Economic modelling of controlled traffic for vegetable production

JE McPhee [1], JR Maynard [2], PL Aird [3], HH Pedersen [4] and JN Tullberg [5]

[1] Tasmanian Institute of Agriculture, University of Tasmania, Burnie, Tasmania, Australia

[2] Macquarie Franklin, 112 Wright St, East Devonport, Tasmania, Australia. Current address: Cliff Top Consulting, Blackmans Bay, Tasmania, Australia

[3] Serve-Ag Pty Ltd, PO Box 690, Devonport, Tasmania, Australia

[4] Aarhus University, Department of Engineering, Aarhus, Denmark

[5] CTF Solutions, 8 Hakea Crescent, Chapel Hill, Queensland, Australia

Correspondence - john.mcphee@utas.edu.au

Abstract

Although controlled traffic farming (CTF) has been shown to provide production, environmental and economic benefits in a number of cropping industries, uptake in vegetable production is limited. In many situations adoption is constrained by the lack of harvest equipment suited to CTF. Research shows there are important soil benefits, and potential yield improvements, to be gained from CTF in vegetable production. With little on-ground experience to provide economic data, a model was developed to determine the difference in returns between three different vegetable farming systems. Returns were calculated as income minus operating and ownership costs (including interest and depreciation). Case study farms were used as data sources, and despite using very conservative estimates of the production and management changes likely to occur under CTF, modelling indicated median increases in average returns of up to 29%. These results were obtained even when the costs of meeting harvest integration were taken into account, indicating that the benefits of controlled traffic in vegetable production should adequately cover the costs of transition.

Keywords: controlled traffic, economic modelling, vegetables, farm return, probability distribution

Introduction

Controlled traffic farming (CTF) keeps all machinery traffic associated with cropping operations in the same wheel tracks year after year. This improves soil health and crop productivity by eliminating compaction from the crop growth zone, and increases the window of opportunity for crop operations, in part due to improved trafficability on permanent compacted wheel lanes (Dickson *et al.* 1992; McPhee *et al.* 1995; Stirling 2008).

Although adoption of CTF has occurred in the Australian grain and sugar cane industries (Garside *et al.* 2004; Tullberg *et al.* 2007), uptake in the vegetable industry is limited, apart from some specific instances which feature simple crop rotations and rely on either hand harvest or a limited suite of mechanical harvesters. The Tasmanian vegetable industry faces some particular challenges in adoption of controlled traffic, because of diverse cropping rotations, with consequent diversity of harvest machinery, a range of machinery ownership arrangements (private, contractor and company) and undulating topography in some parts (McPhee and Aird 2013; McPhee *et al.* 2013). While advantages for soil management in the vegetable industry have been demonstrated in controlled traffic research (McPhee *et al.* 2015), it is important to better understand the economic costs and benefits associated with this alternative farming system.

The commercial uptake of CTF in the Australian grain industry has been largely grower-driven, and there is little peer-reviewed economics research. After machinery changes have been made to accommodate CTF, there is little opportunity to compare, side by side on the same farm, the performance of CTF and non-CTF systems. CTF provides system benefits, such as improved timeliness and more cropping opportunities, which further complicate side-by-side comparisons that might depend on both sowing and harvesting crops at the same time in both treatments (Tullberg 2010). Consequently, economic analyses of conversion to CTF are rare, generally performed after the event, and limited by the quality of historical data. Nevertheless, modeling and case study economic analyses provide evidence that CTF improves productivity and profitability (Bright and Murray 1990; Chamen and Audsley 1993; Bowman 2008; Halpin *et al.* 2008; Kingwell and Fuchsbichler 2011; Jensen *et al.* 2012).

A study in Australian grain production showed that conversion to CTF would produce internal rates of return (IRR) ranging from 13.5% to 18.9%, based on variables such as savings/ha and discount rate (Bright and Murray 1990). Modelling of UK grain cropping systems with conventional and zero-traffic management approaches relied predominantly on yield increases to maintain or improve profitability (Chamen and Audsley 1993). It was estimated that unpowered tillage equipment used in controlled traffic could be lighter, and 35% cheaper, than conventional system equivalents, due to lower draft arising from better soil conditions.

While not an economics study as such, a 17% increase in the marketable yield of potatoes was reported in Scottish controlled traffic research (Dickson, Campbell et al. 1992). Under conventional traffic systems, 30% more clods were recovered at harvest, which impacts harvest efficiency, and post-harvest tillage required 70% greater draft force, adding cost to the conventional production system. Although average gross margins for potatoes favoured controlled traffic, seasonal variability was greater than the differences between traffic management systems, so the results were not significant (Stewart *et al.* 1997; Stewart *et al.* 1998). Other crops in the rotation showed significant improvements under controlled traffic, with gross margins being higher than conventional traffic systems for spring barley (23%), winter barley (35%) and oil seed rape (42%).

Significant reductions were recorded for total and peak tillage power requirements for irrigated grain crops under CTF in a tropical environment (McPhee *et al.* 1995). When applied to machinery investment decisions, these results indicated the potential of a 69% reduction in capital cost (smaller tractors), a 71% reduction in operating costs, and a 73% reduction in total costs. Benefits of the system included improved timeliness, allowing more frequent and reliable crop production, further enhancing the economies of the system.

