blackmore and Moore, 1999; Beck *et al.*, 2001; Robinson and Metternicht, 2005). The use of a stepwise process (Thylen *et al.*, 2000) removed, 10%, 25% and 50% of the data. Further studies using a sequential post processing structure (Simbahan *et al.*, 2004a; Ping and Dobermann, 2005; Drummond and Sudduth, 2005a; Sudduth and Drummond, 2007) reported that 13% 27% of the dataset was removed with the first two steps accounting for 71% of all removed data (Simbahan *et al.*, 2004a; Ping and Dobermann, 2005). However, the statistical validation criterion of whole files does not necessarily imply the removal of erroneous data. The purpose of filtering is not to provide better field averages but to eliminate inaccurate yield measurements that affect the yield at local regions of the field (Beck *et al.*, 2001). While post processing routines may reduce the standard deviation, this may simply be an expected effect when filtering data of any kind and does not necessarily prove the removal of errors (Noack *et al.*, 2003).

The visual identification of the location of errors through their 2 dimensional mapping provides a preliminary method for error validation (Beck *et al.*, 2001; Simbahan *et al.*, 2004a; Sudduth and Drummond, 2007). Although several interpolation methods can be used to produce a 2 dimensional representation of grain yield, the derivation of the information used in the kriging interpolation method provides several criteria to evaluate the application of post-processing routines. Kriging is based on the regionalized variable theory, which assumes that the spatial variation of any variable can be expressed as the sum of three components which make up the semi-variogram. These are the deterministic variation which has a constant mean or trend, a random but spatially correlated component known as the regionalized variable and a spatially uncorrelated random noise or residual error known as the nugget (Burrough and McDonnell, 1998). In the prediction process, the kriging procedure gives weighting to data based on the relationship between physical distance and variance (Thylen and Murphy, 1996). Two efficiency criteria can be developed from the kriging procedure, which rely on the assumption that the general spatial structure of yield variation holds even after the removal of data by the post processing routines. The calculation of the nugget provides one way to evaluate error removal techniques and has been used by a number of studies (Thylen *et al.*, 2000; Simbahan *et al.*, 2004a; Robinson and Metternicht, 2005; Sudduth and Drummond, 2007). The nugget quantifies a high proportion of short distance measurement error or noise (Sudduth and Drummond, 2007) which relates specifically to erroneous yield variation. A low nugget value is desirable since it indicates that more of the data is related directly to the model and not influenced by random error (Simbahan *et al.*, 2004a). For raw yield files, results of the later studies showed that the total variation contribution by the nugget was quite large. With the proportion of spatially uncorrelated variation to the total variance ranging from between 14% to 49% (Simbahan *et al.*, 2004a), 57% (Robinson and Metternicht, 2005) and 47% to 100% (Sudduth and Drummond, 2007) for the yield data files investigated. The application of filtering routines showed a reduction in nugget contribution by 9% to 32% (Simbahan *et al.*, 2004a), 50% (Robinson and Metternicht, 2005) and 13% to 68% (Sudduth and Drummond, 2007). These reported reductions were also similar for the earlier study (Thylen and Murphy, 1996). These results of these studies demonstrate that the implementation of post processing error removal software reduction in the nugget are possible and therefore can provide a suitable validation criterion. Another validation criterion that can be derived from the kriging interpolation technique is associated with the calculation of the prediction variance estimate or kriging variance associated with the estimation of grain yield. In the prediction process, the kriging prediction model minimises the estimation variances making the procedure optimal (Thylen and Murphy, 1996). Higher kriging variance values that are produced by the prediction model indicate a greater variation in the values of neighbouring yield data. One field scale study (Thylen and Murphy, 1996) reported that the average field kriging variance was reduced when post processing methods were implemented. The capability to associate a prediction variance estimate with an interpolated yield value provides us with an ability to map the spatial distribution of prediction error. The mapping of this distribution for the interpolated dataset provides a measure of estimation confidence on the predicted values (Whelan *et al.*, 2001). Figure 11 shows the kriging standard deviation (SD) (in tonnes per hectare) for the field identified in Figure 9 generated from the VESPER software (Minasny *et al.*, 2005).

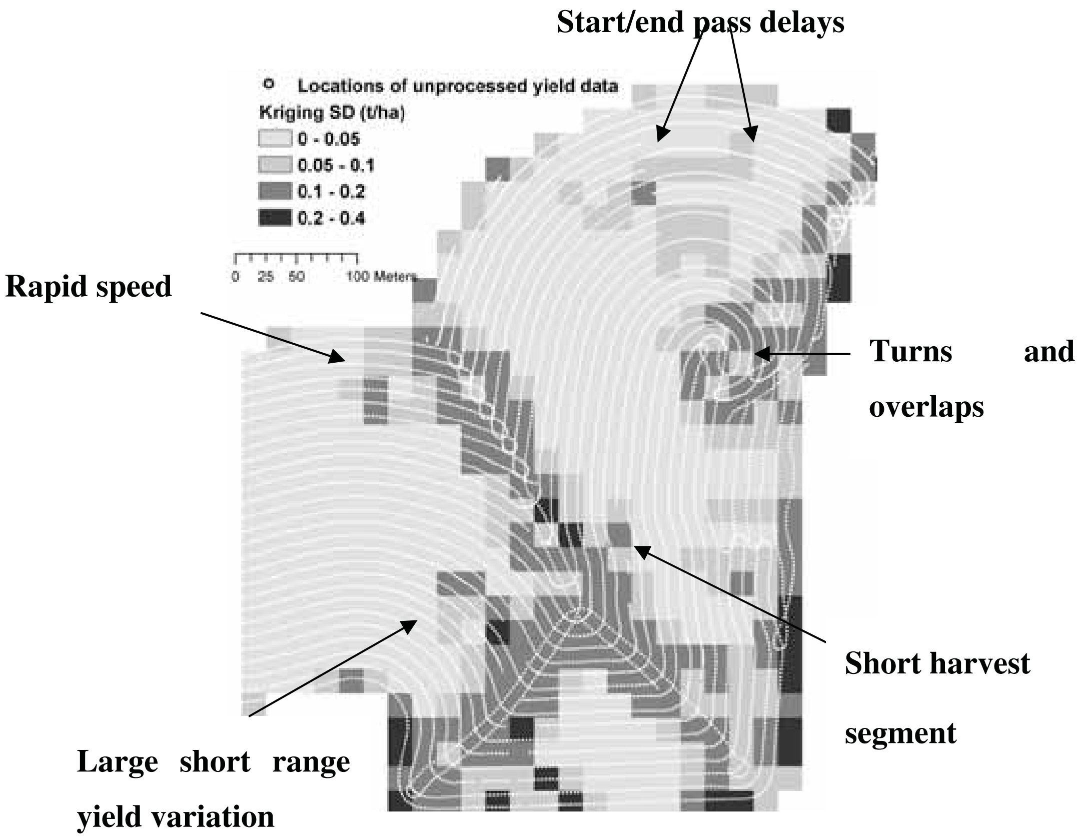

Figure 11 Map of kriging standard deviation (SD in t/ha) indicating the yield prediction error associated with the recording of erroneous grain yield measurements

For the majority of the field the correct recording of yield measurements shows a marginal prediction error (< 0.05 t/ha). In certain situations where measurements have been highlighted as erroneous, prediction error was higher. A similar spatial comparison technique based on the standard deviation of yield measurements within a specific search radius for both raw and post processed datasets has also been used (Noack *et al.*, 2003). Spatial comparisons of the standard deviation maps showed that areas with large yield variation (2 t/ha or more) derived from the raw yield monitored data were almost entirely removed when post processing routines were implemented. While not using the kriging variance, one study (Noack *et al.*, 2005), compared the difference between the actual yield monitored measurements and the nearest kriged interpolated grid value as an efficiency criterion. The aggregated field results showed that when post processing algorithms were implemented, the standard deviation of the grid residuals almost halved. One potential criticism of using kriging variance as a validation criteria is that areas with few data points, noisy data or points near the edges of fields tend to have higher kriging SD values (Taylor *et al.*, 2007). The use of post routines has been shown to remove large amounts of data and therefore may constrain this methods ability to gain a greater insight into the benefits of error removal. Results of several field based studies suggest that because of the intensity and spatial density of yield monitoring data, the data voids produced in the filtering process may not have a significant effect on prediction estimation and error (Simbahan *et al.*, 2004a; Noack *et al.*, 2005; Robinson and Metternicht, 2005). However, these conclusions may not hold in areas within fields as proposed in Figure 11.

3.13 Discussion and conclusion

Natural grain variability must be separated from the variability caused by erroneous measurements inherit in the harvesting process before any management decision based on this information can be made. Continuous grain yield monitoring can produce accuracy rates of up to 95-99.5% but this rate only holds for certain specific harvest situations. Straying from these conditions will produce erroneous yield measurements and these must be removed if any management decision can be made on the data. The review of the literature on the identification yield mapping errors has highlighted numerous methods that have been incorporated into a range of expert filters, spreadsheet macros and standalone programs. These programs have highlighted the typical errors that are apparent in the yield monitoring process and have identified a set of methods that can be used to highlight and remove them. However, none are seen as comprehensive. This paper has reviewed the post processing literature and identified four types of yield mapping errors associated with yield monitoring. These reflected issues associated with combine harvester dynamics, the continuous measurement of grain yield and moisture, the position of the harvester, and the harvest operator. Error removal routines have ranged from simple identification measures that use threshold values or statistical methods to highlight outlying data. To more intuitive methods that include the inspection of the surrounding local neighbourhoods to locate harder to identify errors. Bringing together the literature we have proposed what we believe is a comprehensive logical post processing error removal structure, which reflects and expands on an order of generally agreed error removal processes. This structure provides a further step towards the automation of what is a time intensive process.

Yield mapping is a destructive technique of data collection with the true yield variation lying somewhere between the measurements provided by the raw dataset and that of the post processed. As we are can only make informed assumptions on the choice of thresholds and base decisions on the local variation of yield measurements within a given area we are still unable to determine whether essentially good or bad data is being removed. Review of the literature has shown that the cleaning ability of these programs have been limited by their application to only a small number of fields and the choice of evaluation technique. These techniques have been based on their effect on the statistical distribution of the whole dataset concentrating on the possible reduction in descriptive statistics such as standard deviation, skewness and kurtosis. Although this gives some insight into their effectiveness, additional efficiency measures can be calculated. The derivation of the prediction variance associated with the interpolation of yield maps via kriging provides two benefits. The technique allows for the visual identification of erroneous data based on high prediction variance values and helps justify the use of particular routines that target certain harvest processes that cause incorrect yield measurements. The creation of the prediction variances of the interpolated yield predictions also provides an effective efficiency criterion when a comparison can be made between the raw and post processed datasets. However, care must be taken when using this criterion as the removal of a large number of points within the filtering process may affect its effectiveness.

This review has also highlighted specific areas where the current literature can be further developed. The identification of erroneous data associated with harvest speed and the incorporation of locational information for identification of narrow finishes, harvester turns and overlaps are areas that should be addressed further. For these developments to occur robust algorithms must be developed to smooth variations in positional data or the positional accuracy of commercial agricultural grade receivers must increase. Furthermore, any development of future algorithms must be pursued outside of 3rd party systems such as geographic information systems so that they will be more widely accepted.

For consistency some input and manual editing is required from people who have intimate field knowledge or who actually collected the data (Simbahan *et al.*, 2004a; Shearer *et al.*, 2005; Drummond and Sudduth, 2005a). It is hoped that the cataloguing of the cleaning methods associated within the yield mapping literature will allow for the development of an automated post processing error removal system.

3.14 Acknowledgements

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Chapter 4: The effectiveness of post processing routines to remove erroneous yield mapping measurements

***Keywords**: yield mapping, errors, post processing methods, software.*

Further information for this chapter can be found in Appendix 2.

4.1 Abstract

The major premise behind precision agriculture technology is matching the supply of inputs to spatial yield variability. The data collected through this technology, such as yield mapping, must be accurate so that crop management decisions match the true crop yield variation. Some have questioned the accuracy of the estimates recorded, suggesting situations where errors occur and proposing post processing error removal techniques to remove them. This study developed these post processing methods further by proposing a structure of 10 algorithms which identified and removed yield mapping errors based on previously cited and newer methods proposed by the authors. The software removed widely reported yield mapping errors such as start and end pass delays and short harvest segments. In addition, newer methods utilised positional information, harvest track search filters and thresholds to target specific erroneous data associated with harvester speed changes, yield fluctuations and harvest turns and overlaps.

In order to judge the overall error removal effectiveness of these methods, comparisons were made to results using two less targeted statistical methods with criteria based on the reduction in standard deviation of yield caused by the removal of erroneous data. Each individual algorithm's effectiveness was also assessed by identifying its contribution to the overall reduction in standard deviation of yield. Both assessments were calculated over 183 selected fields. A further statistical and visual assessment was undertaken with a randomly selected field by spatially comparing local yield variation within harvest paths and interpolated yield estimates between both raw and processed datasets.

Overall, the implementation of the methodology reduced the standard deviation of yield for all files by 26% (0.65 t/ha to 0.49 t/ha). This reduction was double that of the less targeted, statistical based, error removal methods. The newer individual algorithms removed over 57% of this reduction, although optimisation of these routines must be investigated further to avoid removal of fundamentally good yield data. Assessment of the each algorithms effectiveness in removing specific yield mapping errors showed that the newly developed routines contributed to 57% of the total reduction in standard deviation. For the example field, results showed a 47% reduction in standard deviation and an 11% increase in average field yield when the algorithms were implemented. The creation of interpolated yield maps from both datasets showed that the yield prediction error was significantly reduced in areas where specific errors were removed. This result further corroborated the effectiveness of the approaches taken.

4.2 Introduction

A major premise behind the use of precision agriculture technology is matching the supply of variable inputs to the spatial variability of yield (Cook and Bramley, 1998; Bullock and Bullock, 2000; Whelan and McBratney, 2000). One tool used to quantify the spatial variation in crop production is yield mapping. This process involves the calculation of yield mapped at locations within a field by measuring grain flow, the distance traveled, length of the combine's cutter bar and positional information recorded by a Global Positioning System (GPS). The mapping of yield can then be used to assess the spatial and temporal persistence of crop production (Stafford *et al.*, 1996; Lark and Stafford, 1997; Blackmore, 2000; Blackmore *et al.*, 2003; Joernsgaard and Halmoe, 2003; Sadler *et al.*, 2005).

To address spatial and temporal crop yield variability, yield maps are used to inform the opportunity and application of precise crop management based on yield differences (Ping and Dobermann, 2003; Pringle *et al.*, 2003; Brock *et al.*, 2005; Cox and Gerard, 2007; Xiang *et al.*, 2007) or as ancillary data to other proximal or remotely sensed agronomic variables (Adams *et al.*, 2000; Wong *et al.*, 2001; Anderson-Cook *et al.*, 2002; Flowers *et al.*, 2005; King *et al.*, 2005; Li *et al.*, 2007; Taylor *et al.*, 2007). Yield mapping has been used to quantify the expected economic benefits of changing from uniform input applications to a more targeted input management (Bongiovanni *et al.*, 2007; Robertson *et al.*, 2008) as well as the profitability of individual fields (Massey *et al.*, 2008). They have also been used to develop relationships between yield and variables such as protein (Skerritt *et al.*, 2002; Norng *et al.*, 2005), soil water holding capacity (Timlin *et al.*, 2001) and remotely sensed biomass indexes (Yang and Everitt, 2002; Chang *et al.*, 2003; Dobermann and Ping, 2004). While others (Basso *et al.*, 2001; Batchelor *et al.*, 2002 Wong and Asseng, 2006; Basso *et al.*, 2007) have used them to assess and validate the accuracy and predictive power of crop modelling.

The potential user benefits of yield mapping are dependent on the measurement accuracy of within field crop variation (Pierce and Novak, 1999) and the ability to differentiate natural or management induced crop variation from yield variation caused by measurement errors within the yield monitoring process itself (Simbahan *et al.*, 2004a). Six types of error sources from yield mapping have been reported (Blackmore and Marshall, 1996; Blackmore and Moore, 1999). A further review of literature (Lyle *et al.*, In review) suggests that these error sources can be classified into 4 areas; (i) harvester dynamics, (ii) the interaction of measured parameters in the calculation of yield, (iii) GPS errors and (iv) the propagation of errors caused by the combine harvester operator. The removal of these errors by hand is tedious especially when large numbers of fields are examined. Statistical or threshold techniques used for error removal will remove outliers to deliver normal distributions but remove values that represent true yield variation or miss errors within the normal distribution confines (inlier errors). Furthermore, the choice of the optimum threshold may be difficult without knowledge of the field and its yearly productivity (Beck *et al.*, 2001). While the use of interpolation techniques may "smooth over" over these errors, these techniques will mask rather than remove erroneous data which affect the overall quality of yield maps (Noack *et al.*, 2005; Robinson and Metternicht, 2005). Therefore there is a need to integrate filter parameters, standardize filtering procedures and post processing techniques to aid in the generation of accurate yield maps from data acquired using yield monitors (Shearer *et al.*, 2005; Drummond and Sudduth, 2005a).

The objectives of this paper are to develop and assess a post processing error removal structure based on published techniques and ones proposed by the authors. The proposed algorithms overall effectiveness of error removal will be compared with the results produced by simple cleaning algorithms across a large number of yield files. Each algorithm's ability to remove inaccurate yield variation will also be evaluated.

4.3 Datasets

A total of 752 files were extracted from three commercial yield monitoring systems (Ag Leader Technology™, Case IH™, John Deere GreenStar™ and Rinex Technology™) over 4 farms within a ten-year period (1997-2007) from the Western Australian wheatbelt. Multiple occurrences of harvested fields were removed and a random sample of 183 files was extracted. For these extracted files, crop types included lupin (*Lupins consentini, Lupins albus*), canola (*Brassica napus*), oats (*Avena byzantina*), barley (*Hordeum vulgare*) and most predominately wheat (*Triticum aestivum*). The number of records ranged from 720 to 74,978 and the total number of records passed through the proposed post processing routines was 2.6 million. Raw yield files were corrected for a 12 second harvest lag time in their corresponding proprietary software as per manufacturers' guidelines. This value fell into the 6 to 18 second range suggested by other studies (Birrell *et al.*, 1996; Beal and Tian, 2001; Chung *et al.*, 2002; Simbahan *et al.*, 2004a; Ping and Dobermann, 2005). Files were exported or formatted to match the Ag Leader Advanced file export format.

4.4 Methods

A total of 10 methods were applied sequentially (Figure 12) and were programmed as a stand-alone program in Visual Basic 6.0. Three methods were taken straight from the published literature while seven were new or adapted methods to remove specific types of erroneous yield measurements. These methods will now be discussed.