Analysis of a Queensland grain cropping group showed increased cropping frequency and yield, and improved grain prices (due to greater yield reliability in dry years when prices are higher) had the potential to improve gross income by 44% (Bowman 2008). Using historical data, analysis showed a 17% return on capital for individual members of the group. The combined benefits of the CTF system had the potential to almost double business profit for group members. A modelling study of a Western Australian grain farm showed that CTF could increase farm profitability by 50%, even when using quite conservative estimates of yield, quality and input changes (Kingwell and Fuchsbichler 2011). Sensitivity analyses showed the major contributor to increased profit was increased yield.

Trials on the Chinese Loess Plateau showed a projected profit increase of 28% for wheat grown using controlled traffic and zero-till, compared to conventional random traffic and full tillage practices (Bai *et al.* 2009). The change in profit was due to a 6.9% increase in yield, and a 44% reduction in the cost of field operations, which was partly offset by a 20% increase in herbicide costs.

The Sugar Yield Decline Joint Venture (SYJVD) program (1993-2006) (Garside, Watters et al. 2004) investigated a combination of controlled traffic, legume break crops and reduced and zonal tillage practices to develop a more sustainable cane growing system. Application of these principles in one commercial enterprise reduced land preparation and planting operations, resulting in 54% less tractor use, contributing to a change in return on investment from 1.6% to 2.7% (Carr *et al.* 2008).

The controlled traffic economics literature is largely focused on the grain and cane industries, with very little reported from the vegetable industry. Given the current level of incompatibility in vegetable machinery configurations (McPhee and Aird 2013), early adopters in the vegetable industry are more likely to start with seasonal CTF (SCTF). In SCTF, the difficulty of integrating harvesters into the system is accepted, while all other operations are conducted on permanently located wheel tracks (Vermeulen *et al.* 2007). Tillage immediately post-harvest is more likely to represent conventional practice.

In the absence of economic case studies in the vegetable industry, modelling can provide useful insights into the economic changes that might occur with the implementation of controlled traffic. A model was developed to provide estimates of the economic benefit of adopting seasonal controlled traffic and fully controlled traffic in the Tasmanian vegetable industry.

While modelling allows investigation of a number of "what if" scenarios, the adoption of a fully integrated CTF system is challenging in the Tasmanian vegetable industry due to equipment incompatibilities, primarily between harvesters, few of which lend themselves to easy modification (McPhee and Aird 2013). Recent developments in wide-span (WS) technology point to new forms of mechanisation which would make CTF possible for vegetable production (Pedersen *et al.* 2013).

Economic model development

Background

Gross margin models are well developed for the vegetable industry in Tasmania, and these provided the basis for the model. A gross margin is defined as the gross income from an enterprise minus the variable costs incurred in producing it. Variable costs are directly attributable to an enterprise and vary in proportion to the size of an enterprise – e.g. if the area of crop doubles, then the variable costs associated with growing it, such as seed, chemicals and fertilisers, will double. A gross margin is not profit, because it does not include fixed or overhead costs such as depreciation, interest payments, rates and permanent labour, which have to be met regardless of enterprise size.

The model was developed in Microsoft Excel® and used ModelRisk® Version 4 (Vose Software) risk analysis software to allow a number of inputs (e.g. yield, cost of modifications etc.) to be varied over a range of expected values to provide a distribution of likely outputs. The model allowed selection of different inputs and crop rotations for different management systems.

Capacity was provided to incorporate changes likely to occur with a change from conventional farming to SCTF and CTF, such as different cropping rotations and machinery suites. Given the lack of experience with CTF in mixed farming vegetable production, there is inevitably a degree of speculation about how some practices might change with the uptake of controlled traffic. In all cases, conservative estimates were used based on published literature, concurrent vegetable industry research, the knowledge of case study growers and advisors, and reports from other industries and countries.

Systems modelled

Three farming systems were modelled:

- Conventional (Conv) – this system was based on current grower management and rotations, with all variables selected to represent standard practice for the farming operation in question.
- Seasonal Controlled Traffic Farming (SCTF) – increased costs were allowed for modification of machinery, excluding harvesters, to achieve common track and working width. Extra investment in Global Navigation Satellite System (GNSS) guidance was also included, while small savings in some inputs and small increases in yield were also allowed.
- Controlled Traffic Farming (CTF) – in addition to machinery modification and GNSS guidance costs, extra costs were allowed for harvest to accommodate loss of field efficiency imposed by controlled traffic constraints (Bochtis *et al.* 2010). Larger input savings and yield gains were also included.

Machinery

Decisions regarding machinery inventories can lead to significant differences in capital investment between farming systems. The major differences expected between the three systems used in the model were:

- Purchase of GNSS guidance for SCTF and CTF
- Reduced tractor and implement inventory for CTF on account of reduced tillage needs
- The exclusion of some equipment options (e.g. mouldboard plough) from the CTF system, due to incompatibility with maintaining permanent wheel tracks
- A % surcharge on the capital cost of implements used in SCTF and CTF to account for the cost of modifications to achieve track gauge and working width integration
- A % surcharge on the cost of harvest in CTF to account for likely negative impacts on field efficiency as a result of machinery movement constraints imposed by controlled traffic. The surcharge was added to contract harvest prices to reflect increased operating costs, and to cover the costs associated with modifications to harvesters, or the replacement of current technology with more CTF compatible machines.