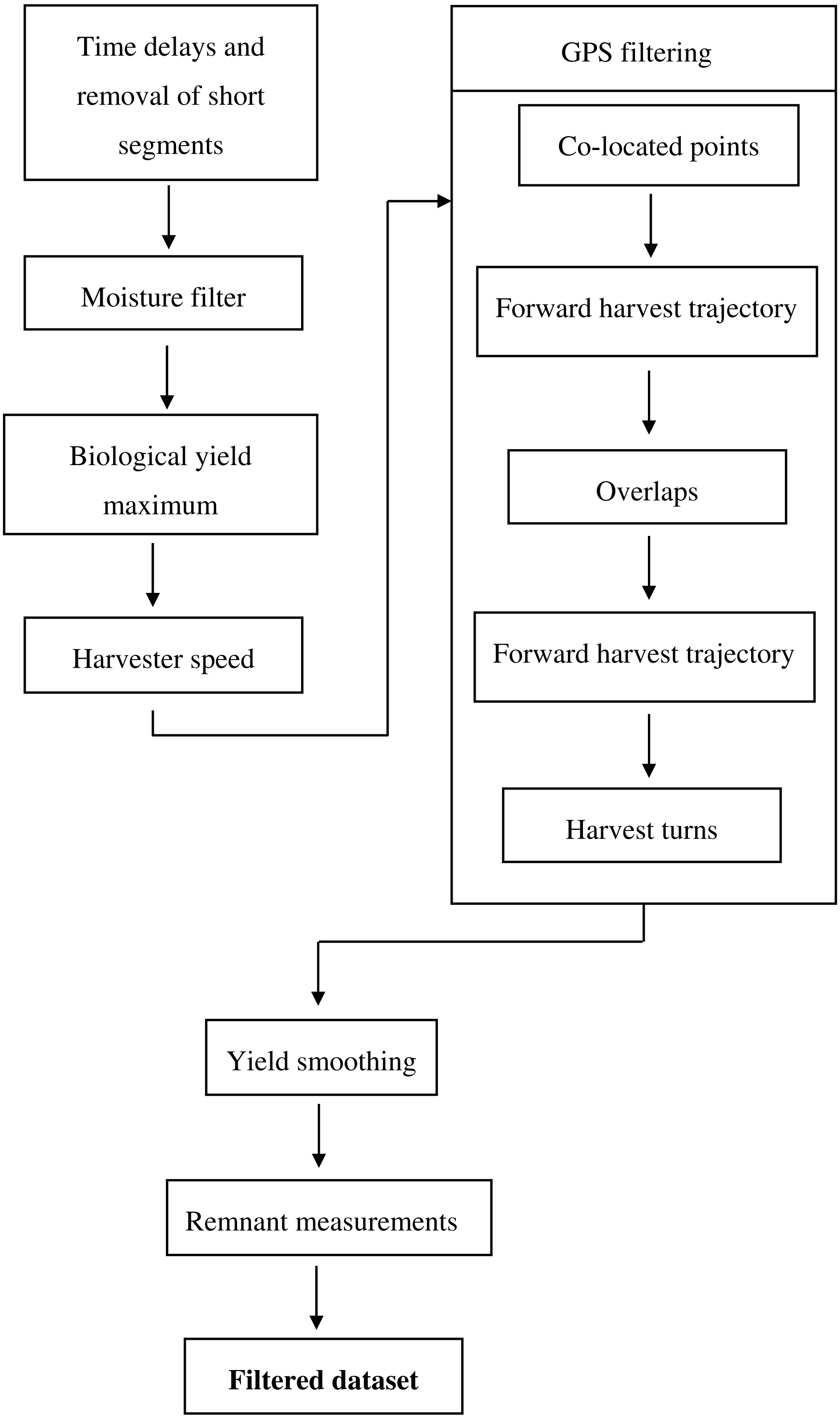


Figure 12 Structure of the 10 sequential methods programmed to remove erroneous yield mapping measurements

4.4.1 Removal of harvest fill and finish mode errors

These errors occur at the time where the harvester is either filling up in the starting seconds of a run or finishing when harvesting has stopped but the yield monitor is still recording. Within the yield mapping data file, harvest runs are recorded as a unique counter with new runs signalled by a new number. The module added unique numbers where resetting had occurred and where pass numbers were missing based on a 5 second GPS time difference between consecutive records. This unique number also identified where measurements were recorded within a harvest pass. To remove this error a constant delay time was used to remove data for the first 12 and last 6 seconds of each harvest pass. This delay time and method was similar to that used by other studies (Crisler *et al.*, 2002; Saraswat and Ehsani, 2004 Simbahan *et al.*, 2004a; Ping and Dobermann, 2005).

The module also removed short harvest segments where the measurements are predominately fill and finish mode errors or where the operator has cleaned up missed crop. Segments of less than 180 metres (m) were removed equating to around 60 seconds of data recording time. These lengths are more conservative than the 30m to 108m proposed by other studies (Blackmore and Moore, 1999; Simbahan *et al.*, 2004a; Griffin *et al.*, 2005; Ping and Dobermann, 2005).

4.4.2 Removal of erroneous moisture values

Harvesting conditions such as extreme temperatures or dusty environments have been identified as causing errors in grain moisture measurements (Beck *et al.*, 1999). Normal grain moisture estimates lie between 14-17% for the United States while in Australia, to avoid post-harvest drying grain is harvested at less than 13% (Taylor *et al.*, 2005). Thresholds have been proposed to remove measurements below 6% and above 35% (Beck *et al.*, 1999). A thresholding routine was implemented to remove data that fell outside the 5-15 % moisture range.

4.4.3 Removal of extreme yield estimates

Setting yield limits based on local conditions and biologically limits has been an effective method of erroneous data removal (Blackmore and Marshall, 1996; Shearer *et al.*, 1997;

Beck *et al.*, 1999; Kleinjan *et al.*, 2002; Ping and Dobermann, 2005; Shearer *et al.*, 2005). Here, extreme yields by Western Australian standards were removed (> 8 t/ha).

4.4.4 Removal of rapid speed changes

Rapid changes in harvester speed will cause erroneous measurements of yield. Figure 13 shows an example of the resulting yield estimates recorded with a rapid deceleration and acceleration in ground speed (grey area). High yield estimates occur when the speed reduced dramatically and low yield values where the speed rapidly increased (Figure 13).

Setting speed limits and thresholds has been one method to filter speed changes (Beck *et al.*, 2001; Drummond and Sudduth, 2005a). However, only extreme speed values outside these set limits are identified. Others have incorporated smoothing algorithms which remove records where velocity exceeds a percentage threshold of the subsequent record's initial velocity (Kleinjan *et al.*, 2002; Griffin *et al.*, 2005). This pair-wise comparison is also limited because it assumes that the first value is always correct.

We propose a speed algorithm that identifies periods of harvester deceleration and acceleration within a defined path. By comparing each records speed with the average speed of a user defined neighborhood of sequential forward and backward records, rapid changes can be highlighted when a threshold value is exceeded. For example, in Figure 13, record 11 highlights the start of a change in speed as the speed is greater than the average speed of forward records. Alternatively record 25 highlights the end of a speed change since the record's speed is greater than the average speed of the previous records. A filter is then run over the dataset to identify and remove measurements within an identified speed change that do satisfy the forward and backward comparisons (record number 16). Although speed across a field will never be constant, this algorithm helps remove records that are involved in the start, middle and end of a sudden change in speed.

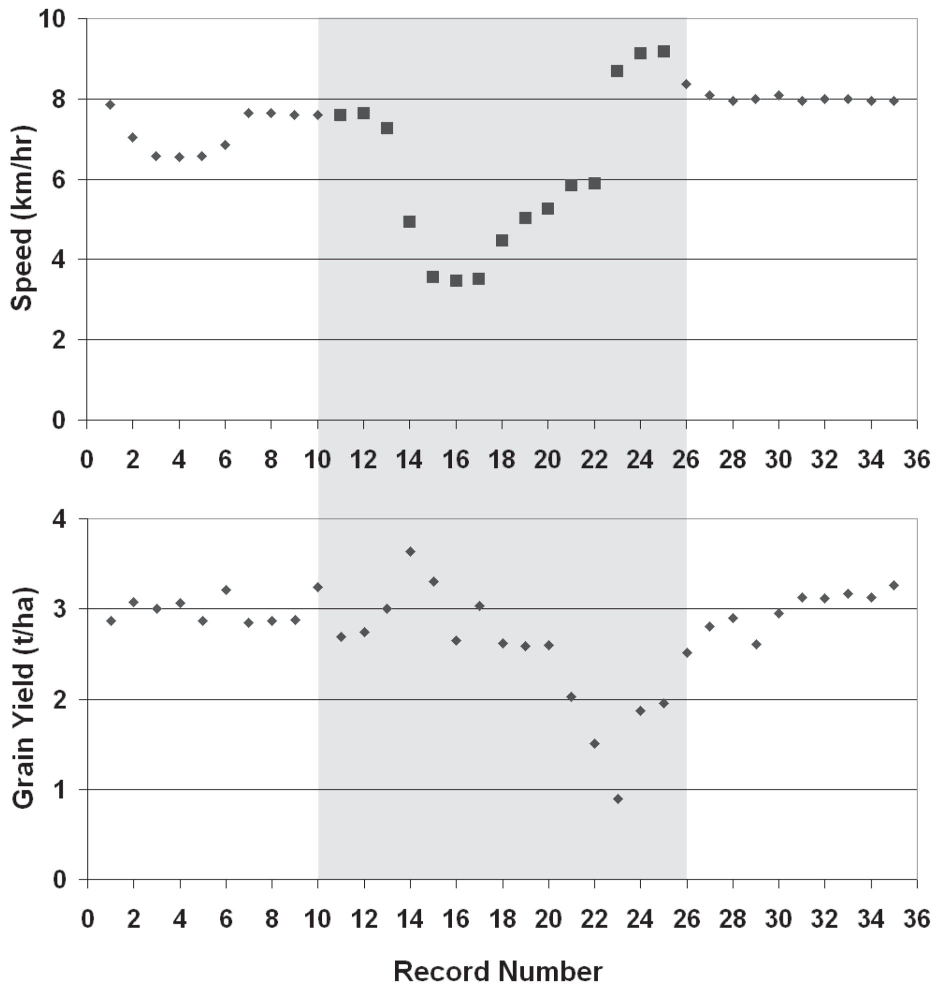
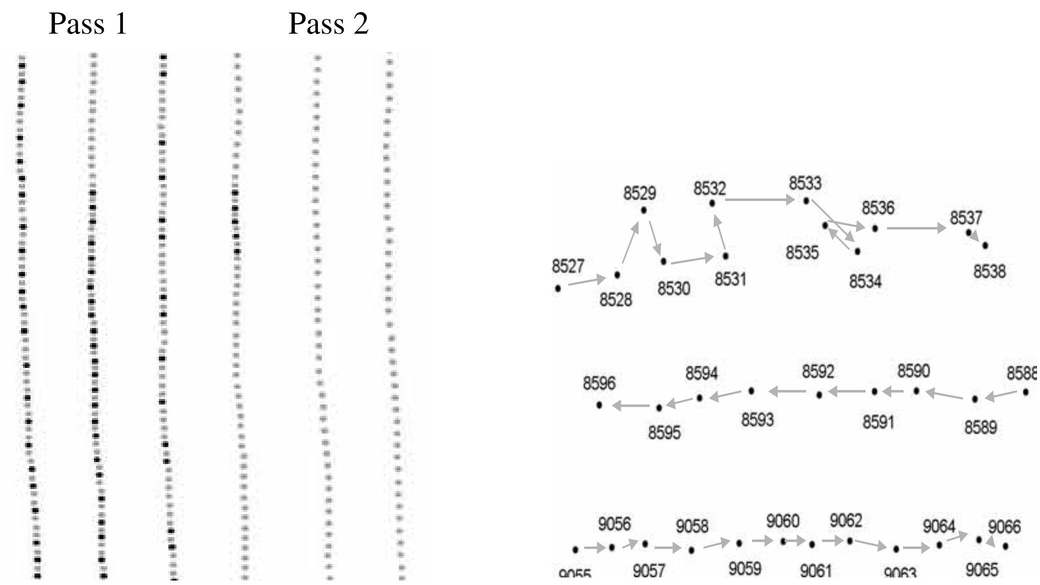