The model provided options to accommodate operations performed by contractors or grower-owned machinery, with the associated operating and overhead costs.

Rotations

Rotations of up to 15 crop sequences were constructed, including periods of fallow or green manure crops. Dates representing the beginning and end of the cropping season were entered to check that rotations were realistic, and to ensure rotations used to model different farming systems on the same farm were approximately the same duration. Different rotations were used for alternative farm enterprise scenarios and different locations. The rotation could also be tailored to capitalise on the timeliness or soil benefits of controlled traffic, while retaining the original rotation for the conventional and SCTF systems. This made it possible to reflect system benefits that may be possible with CTF, such as earlier planting, which would not be recommended or possible under conventional cropping situations. Although the rotations were constructed over time, the economic analysis was done on the basis of returns for one year of the rotation.

Input variables

Variables used in the model related to factors which might change as a result of changing the farming system (i.e. Conv to SCTF or CTF), as well as external factors, such as interest rates, depreciation rate and insurance. Some variables, such as those with reasonably standard estimates (e.g. depreciation rate), were held constant for any given model simulation. Others, such as yield change due to the farming system used, were given a distribution profile, and were automatically adjusted over a predetermined range as part of the risk analysis modelling process (see below regarding use of ModelRisk®). Associated effects, such as the impact of a higher yield on harvest costs, were also incorporated. A summary of variables, and how they were adjusted, is given in Table 1.

Use of ModelRisk®

ModelRisk® (Vose Software) provided the capacity to perform Monte Carlo simulations within the Microsoft Excel® model, allowing the impact of changes in a large number of variables to be rapidly simulated many thousands of times. The following description outlines how these variables were used in the model.

For each variable, a range was allocated representing the expected minimum, maximum and most likely figure for the conventional cropping system. The variation was given a ModelRisk® distribution profile (e.g. PERT distributions were used, based around the minimum, maximum and most likely values of the variable). When a simulation was run, ModelRiskR® randomly selected values for each variable between the minimum and maximum to fit the chosen distribution. In a simulation run, variables changed 10,000 times over their likely ranges to generate a range of possible results.

How inputs were varied differed between the Conv, SCTF and CTF systems. Using crop yield as an example, the range of, and most likely, conventional yields were based on local knowledge and experience – e.g. 45-80 t/ha (with a most likely yield of 55 t/ha) for potatoes, 8-18 t/ha (most likely yield of 12 t/ha) for green beans, and similarly for other crops. The yield in the SCTF and CTF parts of the model was adjusted by a predicted % change, as outlined in Table 1. For example, a yield improvement of 0-5% (most likely 2%) might be appropriate for SCTF, while for CTF the range might be 0-20% (most likely 10%). When a simulation was run, the conventional yield varied over the specified range according to its distribution profile, and each value generated for the Conventional system was changed by the % increase for the relevant farming system (e.g. 0-20% (most likely 10%) for the CTF system). In this way, both seasonal variations in conventional yield, and changes due to different farming systems, were accommodated in the output.

Outputs

ModelRisk® allowed a number of outputs to be selected which could be used to generate:

- ascending probability distribution curves, showing the range of results arising due to variation of inputs, and
- tornado plots, which illustrated the sensitivity of the result to the impact of various inputs.

The key factor of interest in this work was the difference in returns between different farming systems. This is described as the Average Annual Farm Return, and was calculated as income minus operating and ownership costs, inclusive of interest and depreciation. While the impact of system changes could be shown for each individual crop gross margin, three key whole of farm outputs were chosen to illustrate the differences between farming systems:

- Average Annual Farm Return – the average of all returns for the selection of crops in the rotation. If extra crops were grown in the rotation under CTF, the length of the rotation for all farming systems was kept approximately the same to ensure comparisons were made over similar durations of time.
- % change in Average Annual Farm Return for SCTF and CTF, compared to Conv.
- Average Net Farm Return – defined as the [Total Return – (depreciation + insurance)]/Total machinery cost. Machinery cost was the total investment in mobile plant and equipment (i.e. tractors, implements etc.) The machinery cost of interest was that which may change as a result of changing farming systems. For example, adoption of controlled traffic generally reduces investment in tractors and implements, although it may require additional investment in modifications.

Modelling of various scenarios

Modelling scenarios were developed in conjunction with the operators of a number of vegetable production enterprises. Selection of machinery, crop rotation and irrigation details for the Conv system were the choice of the individual grower based on their own experiences. Changes that might arise with the adoption of SCTF or CTF were discussed and appropriate selections made. In three out of four cases, the same tractor suite and crop rotation were selected by growers for the case study farms for Conv, SCTF and CTF systems, even though there is good evidence that tractor size can decrease, and cropping opportunities increase, with the change in management associated with CTF adoption. This reflects the limited experience with commercial adoption of controlled traffic in vegetable production, so despite evidence from other industries, the growers involved in the case studies had little or no evidence within their own experience of the potential for reducing tractor power requirements.

A number of Tasmanian vegetable farm scenarios were chosen for modelling. Four have been chosen for reporting to illustrate the range of results obtained. The characteristics of the four farms were:

- North-west (NW) coast mixed cropping farm growing mainly vegetables. The owner was aware of the potential soil and timeliness benefits arising from controlled traffic, and predicted the cropping rotation could be adjusted as a result.
- Northern midlands vegetable farm engaged in summer cropping only.
- NW coast mixed farm for which the main crop was processing potatoes.
- NW coast mixed farm with only two vegetables in the rotation, and significant existing uptake of reduced tillage for non-vegetable crops.

Presentation of model outputs

Ascending probability curves were produced to illustrate the probability of changes in Average Annual Farm Return over the rotation, percentage change in return, and Average Net Farm Return between the different farming systems. Sensitivity analyses were conducted to identify the factors that were most important in determining the outcomes for each parameter. Results of the sensitivity analyses are presented as tornado plots, which show the relative importance of input variables on the output. If the input x-axis value is negative, the output decreases as the input value increases. A value of 0 indicates no influence of the input on the output, while a positive value indicates the output increases as the input increases. Therefore, it would be expected that inputs which represent a cost factor (e.g. machinery modification costs) would register negative values, while those representing an income factor (e.g. crop yield) would register positive values. For ease of comparison between cropping systems and case studies, the tornado plots have been normalised so the most significant input is either -1 or +1, depending on its influence on the output. In each case, the five most influential factors are shown in the tornado plots for each parameter and case study.

Results and Discussion

The results for case study 1 are presented in both graphical and tabulated form in order to demonstrate the presentation and interpretation of data. Results for other case studies are summarised in tabulated form.

Farm details

Rotational details of the case study farms are given in Table 2. Details on area and differences in machinery for the three different farming systems modelled on each of the four case study farms are given in Table 3. None of the growers elected to change the rotation of crops for the different farming systems modelled. However, for case study 1, based on personal observations of the soil impacts of controlled traffic, the grower predicted that improved soil conditions under CTF would allow for a greater area of carrot production. The area grown in the conventional rotation was quite small compared to other crops, and a lengthy restitution time was allowed in the rotation, due to current carrot harvest operations being very damaging to the soil. It was considered that implementation of CTF would overcome these limitations, allowing carrots to be grown over an increased area, or more often. The option chosen in this modelling was to grow a larger area.

It can be seen from Table 3 that there are not large differences in the machinery suites chosen for the three different farming systems, regardless of the case study. This reflects that a lack of relevant first-hand experience made it difficult for most growers to contemplate the potential to reduce equipment investment. Reduced tractor power requirements are often promoted as a benefit of CTF through lower draft (Dickson, Campbell et al. 1992; Tullberg 2000) and the need for fewer tillage operations (McPhee, Aird et al. 2015). However, in vegetable farming, three-point linkage lift capacity is often a significant determinant of tractor size, and therefore most growers were reluctant to consider smaller tractors while still seeing a need for powered implements.

Probability curves

Figure 1(a-c) shows the ascending probability curves for these parameters for the three different farming systems evaluated in case study 1. The dotted lines indicate the median (50% probability) values on each graph. Key values (5%, 50% and 95% probability) for each of the graphed parameters are summarised in Table 4, covering all four case studies.

Figure 1(b) shows the ascending probability curves for change in Average Annual Farm Return for the SCTF and CTF systems, compared to the Conv system. The median increase was 8% for SCTF and 29% for CTF. There was a large spread of possible values, particularly for the CTF system.

Figure 1(c) shows the ascending probability curves for Average Net Farm Return for the SCTF and CTF systems, compared to the Conv system. The median increase in Average Net Farm Return was 0.7% for SCTF and 9.5% for CTF.

Important points to note in relation to the probability curves for case study 1 are that while the median Conv Average Annual Farm Return was $2,252/ha, the same value for SCTF was reached at 0.31 probability, while for CTF it occurred at 0.04 probability. Therefore, 69% of the SCTF, and 96% of the CTF, modelling results were greater than the Conv median. This indicates that not only was the median Average Annual Farm Return higher under a SCTF or CTF system, but the probability of achieving that result was greatly increased.

Sensitivity analysis

Tornado plots illustrate which inputs have the greatest impact on the outputs. Impacts arising from changes in variables can be positive (increase income or reduce cost) or negative (increase cost), as shown in Fig 2(a-d). Positive impacts are shown as solid black bars, while negative ones are shown as grey bars. Data for Fig 2(a-d) have been normalised such that the factor with the greatest influence has a value of either -1 or +1. This does not mean that the value is comparable between graphs, but shows the relativity between factors within a graph.

A summary of the tornado plot data (Table 5(a-d)) for all case study farms shows that projected yield and quality improvements arising from the implementation of SCTF or CTF were by far the most common positive influences on the Average Net Farm Return. The most common negative influences were the cost of machinery modifications and changes to the harvest cost of root crops as a result of accommodating the more restrictive traffic patterns of CTF. Positive influences are shown in standard font, and negative influences in italics, in Table 5(a-d)).