Figure 13 Yield measurements associated with rapid changes in combine speed

4.4.5 Use of GPS information for error removal: Co-location method

Several authors have used GPS data to effectively remove erroneous yield measurements (Blackmore and Moore, 1999; Robinson and Metternicht, 2005; Shearer *et al.*, 2005; Drummond and Sudduth, 2005a). The data has also been used to highlight the harvester trajectory in order to identify operator induced errors such as turns and overlaps (Beck *et al.*, 1999; Beck *et al.*, 2001). However, a major limitation to its application to error identification is the positional accuracy of the GPS signal provided by commercial agricultural GPS receivers. Two limitations can be identified. Firstly, records can be co-located or within a very close proximity of each other. In Figure 13a, Pass 1 indicates measurements logged in less than 1.5m of their neighbors (black points), without GPS signal degradation measurements should be equally spaced (Pass 2). Recording of incorrect positional data pose significant yield prediction problems when interpolation techniques are used to create yield maps (Simbahan *et al.*, 2004a; Ping and Dobermann, 2005; Robinson and Metternicht, 2005) especially when over or under estimation of yield occurs in close vicinities. Secondly, GPS accuracy can be so degraded that the harvest trajectory (Figure 14b), measured by the position of sequential measurements, can record unrealistic harvester travel path (points 8528-8530) or in the reverse direction (points 8533-8536).

The positional variations of the two neighboring harvest passes indicate the expected positional error associated with yield mapping. Therefore, before using any locational attributes for error detection it has been recommended to exclude miscalculated GPS positions (Arslan and Colvin, 2002b) and establish a continuous forward harvesting direction.



(a) (b)

Figure 14 Close and co-located measurements (black coloured points) (a) and unrealistic and realistic harvester directions (b)

To identify close and co-located errors an algorithm was created to search the file sequentially based on a user inputted search distance. The distance was set to 1.5 metres in the X and Y direction (Figure 15a) and records whose geographical positions fall within the search area were removed.

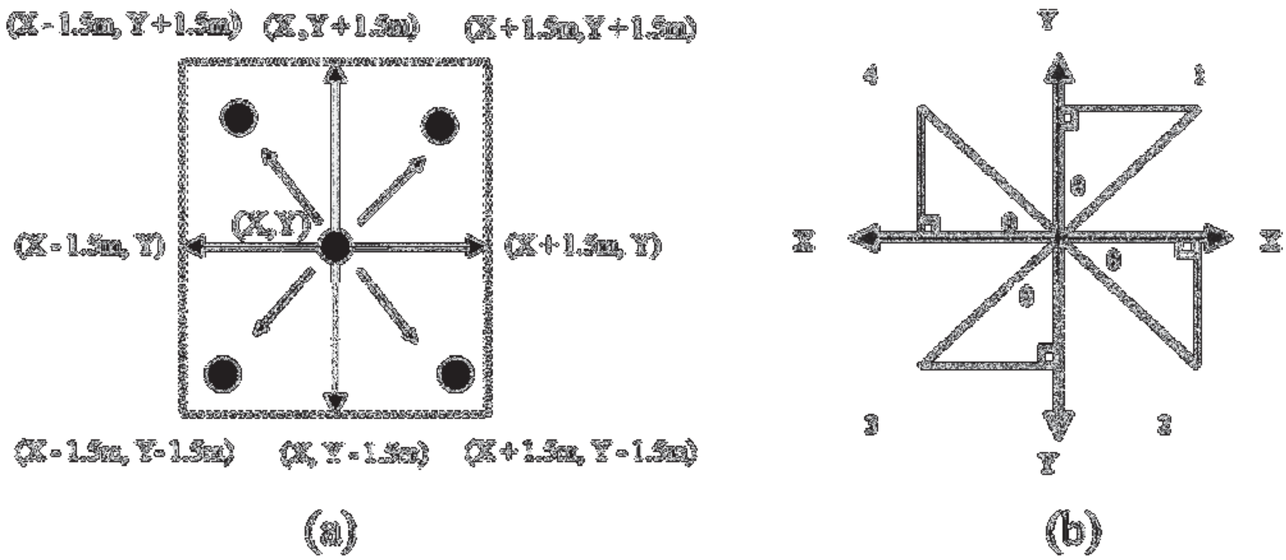


Figure 15 Example of the search methodology to find co-located measurements (a) and the heading structure used to determine of a harvest direction

4.4.6 Use of GPS information for error removal: Obtaining a forward harvest trajectory

Positional information and Pythagoras's theorem was incorporated to identify the true north bearing of sequential harvest records. The establishment of a north bearing provided a consistent 360 degree structure and four specific quadrants to identify and compare the harvester direction of travel (Figure 15b).

To determine the forward motion of the harvester, a three record sequential search filter was established (Figure 16) based on the comparison of the true north bearing of each GPS measurement. For example, the heading between Points 2 and 3 (H2-3) is subtracted from the heading between 1 and 2 (H1-2). The difference is then compared to a user inputted direction threshold (90 degrees) which defines an improbable turning angle within the logging time period. Figure 16a shows that H2-3 fails the criteria and is marked as an error. H2-4 is then compared to the threshold and is processed as a forwards heading. The algorithm also deals with multiple occurrences of GPS error (Figure 16b) with H2-3 and H2-4 being compared and marked as errors before the forwards heading is found H2-5. This is process is run iteratively through the file.

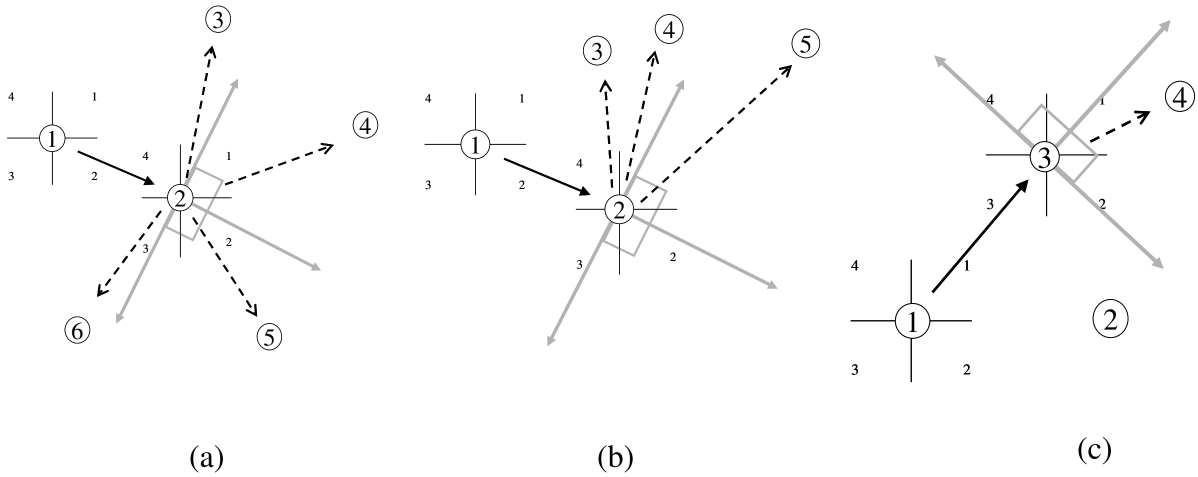


Figure 16 Search methodology to remove erroneous GPS locations, (a) represents the start of the search criteria, (b) represents the comparison between heading values greater than 90 degrees, (c) represents the identification and process of dealing with positional error in the initial recordings of a harvest track

An adjustment was made to handle large distances between measurements caused by GPS error, remnant measurements from previous error removal algorithms and in the establishment of the initial heading of the combine. A user inputted distance threshold (10 metres) was incorporated into the methodology to terminate the search process. For example, Figure 16b shows the selection of H2-5. If the distance between H2-5 was greater than the threshold the algorithm would flag Point 2 as an error. Point 3 is then interrogated as the next point (Figure 16c) and H3-4 is compared to H1-3. However, if the distance between H1-3, now the initial starting heading, is further than the threshold, then Point 1 will be flagged as an error and Point 3 will be selected as the new starting point.

4.4.7 Use of GPS information for measurement overlap: Point in polygon method

Harvester overlaps occur where the yield monitor records measurements over previously harvested areas. This situation produces erroneously low yield estimates (Figure 17).