Key findings

Capital investment: A number of important factors are highlighted by the results of the modelling. In all but case study 4, the capital investment in tractors and machinery decreased for CTF compared to Conv, largely as a result of the expectation that fewer tillage implements would be required. Case study 4 represented a farm which had already achieved a significant reduction in machinery inventory as a result of adopting reduced tillage techniques for a number of crops. This farm also grew fewer vegetables in the rotation, so there was already a lower investment in tillage equipment. Based on experiences in other industries, it is expected that tractor inventories would decrease with the adoption of CTF. However, with a lack of experience in CTF amongst the case study growers, they were generally not prepared to predict a reduction in tractor power or number.

In all case studies, the capital investment increased with the adoption of SCTF. This was brought about by two factors – (i) the need for GNSS guidance for SCTF, which was not a requirement for the Conv system, although it is being increasingly used by growers irrespective of decisions about SCTF or CTF, and (ii) modification costs to tillage equipment to provide dimensional compatibility.

Farm returns*:* In all but case study 2, the Average Net Farm Return increased for both SCTF and CTF compared to the Conv system. Because the benefits of SCTF have been judged to be considerably less than for CTF, the extra investment in machinery and technology required for SCTF was not significantly offset by the benefits of the change, leading to only very small increases in Average Net Farm Return, or a decrease in case study 2, compared to the Conv system.

Most important factors: Given the general lack of experience with SCTF and CTF in the vegetable industry, the modelling of these systems has relied heavily on a range of assumptions deduced from other data and experiences. The tornado plots provide guidance on which factors are likely to be most important in determining the economic performance of each system, and therefore provide guidance for future research and data collection to improve the reliability and accuracy of similar modelling. Across all case study farms, projected crop yield and quality was the most common positive influence on the two measures of farm returns, while harvest costs (for CTF) and modification costs (for SCTF and CTF) were the most common negative influences. This indicates that more evidence to support the expectation of yield and quality improvements is required in order to improve the predictions of similar modelling. Further, attention should be given to the cost of machinery modifications and the impacts on harvest logistics in order to reduce the costs of changing to CTF.

Conclusion

The results presented were generated using a range of data and assumptions drawn from the limited application of CTF in the Tasmanian vegetable industry, and more extensive use of CTF, and thus more extensive data, from other industries. Despite the absence of data from converted systems, the use of grower's information from specific farms, rather than a generic "representative" farm, and deliberate conservatism in the estimates and assumptions, gives a greater level of confidence in the modelling results.

Experience in other industries (e.g. grain) suggests that system effects, such as timeliness, are likely to provide greater economic benefit than the individual components of fuel saving or lower capital investment. However, given the lack of experience with CTF in the vegetable industry, it was difficult to incorporate assumptions about those factors, and so it is likely that the overall economic benefits of the system have been under-estimated.

Notwithstanding the limited data available, it is apparent there is potential for economic benefits from adoption of CTF. Further, the probability of achieving those benefits is quite high, particularly if crop yield increases, a result which has been observed in most CTF adoption situations. The economic benefits may also be increased if CTF allows changes to the rotation which allow higher value crops to be grown more often. It will clearly be of value to do retrospective economic analyses when more information is available from case studies of adoption of controlled traffic in the vegetable industry.

While the potential economic benefits of controlled traffic are substantial, these have not yet been attained in commercial practice due to equipment integration issues (McPhee and Aird 2013). Not only does a diversity of vegetable crops lead to a range of mis-matched equipment, the situation is further complicated because many growers, particularly in Tasmania, also grow crops that are broadacre in nature, such as poppies, pyrethrum and cereals. The diverse equipment mix presents a significant challenge to the integration of working widths and track widths. This is one of the key issues facing the adoption of CTF in vegetable production.

Acknowledgements

Funding support for this work from Horticulture Australia Limited is gratefully acknowledged. Thanks is given to the vegetable farm owners and managers who contributed their time to providing information for the case studies.

References

Bai, Y, He, J, Li, H, Wang, Q, Chen, H, Kuhn, NJ, Hikel, H, Chen, F and Gong, Y 2009, Soil structure and crop performance after 10 years of controlled traffic and traditional tillage cropping in the dryland Loess Plateau in China, *Soil Science* 174, 113-119.

Bochtis, DD, Sørensen, CG, Green, O, Moshou, D and Olesen, J 2010, Effect of controlled traffic on field efficiency, *Biosystems Engineering* 106, 14-25.

Bowman, K 2008, Economic and environmental analysis of converting to controlled traffic farming, *6th Australian Controlled Traffic Farming Conference, Dubbo, NSW, 12-14 Aug., 2008, 61-68.* Australian Controlled Traffic Farming Association, pp 61-68.

Bright, FA and Murray, ST 1990, Economic viability of controlled traffic farming, *Agricultural Engineering Conference 1990 - Preprints of Paper*. Instituion of Engineers, Australia, pp 15-18.

Carr, AP, Carr, DR, Carr, IE, Wood, AW and Poggio, M 2008, Implementing sustainable farming practices in the Herbert: the Oakleigh Farming Company experience, *Proceedings of the 2008 Conference of the Australian Society of Sugar Cane Technologists held at Townsville, Queensland, Australia, 29 April - 2 May 2008.*, pp 25-33.

Chamen, WCT and Audsley, E 1993, A study of the comparative economics of conventional and zero traffic systems for arable crops, *Soil and Tillage Research* 25, 369-390.