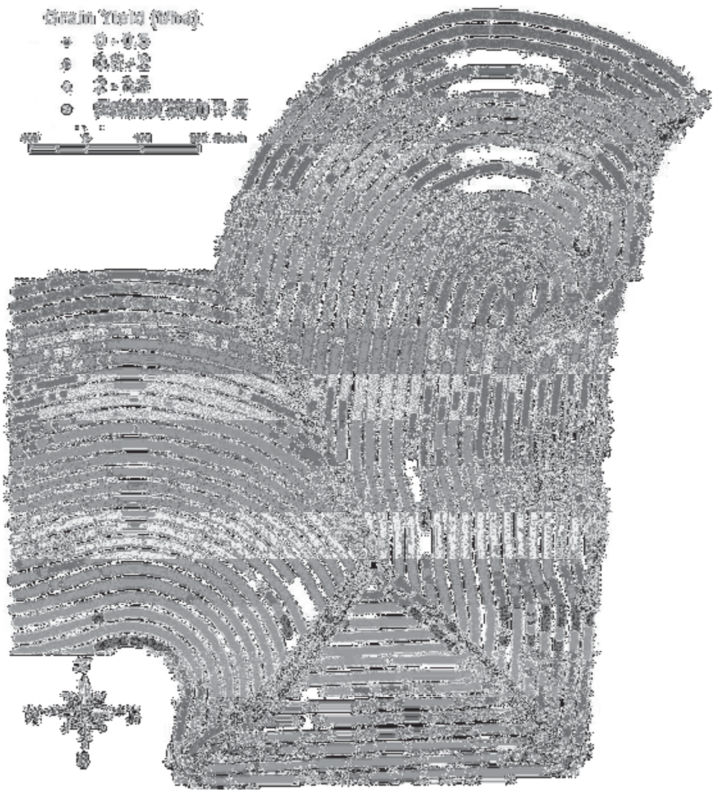


Figure 17 Example of yield measurements recorded in harvester turns and overlaps

The removal of close or co-located records in Step 5 is limited by its search area's spatial orientation as it does not cover the full swath width of the cutter bar and search in the direction of harvester travel. A second search algorithm, point in polygon algorithm (Burrough and McDonnell, 1998), was developed based the sequential position of record within the file (harvest position) and the harvest area (Figure 18 - greyed out area) defined as the cutter bar width and the direction and distance to the next record. In this algorithm it is assumed that the GPS measurement is taken at the centre of the harvester.

The file is searched sequentially with the positional co-ordinates of later records examined to determine if they fall within the harvested area defined by points 2-3 (Figure 18). In the example, points 11 and 12 will be removed. This method was similar to two studies (Beck *et al.*, 2001; Shearer *et al.*, 2005) which developed algorithms within a geographic information system to highlight measurement overlaps, variable harvest widths and narrow finishes.

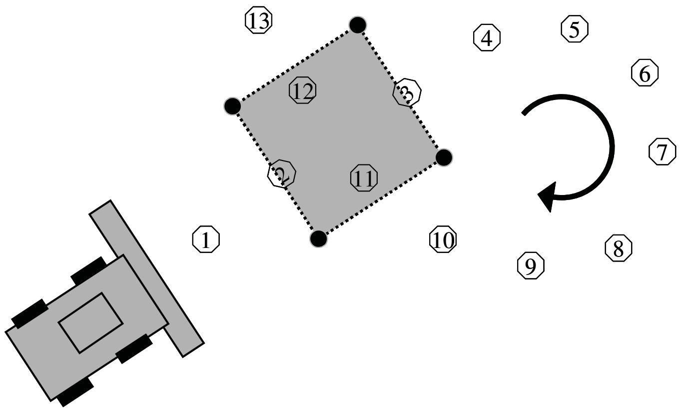


Figure 18 Point in polygon search routine to identify harvest overlaps based on harvester swath width

4.4.8 Removal of harvester turns

Low yield values are generated in harvest turns (Figure 17). These errors occur because the full width of the cutter bar has only been partially used. This is due to the pivoting motion of the combine while harvesting on acute turns. With one exception (Beck *et al.*, 2001), a major limitation in previous research has been the inability to identify harvester turns within the field.

An algorithm was created to detect extreme changes in the true north heading of the harvester, since heading errors have been removed in Step 6. Any change in heading would now reflect harvester turns. The current direction of travel was measured between sequential records and compared with the average direction of both the forward and backward headings derived over a user-defined neighbourhood (4 point occurrences) plus a predefined user threshold (30%).

The start of a turn is identified when the current direction of travel falls outside the average backwards thresholded heading (point 5 in Figure 18). Records are identified as being a part of turn where current harvesting direction fall outside the average of previous and next 4 headings (point 6) or coming out of a turn where the value fails the average forward condition threshold (point 8). As in the speed algorithm, a smoothing filter was then applied to highlight points (point 7), which have satisfied the threshold criteria but is part of the harvester turn. In order to account for the comparisons between the harvester traveling in a true north direction, 360 degrees was subtracted from the true north heading in quadrant 4 to provide the appropriate comparisons. All points identified as being part of a harvester turn were removed.

4.4.9 Yield smoothing filter

To remove random fluctuations in yield estimates along a harvest path, a smoothing algorithm was developed. The routine searched both backwards and forwards over a user–defined neighbourhood (4 points) and calculated the average yield for each direction. The yield estimate for the point under investigation was then compared to a threshold value (40%) with values falling outside this threshold removed.

4.4.10 Removal of start and end harvest measurements

The implementation of the harvest path searches using the forwards-backwards and smoothing routines left singular measurements at the start and end of harvest paths. As they had no neighbouring values due to the error removal process, these point were classified as erroneous and removed.

4.5 Comparison of cleaning methodologies

The aim of post processing error removal methods is to target known harvesting situations that produce erroneous yield measurements so as to create yield maps that are comparable to actual yield variation. This process will reduce the variation of yield around the field mean and produce a yield distribution that resembles statistical normality. This progression to statistical normality offers a way to judge the effectiveness of these routines based on a before and after comparison of descriptive statistics.

4.5.1 Overall effectiveness

An algorithm was coded to derive the average yield, standard deviation, coefficient of variation (CV), skewness and kurtosis for each of the 183 yield files investigated and was applied both before and after post processing. Two other post processing methods were coded for comparative purposes which are often used for yield map cleaning. These were a routine that represented the removal of 0 t/ha values and extreme yield values (> 8 t/ha) (Zero-Max) and a method that removed yield values that fell outside ±3 standard deviations (Std-Dev).

Comparison of each method's effectiveness was demonstrated using two statistical tests, a paired sample t-test and the effect size. These were based on each method's effectiveness to remove yield variation and were measured by the reduction in standard deviation between each cleaning method and the raw dataset. For the effect size, we derived the overall average difference between the resultant standard deviation caused by each removal method and standard deviation of the raw files. For cross comparison, these differences were normailsed by the standard deviation, which in this case is the overall mean standard deviation of each of the raw files' standard deviation in the dataset. This averaged raw files standard deviation represented a population that has not been affected by the processing interventions. The estimated values for the each method's effect size will range from between 0 and 1 indicating a differing effect and therefore error cleaning ability. For example, when a value of 0.2 is calculated, this equates to a small effect, 0.5 a moderate effect and 0.8 a large effect (Cohen, 1988). Confidence intervals (95%) were then applied (Hedges and Olkin, 1985) to determine the margin of error. If the effect size confidence interval includes a zero value then the result is not statistically significant.

4.5.2 Individual routine effectiveness

Each routine's ability to remove yield variation was investigated. Comparison were made between how many records were removed and the subsequent reduction in standard deviation. As the error removal processes are additive, the results of previous algorithms affect the magnitude reduction in later methods.

4.5.3 Validation for local area estimation of yield

Another method to determine the effectiveness of the proposed routines is to visually compare where erroneous data has been removed. Although subjective, it is an effective measure for error identification and has been preferred by many authors (Beck *et al.*, 2001; Simbahan *et al.*, 2004a; Sudduth and Drummond, 2007). This method can be extended to visualize the yield prediction differences between post processed and raw yield datasets that have been interpolated through kriging. While having the ability to visually determine where errors occur, this technique has an additional evaluation criterion because it generates the associated prediction uncertainties and provides a measure of estimation confidence on the predicted values (Whelan *et al.*, 2001). For a local investigation of how effective the proposed algorithms perform, yield data from Figure 17 was used to produce interpolated yield maps for both the raw and post processed datasets. The VESPER program (Minasny *et al.*, 2005) and published specifications for yield map generation (ACPA, 2006) were used. This program provides a kriging standard deviation rather than variance so that the potential error on the predicted estimate can be calculated (Taylor *et al.*, 2007). These visual and spatial comparisons demonstrated the effectiveness of our routines over just interpolating the raw dataset.

4.6 Results

4.6.1 Overall routine effectiveness

To compare the effectiveness of removing yield mapping errors we calculated the effect on the average descriptive statistics of implementing the three error removal methods across 183 files (Table 3). The variation in yield was largest for the raw files with extreme yield values evident by high values of skewness and kurtosis, 2.5 and 204 respectively. All three methods reduced the average yield variation with the proposed algorithms having the highest reduction in standard deviation, 0.16 t/ha (26%) while the coefficient of variation (CV) declined by 36%. The Zero-Max and Std-Dev filters reduced standard deviation by 0.04 t/ha (6%) and 0.06 t/ha (9%) while the CV declined 14% and 12%, respectively. With these routines the average skewness and kurtosis values were also reduced, however, the Zero-Max method still recorded a high kurtosis value across all files.

Implementation of the proposed and the Zero-Max filters increased the average yield (8% and 1.5% respectively). No change in average yield was recorded from the Std-Dev filter.

Table 3 Average descriptive statistics for raw and post processed datasets

Data	Yield (t/ha)	Standard deviation (t/ha)	Variance	Coefficient of Variation (CV)	Skewness	Kurtosis
Raw	1.95	0.65	0.49	0.40	2.5	204
Proposed algorithms	2.11	0.49	0.27	0.25	-0.03	0.8
Zero-max filter	1.98	0.61	0.41	0.34	0.16	7.38
Standard deviation filter	1.95	0.59	0.39	0.35	-0.26	0.6

Application of the proposed algorithms removed over 1 million records or 40% of the total dataset. Across the 183 files, 53% had between 10-40% of their records removed, with 16% having 60-100% removed (Figure 19). The maximum removal of data was 94% for two files that represented cases where the moisture measurements fell outside the set thresholds. Large deletions of records did not occur for the two other methods where 3% (Std-Dev) and 1% (Zero-Max) of records were removed.

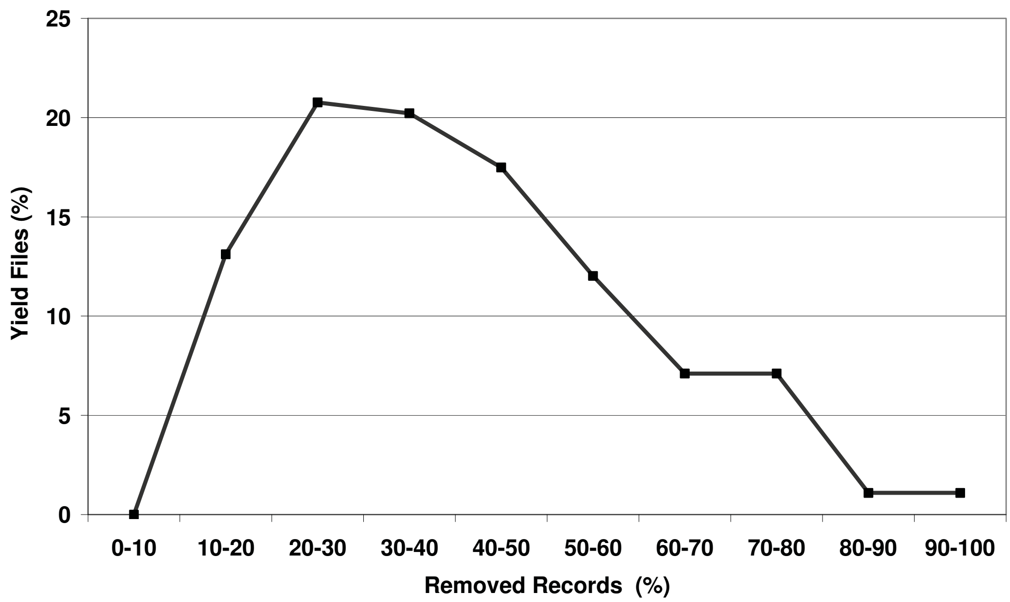


Figure 19 Percentage of total files associated with the percentage reduction in yield records

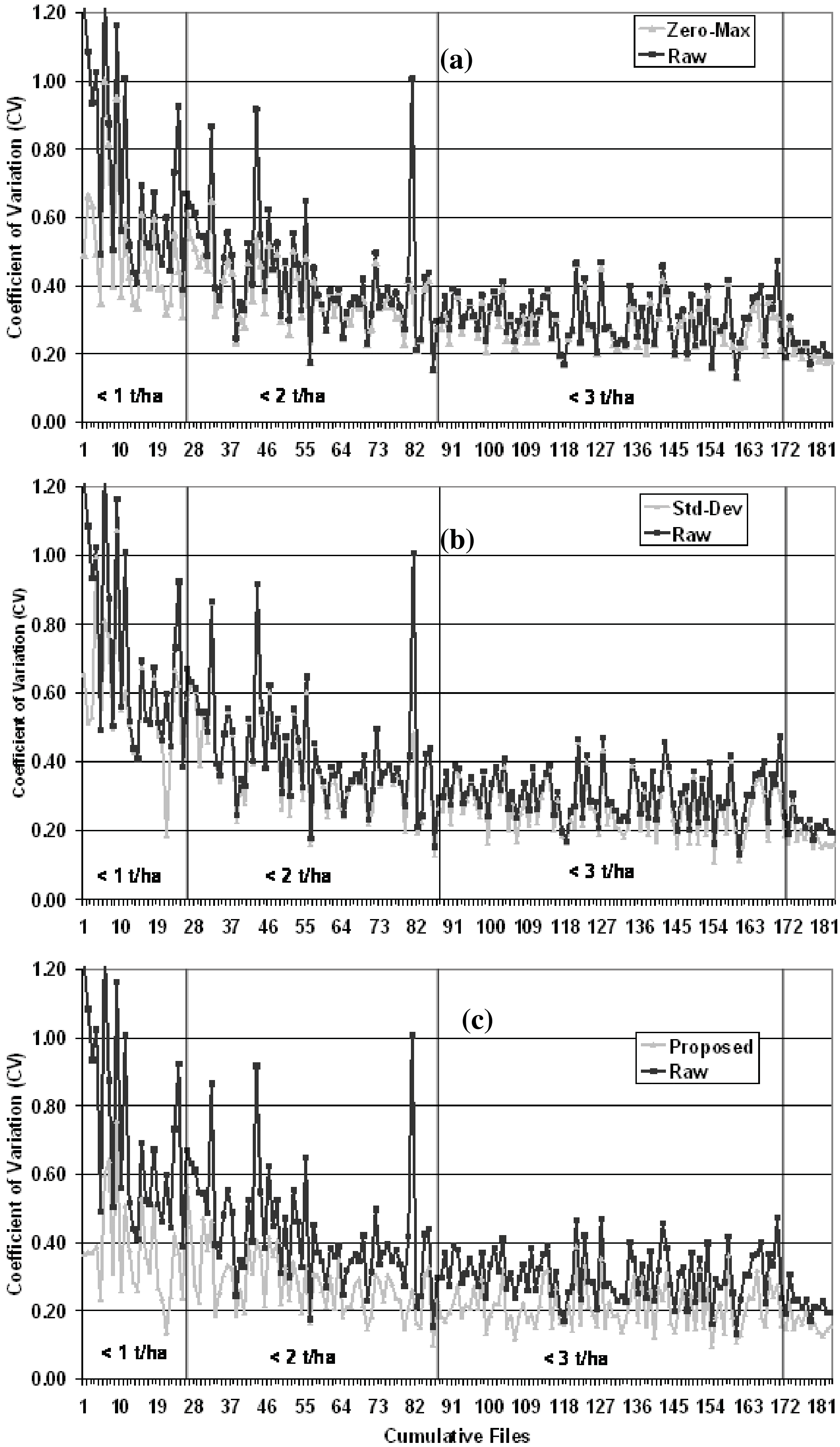


Figure 20 Coefficient of variation values for raw and Zero-Max (a), raw and Std-Dev (b) and raw and proposed (c) post processing routines sorted by average field yield for the 183 datasets

Figure 20 shows the comparison between the coefficient of variation (CV) for the distribution of raw files sorted into ascending order by average field yield and the corresponding reduction in CV caused by the three error removal methods. High CV are apparent for the files where average yield was less than 1 t/ha in the raw dataset. This gradually reduces as average yield increases. Implementation of the Zero-Max filter (Figure 20A) shows the greatest reduction in CV was in the less than 1 t/ha category caused by the removal of significant numbers of 0 t/ha values. The removal of maximum values had less effect on reducing CV values.

As the Std-Dev method depends on the standard deviation of yield and the average yield value, high values of standard deviation and lower yield values within the raw data hamper its effectiveness, evident in the less than 2 t/ha range(Figure 20B). The effectiveness of the method increased as the CV declined caused by the increase in average yield, evident in the greater than 3 t/ha range.

Results for the proposed method (Figure 20C) shows significant reductions in CV caused by the reduction in each files standard deviation and in certain circumstances an increase in average yield. Reductions in CV were evident across the whole yield range.

4.6.2 Overall effectiveness of each routine

Before the paired-sample t-tests were conducted, the distribution of the standard deviation for the raw dataset was tested for violation of normality. Using the Kolmogorov-Smirnov Z statistic the distribution of yield files was found to be normal (results not shown). All three algorithms showed a statistically significant decline in standard deviation indicated by large t scores (Table 4). The comparison between t-scores showed that the proposed methods had a greater statistically significant reduction in standard deviation than the other two filters. The calculation of the effect size and confidence intervals showed that the ability to target specific yield mapping errors through the developed methods had a moderate to large effectiveness (0.78) in the reduction of the standard deviation. This contrasted to smaller effect sizes for the two alternative methods which showed low to moderate performance.

Table 4 T-test and effect size statistic for the post-processing algorithms

Post-Processing Method	t-test	Effect size [Confidence Interval]
Zero-Max	7.37	0.25 [0.05 - 0.46]
Std-Dev	9.63	0.32 [0.12 - 0.53]
Proposed	17.9	0.78 [0.56 - 0.99]

4.6.3 Individual routine effectiveness

As a whole the proposed methods outperformed the other two routines in removing yield variation caused by erroneous measurements. However, the implementation of each routine will have differing effects on error removal. Of particular interest, are the amount of records removed and the reduction in standard deviation caused by each additional cleaning process (Table 5).

Table 5 Total records removed and the cumulative reduction in standard deviation from the proposed post processing methods

Post processing methods	Records removed (%)	Cumulative reduction in standard deviation (t/ha)	Percentage reduction in standard deviation (%)
Start/End Delay and short segment	14	0.043	25
Moisture	7	0.047	3
Yield maximum	<1	0.066	10
Harvester speed	13	0.092	15
Co-location	18	0.094	1
Forward trajectory analysis 1	6	0.098	2
Overlapping harvest path	1	0.107	5
Forward trajectory analysis 2	<1	0.108	0.5
Harvest turn	12	0.117	5
Yield variation	18	0.167	29
Removal of remnant measurements	11	0.176	5

The effectiveness of the first 3 steps of the post processing is reliant on the selection of appropriate threshold values. The start/end delay and short segment filter removed 14% of the data removed by all the cleaning methods and 25% of the total reduction in standard deviation. Around 50% of the files had moisture measurements errors. For 90% of these files, the filter removed less than 10% of the records. A small number of yield maximum (>8 t/ha) errors occurred in 40% of files but their removal contributed 10% to the reduction in standard deviation.

The speed routine contributed to a 15% reduction in the total reduction in standard deviation while removing 13% of all data removed.