Dickson, JW, Campbell, DJ and Ritchie, RM 1992, Zero and conventional traffic systems for potatoes in Scotland, 1987-1989, *Soil & Tillage Research* 24, 397-419.

Garside, AL, Watters, TS, Berthelsen, JE, Sing, NJ, Robotham, BG and Bell, MJ 2004, Comparisons between conventional and alternative sugarcane farming systems which incorporate permanent beds, minimum tillage, controlled traffic and legume fallows, *Sugar Cane International* 15-20.

Grisso, RD, Kocher, MF and Vaughan, DH 2004, Predicting tractor fuel consumption, *Biological Systems Engineering: Papers and Publications* 164.

Halpin, NV, Cameron, T and Russo, PF 2008, Economic evaluation of precision controlled traffic farming in the Australian sugar industry: a case study of an early adopter, *Proceedings of the 2008 Conference of the Australian Society of Sugar Cane Technologists held at Townsville, Queensland, Australia, 29 April - 2 May 2008.*, pp 34-42.

Jensen, HG, Jacobsen, LB, Pedersen, SM and Tavella, E 2012, Socioeconomic impact of widespread adoption of precision farming and controlled traffic systems in Denmark, *Precision Agriculture* 13, 661-677.

Kingwell, R and Fuchsbichler, A 2011, The whole-farm benefits of controlled traffic farming: An Australian appraisal, *Agricultural Systems* 104, 513-521.

Lamers, JG, Perdok, UD, Lumkes, LM and Klooster, JJ 1986, Controlled traffic farming systems in the Netherlands, *Soil & Tillage Research* 8, 65-76.

McPhee, JE and Aird, PL 2013, Controlled traffic for vegetable production: Part 1. Machinery challenges and options in a diversified vegetable industry, *Biosystems Engineering* 116, 144-154.

McPhee, JE, Aird, PL, Hardie, MA and Corkrey, SR 2015, The effect of controlled traffic on soil physical properties and tillage requirements for vegetable production, *Soil & Tillage Research* 149, 33-45.

McPhee, JE, Braunack, MV, Garside, AL, Reid, DJ and Hilton, DJ 1995, Controlled traffic for irrigated double cropping in a semi-arid tropical environment: Part 2, tillage operations and energy use, *Journal of Agricultural Engineering Research* 60, 183-189.

McPhee, JE, Braunack, MV, Garside, AL, Reid, DJ and Hilton, DJ 1995, Controlled traffic for irrigated double cropping in a semi-arid tropical environment: Part 3, timeliness and trafficability, *Journal of Agricultural Engineering Research* 60, 191-199.

McPhee, JE, Neale, T and Aird, PL 2013, Controlled traffic for vegetable production: Part 2. Layout considerations in a complex topography, *Biosystems Engineering* 116, 171-178.

Pedersen, HH, Sørensen, CG, Oudshoorn, FW, Meyer, R, Kjeldahl, JK and Chamen, WCT 2013, A Wide Span Tractor concept developed for efficient and environmental friendly farming, *Land Technik AgEng 2013*. VDI-Verlag, Dusseldorf, Hannover, pp 47-53.

Stewart, LED, Copland, TA and Dickson, JW 1997, Profitability of traffic systems for arable crops in Scottish soils, *Landwards* 52, 23-26.

Stewart, LED, Copland, TA, Dickson, JW and Douglas, JT 1998, Economic evaluation of traffic systems for arable and grass crops on an imperfectly drained soil in Scotland, *Journal of Sustainable Agriculture* 12, 41-56.

Stirling, GR 2008, The impact of farming systems on soil biology and soilborne diseases: examples from the Australian sugar and vegetable industries - the case for better integration of sugarcane and vegetable production and implications for future research, *Australasian Plant Pathology* 37, 1-18.

Tullberg, JN 2000, Wheel traffic effects on tillage draught, *Journal of Agricultural Engineering Research* 75, 375-382.

Tullberg, JN 2010, Tillage, traffic and sustainability - a challenge for ISTRO, *Soil & Tillage Research* 111, 26-32.

Tullberg, JN, Yule, DF and McGarry, D 2007, Controlled traffic farming--From research to adoption in Australia, *Soil & Tillage Research* 97, 272-281.

Vermeulen, GD and Mosquera, J 2009, Soil, crop and emission responses to seasonal-controlled traffic in organic vegetable farming on loam soil, *Soil & Tillage Research* 102, 126-134.

Vermeulen, GD, Mosquera, J, Wel, Cvd, Klooster, Avd and Steenhuizen, JW 2007, Potential of controlled traffic farming with automatic guidance on an organic farm in the Netherlands. in Stafford, J.V. (ed.), *6th European Conference on Precision Agriculture, Skiathos, Greece, 3-6 June, 2007, 473-481*. Wageningen, Netherlands, Wageningen Academic Publishers., pp 473-481.

Table 1. Variables used in economic modelling.

Variable	Basis of selection and adjustment
Tractor and equipment inventory	Based on information relevant to individual farm case studies.
Field operations work rates (ha/h)	Calculated from working width and speed information provided by operators, and adjusted for estimated field efficiency.
Fuel use (l/h)	Based on information relevant to individual farms if available, or estimated from engine power (Grisso *et al.* 2004).
Machinery conversion costs for SCTF and CTF	Adjusted over a range of 0-30% of capital cost, with a most likely value of 10%. (pers. comm. T. Neale, precisionagriculture.com.au)
Interest, depreciation, insurance	Based on current industry figures, not varied within a simulation.
Input costs (e.g. labour, fuel, agricultural chemicals, fertiliser etc.)	Based on current industry figures, not varied within a simulation.
Irrigation application rates	Based on information relevant to individual farm case studies.
Change in water and fertiliser use efficiency	Adjusted from 0-10% improvement over standard systems, with a most likely value of 5% for CTF, and 0-5% improvement, with a most likely value of 2% for SCTF.
Change in cost of harvest on basis of traffic constraints associated with CTF	Adjusted from 0% up to a range of 5-20% (depending on the crop) higher than standard systems, with a most likely value ranging from 2-10% (depending on the crop) (Bochtis, Sørensen et al. 2010).
Base level crop yield	Based on local data and adjusted over ranges relevant to each crop.
Change in crop yield and quality due to system change	Yield was increased by 0-20% over standard system yields, with a most likely value of 10%, for CTF, and 0-5%, with a most likely value of 2%, for SCTF. Quality was varied from 0-10%, with a most likely value of 5%, for CTF, and 0-5% with a most likely value of 2%, for SCTF (Lamers *et al.* 1986; Dickson, Campbell et al. 1992; Vermeulen and Mosquera 2009).
Crop payments	Based on current industry figures, not varied within a simulation.

Note: All currency and interest rates used were in nominal terms.

Table 2. Rotations modelled for four case study farms.

Case study 1 (6 years)	**Case study 2** (4 years)	**Case study 3** (5 years)	**Case study 4** (9 years)
Potatoes	Wheat	Potatoes	Wheat
Fallow	Short term ryegrass (green manure)	Short term ryegrass (green manure)	Carrots
Poppies (spring sown)	Broccoli (spring-summer planted)	Poppies (spring sown)	Wheat
Short term ryegrass (green manure)	Short term ryegrass (green manure)	Fallow	Onions (autumn sown)
Onions (spring sown)	Poppies (spring sown)	Carrots	Short term ryegrass (green manure)
Short term ryegrass (green manure)	Short term ryegrass (green manure)	Wheat	Poppies (spring sown)
Peas	Onions (spring sown)	Broccoli (autumn planted)	Canola
Broccoli (summer planted)		Pyrethrum Y1	Short term ryegrass (green manure)
Short term ryegrass (green manure)		Pyrethrum Y2	Carrots
Carrots			Pyrethrum Y1
Short term ryegrass (green manure)			Pyrethrum Y2
Pyrethrum Y1			
Pyrethrum Y2			

Table 3. Summary of key machinery differences in three different farming systems used in four case studies.

Case study 1 (210 ha)	**Conv**	**SCTF**	**CTF**
Estimated capital cost	$675,000	$790,000	$636,500
% change in capital cost compared to Conv	-	+17	-5.7
Number of tractors	3	3	3
Tractor power intensity (kW/ha)	0.95	0.95	0.95
Number of implements	5, including 2 PTO driven	5, including 2 PTO driven	4, including 1 PTO driven
GNSS guidance	no	yes	yes
Case study 2 (600 ha)			
Estimated capital cost	$1,944,500	$1,976,000	$1,420,700
% change in capital cost compared to Conv	-	+10	-27
Number of tractors	7	6	6
Tractor power intensity (kW/ha)	1.42	1.41	0.96
Number of implements	4, including 2 PTO driven	4, including 2 PTO driven	2, including 1 PTO driven
GNSS guidance	no	yes	yes
Case study 3 (165 ha)			
Estimated capital cost	$970,600	$1,062,000	$794,700
% change in capital cost compared to Conv	-	+9.4	-18
Number of tractors	3	3	3
Tractor power intensity (kW/ha)	2.97	2.97	2.12
Number of implements	4, including 2 PTO driven	4, including 2 PTO driven	4, including 1 PTO driven
GNSS guidance	no	yes	yes
Case study 4 (165 ha)			
Estimated capital cost	$534,700	$590,600	$590,600
% change in capital cost compared to Conv	-	+10	+10
Number of tractors	2	2	2
Tractor power intensity (kW/ha)	1.65	1.65	1.65
Number of implements	3, including 1 PTO driven	3 including 1 PTO driven	3, including 1 PTO driven
GNSS guidance	no	yes	yes