The next 2 algorithms identified errors associated GPS error. Co-located measurements occurred in 85% of files, with 11% of these files having 10-50% of data removed. The minor reduction in standard deviation illustrated the removal of similar valued yield estimates. To derive a forward heading of the harvester, the heading algorithm was implemented twice, both before and after the harvest overlap method and removed around 7 % of the total data removed. After implementation, the harvest overlap routine deleted 1% of the total removed data and contributed to a 5% reduction in total reduction of standard deviation.

The location specific algorithm which removed harvester turns removed the amount of data similar to the speed algorithm but had a smaller effect on reducing standard deviation. Of significance was the incorporation of the forward, backward search and smoothing criteria within the algorithm. The application of the routine without their implementation removed 2% of the total data removed but provided only negligible contributions to the reduction in standard deviation (<1 %) over the studies dataset.

The adaptation of the above method to remove yield fluctuations had the greatest contribution to the reduction in total standard deviation while removing 18% of total records removed. Across the files the majority of removal was at either the start or end of a harvest pass indicated by low or high harvest pass number. The routine removed records in all files with 18% of files recording deletions of between 20-70%.

The implementation of the above routines creates outlying singular data points which have been flagged as either the start or end of a harvest path. It was assumed that if neighbouring yield estimates within the harvest path had been removed then these points would also be erroneous. Removal of these points removed 11% of the total records removed and contributed to a 5% reduction in overall standard deviation.

4.6.4 Local area variation: Visual comparison of original and post processed datasets

The use of Geographic Information Systems to overlay the original (grey points) and post processed (black points) datasets (Figure 21) illustrates the effectiveness of the proposed routines to remove yield mapping errors. This method also highlights the limitations of the coded algorithms especially in the setting of user thresholds and search radii. For example, the harvest turn routine did not remove data in turns that were less acute.

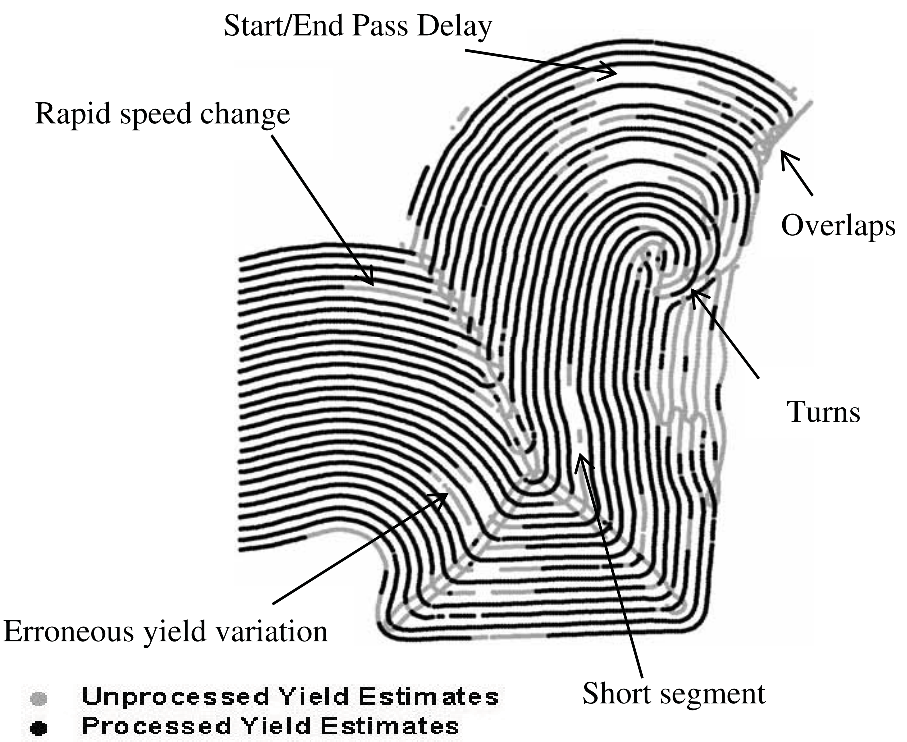


Figure 21 Unprocessed and post processed harvest tracks

The differences between the descriptive statistics for the unprocessed and post processed datasets for Figure 21 show an increase in average yield (11%) while standard deviation and the number of records were reduced by 47% and 20%, respectively (Table 6).

Interpolation of the unprocessed dataset showed a slight increase in average yield while the standard deviation was reduced by 34% when compared to that of the raw dataset. This lack of change in average yield and the large reduction in standard deviation illustrated the smoothing effect that the interpolation technique has on datasets when erroneous measurements are included (Whelan *et al.*, 2001; Robinson and Metternicht, 2005).

Table 6 Descriptive statistics for the unprocessed and processed files and associated interpolated yield maps

Dataset	Observations	Average Yield (t/ha)	Standard Deviation (t/ha)
Unprocessed data	7,497	1.96	0.83
Unprocessed yield map		2.00	0.55
Post processed data	5,854	2.18	0.44
Post processed yield map		2.11	0.44

No change in the standard deviation was recorded for the interpolation derived from the post processed dataset. The comparison between the interpolated datasets showed around a 5% increase in the average yield but a 20% reduction in standard deviation.

4.6.5 Local area variation: Where data was removed along the field's yield distribution

The examination of where data was removed along the field's yield distribution identified inlier yield errors targeted by the post processing algorithms (Figure 22). For Figure 21, 49% of the total data removed was in the 1.5 t/ha or lower range. Of this removal, 58% recorded values of 0.5 t/ha or higher, inside the ±2 standard deviation range of the unprocessed dataset. At the opposite end of the yield spectrum, around 3% of the data was removed in the 3.5-6.5 t/ha range. This occurred mostly in the 3.5-4 t/ha category with all yield records over 4.5 t/ha completely removed. Reductions in these categories ranged from 14%, 16%, 12% and 5% for the 1.5-2, 2-2.5, 2.5-3 and 3-3.5 t/ha classifications respectively.

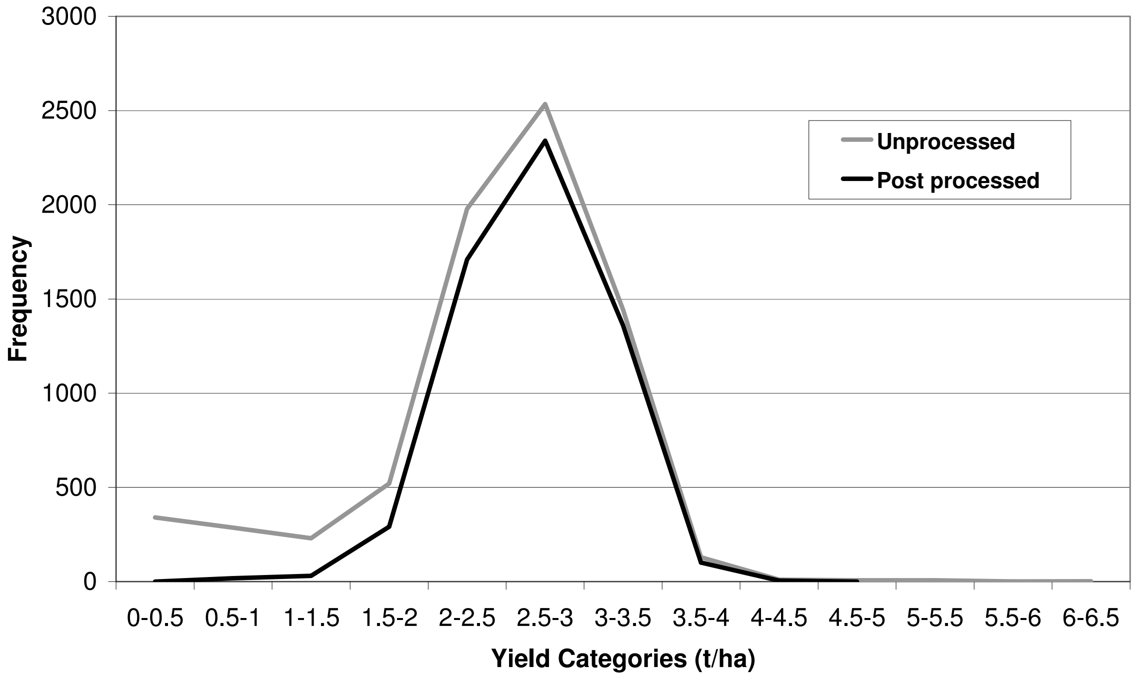


Figure 22 Comparison of histograms from unprocessed and processed datasets

4.6.6 Local area variation: Visual interpretation of interpolated yield maps

Another way to highlight erroneous data is to visually identify artifacts on the yield maps that typify large yield variations. For the unprocessed dataset, two distinctive diagonal patterns and an area with low interpolated yield estimates can be highlighted (Figure 23a). Interpolation of these errors identified as harvester overlaps and turns (Figure 21) create predictions of yield which are underestimated when compared to their neighbouring yield values. Interpolation of the post processed data (Figure 23b) and the spatial comparison of both maps (Figure 23c) show a 64% agreement of yield estimation area (within ±0.05 t/ha category). The interpolation of the unprocessed data caused a 29% underestimation of predicted yield when compared to the post processed yield map with the greatest discrepancies in the highlighted areas of harvest turns and overlap. Over 31% of this yield underestimation was in the 0.5-2.0 t/ha range which demonstrates that when these errors are encountered they have significant influence on the prediction of yield. Spatial comparison also showed areas of yield over prediction (7%) which occurred where short segments, speed variations and pass delay errors caused inflated yield measurements.

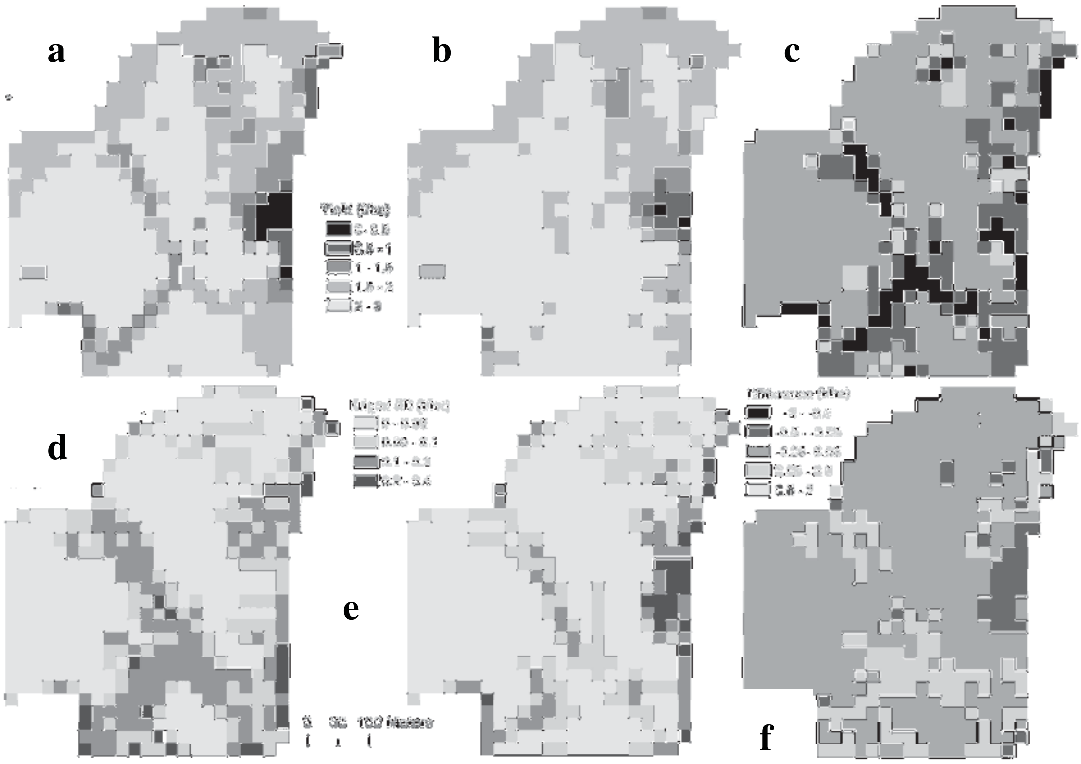


Figure 23 Interpolated yield map for unprocessed (a) and post processed (b) datasets. Map of yield prediction differences (t/ha) between the datasets (c). Maps of kriging prediction error (t/ha) for unprocessed (d) and post processed (e) datasets. Map of differences between kriging prediction error (t/ha) between the datasets (f)

For a field harvested in an uninterrupted process, kriging prediction error should be small (<0.05 t/ha) and this is apparent in the majority area within the interpolated yield maps (Figure 23d and Figure 23e). Interpolation of the raw dataset identifies regions of significant prediction error which occur in areas that have been highlighted as containing measurement error. Applying post processing routines minimises the prediction error in those particular positions although not entirely. One artifact was the creation of a major area of high prediction error associated with data removal and the incorporation of higher yield estimates from neighbouring harvest passes in the interpolation process in this area.

General agreement of prediction error (68%) was shown between the spatial comparison between both maps (Figure 23f). Positive error values indicated a greater amount of prediction variation was present within the neighbouring yield values in the unprocessed data when compared to those of the processed. Around 25% of the field area showed a positive change, between 0.05-0.25 t/ha, indicating a reduction in prediction variation caused by the post processing routines in the areas highlighted as containing yield monitoring errors. Alternatively, negative values indicated a greater amount of variation is present within the post processed dataset when compared to the unprocessed. This equated to around 8% of the field area with a maximum prediction error of 0.3 t/ha.

4.7 Discussion

This study proposed the implementation of post processing algorithms based on the inclusion and adaptation of previously published methods. We have furthered these methods by emphasising the use of location information, harvest track search filters and thresholds, to highlight and remove erroneous data caused by abrupt harvest velocity changes, harvester turns and overlaps, and rapid yield changes.

Application of two out of three post processing routines showed the mean yield for the 183 randomly selected files was higher than what was shown for the raw datasets (Table 3). This post processing result of reducing average yield was similar to other studies (Beck *et al.*, 2001; Simbahan *et al.*, 2004a; Ping and Dobermann, 2005; Shearer *et al.*, 2005; Sudduth and Drummond, 2007). Further investigation into the effectiveness of the three post processing routines showed that the two statistical threshold algorithms reduced standard deviation of the datasets by 8% to 12%. While the studies proposed targeted algorithms reduced the standard deviation by 26%. The reduction in these descriptive statistics clearly demonstrates the need for and value of applying a cleaning procedure to raw yield datasets (Sudduth and Drummond, 2007).

All three methods were statistically significant in the reduction in standard deviation, however, the targeted algorithms out performed the other two filters focussing on identifying inlier and outlying errors rather than just identifying outlying values. The proposed algorithms removed data across a range of field average yield and removed the majority of error within ±2 standard deviations. For the two other methods, their effectiveness was limited by the distribution of actual yield estimates. While all methods produced a reduction in standard deviation, a decrease in the standard deviation is an expected effect when filtering data of any kind and does not necessarily prove the removal of errors (Noack *et al.*, 2003). However, the authors feel that a targeted approach has a higher probability of removing erroneous data than one that just relies on user input or statistical thresholds and has the added benefit of being automated.

As the proposed sequence of error removal algorithms are applied one after another, it is hard to determine the best performing, however, some important points can be derived. Results from the fill and finish mode errors were comparative to other studies (Ping and Dobermann, 2003; Simbahan *et al.*, 2004a). However, some uncertainty about the correct time delay value to use is still apparent. This was highlighted by the yield variation filter where the majority of data removed were either at the start or end of a harvest pass. While this indicated that the delays may have been set too low, the presence of the filter provides some assurance of removing these errors when delays are underestimated.

The identification of errors associated with rapid change of harvester velocity, overlapping of harvest areas and harvest turns represented 26% of total records removed and 25% reduction in standard deviation. These routines may be more suited to the Australian grain growing regions where the majority of fields are large (> 100 hectares) and are harvested in a 'round and round' harvesting pattern rather than the 'up and back' method. This is illustrated by previous studies where the majority of error removal is at the field boundaries representing start and end pass delay errors with fewer removals within the remainder of the field (Simbahan *et al.*, 2004a; Sudduth and Drummond, 2007). With the increased adoption of RTK GPS guidance and the up and back harvesting strategy, these problems may apply more to historical data than those recorded in the future.

Of particular concern is the accuracy of commercial agricultural GPS guidance with 25% of the data removed due to what we considered as GPS error. These represented logged co-located measurements (18%) and records that did not align with the current travel trajectory of the combine harvester (6%). Once again, the adoption of RTK guidance will reduce this error but further analysis will be undertaken to determine if these large initial errors are a function of low harvest speed (< 1.5 m/sec) rather than GPS accuracy error.

A concern of the post processing routines is the magnitude of records removed as large reductions will effect yield map interpolation. Our routines on average removed around 40% of the data, much more than the other two methods investigated. These reductions were higher than results from other studies which have ranged from 0.4-50% (Shearer *et al.*, 1997; Beck *et al.*, 2001 Blackmore and Moore, 1999 Thylen *et al.*, 2000 Simbahan *et al.*, 2004a; Ping and Dobermann, 2005; Drummond and Sudduth, 2005a). The large number of records removed is somewhat expected given the 10 steps of error removal. Only one other study (Sudduth and Drummond, 2007) has had more steps (13) with 13-27% of data removed. The majority of error removal within these proposed methods relies on setting thresholds and search radii, further sensitivity analysis should be carried out to determine the optimal settings to reduce this concern.

The use of interpolation techniques has been seen as a way to reduce or "smooth over" the effect of erroneous yield data. For the data presented in this paper, we showed yield variability for the interpolated unprocessed data was 20% greater and average yield 5% less than the values of the interpolated post processed dataset. We demonstrated an under prediction of yield occurred in specific areas where measurement error occurred. This will have negative repercussions on any site specific management actions taking place in these areas. Given that the example field was harvested fairly consistently, a 68% agreement between both unprocessed and processed yield maps. Other fields with less consistent harvesting regimes will pose greater problems for site specific management. We have also demonstrated that improvements in prediction accuracy will not always be seen, due mainly to the sometimes large removal of erroneous measurements. This has also been shown by other studies (Thylen *et al.*, 2000; Robinson and Metternicht, 2005). Nevertheless, the uncertainty in the estimation of yield caused by removal of erroneous data will be smaller than if no error removal was implemented.

Several studies have focused on a small number of fields for a case study approach to justify the removal of errors (Beck *et al.*, 2001; Dobermann and Ping, 2004; Ping and Dobermann, 2005). As these methods will have differing degrees of effectiveness on each file, this study has focused its analysis on a 183 independent fields across 4 farms using 4 different yield mapping systems. This large and diverse dataset provides additional evidence to suggest that post processing is needed in yield map analysis and to understand the overall effectiveness of post processing error removal algorithms.

4.8 Conclusion

Extensive yield variation is apparent in raw yield mapping files. This variation is predominately of a mixture of natural and management induced variation and to a lesser extent, yield variation caused by measurement error. Removal or minimization of this erroneous variation is required to allow more informed management decisions. This study proposed the implementation of post processing algorithms based on the inclusion and adaptation of previously published methods. We have furthered this literature by emphasising the use of location information, harvest track search filters and thresholds to identify erroneous data caused by abrupt harvest velocity changes, harvester turns and overlaps, and rapid yield changes. These targeted methods were tested for overall and individual algorithm effectiveness on a total of 183 random selected files.

Local area verification of error removal through the spatial comparisons of harvest paths and interpolated yield map values from both raw and post processed datasets illustrated another way to evaluate the overall effectiveness of the proposed algorithms. This type of post processing is a more intuitive approach for error removal because it focuses on differentiating yield variation caused by erroneous yield data from the natural yield variation. Further research is needed to determine the optimal setting of thresholds and search radii to minimize the removal of valid data.

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4.10 References

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