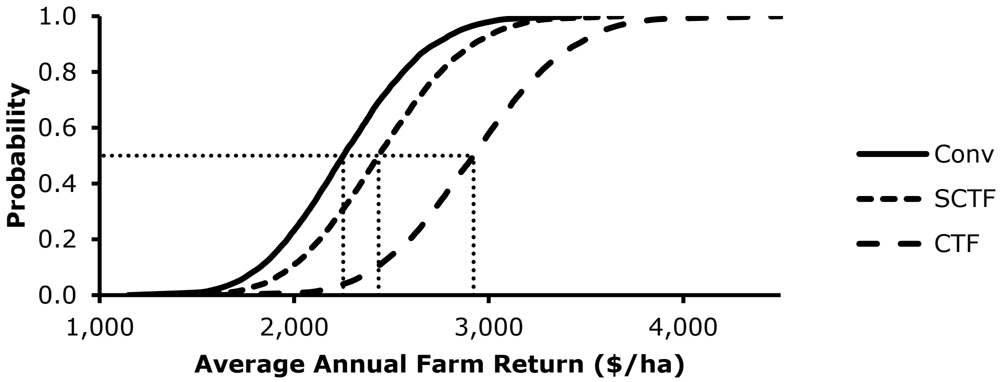

Fig. 1(a). Ascending probability curves for Average Annual Farm Return for the three different farming systems used in case study 1. ($ = AUD)

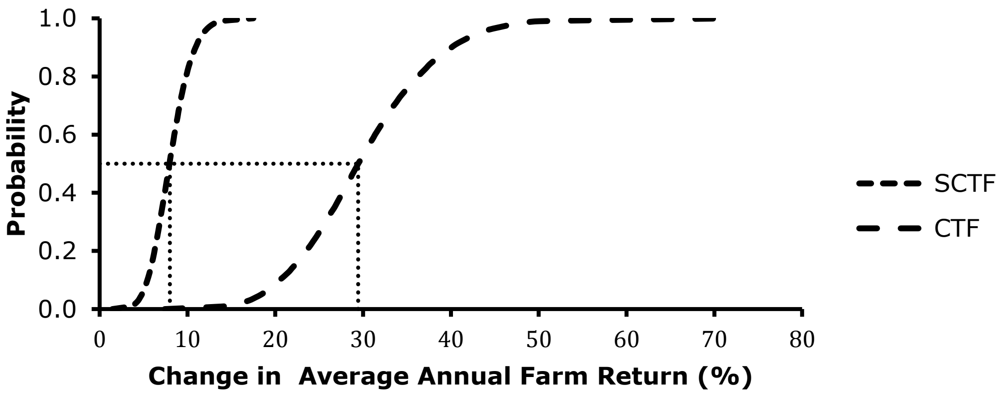

Fig 1(b). Ascending probability curves for the percentage change in Average Annual Farm Return for SCTF and CTF systems, compared to Conv, for case study 1.

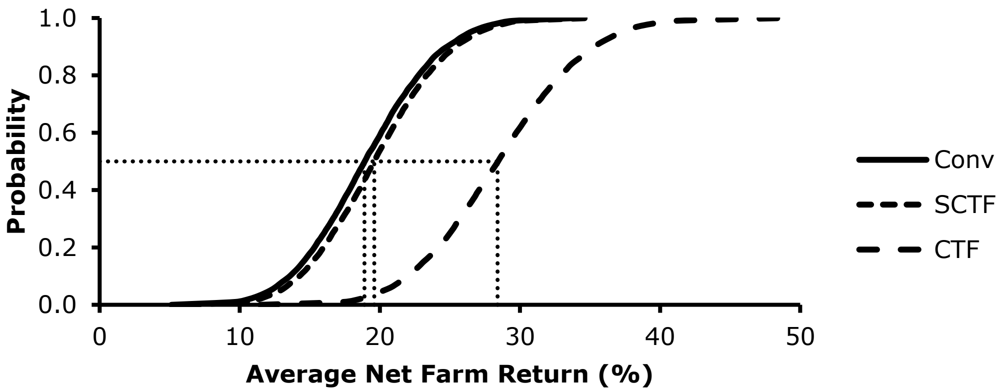

Fig. 1(c). Ascending probability curves for the percentage Average Net Farm Return for the three different farming systems used in case study 1.

Table 4. Summary of median values for different parameters across the three different farming systems used in case studies 1 – 4. 5% and 95% values for each parameter are shown in parentheses.

	Conv	SCTF	CTF
Case study	**Average Annual Farm Return** ($/ha)		
1	2,252 (1,712 – 2,854)	2,434 (2,852 – 3,058)	2,922 (2,295 – 3,594)
2	2,455 (1,739 – 3,161)	2,421 (1,693 – 3,142)	2,928 (2,162 – 3,664)
3	3,338 (2,561 – 4,302)	3,706 (2,853 – 4,750)	4,200 (3,323 – 5,300)
4	2,301 (1,886 – 2,750)	2,388 (1,963 – 2,834)	2,488 (1,987 – 3,019)
	Change in Average Annual Farm Return (%) ***cf*** **Conv**		
1	-	8 (5 – 12)	29 (18 – 43)
2	-	-2 (-4 – 1)	19 (12 – 31)
3	-	11 (5 – 17)	26 (17 – 37)
4	-	3 (1 – 8)	8 (-5 – 21)
	Average Net Farm Return (%)		
1	18.9 (12.2 – 26.4)	19.6 (12.9 – 27.0)	28.4 (20.3 – 37.1)
2	21.3 (12.4 – 30.1)	20.1 (11.3 – 28.9)	31.0 (20.4 – 41.0)
3	22.1 (14.8 – 31.1)	23.9 (16.2 – 33.3)	34.6 (25.4 – 46.1)
4	19.4 (14.3 – 25.0)	19.6 (14.5 – 25.1)	20.8 (14.8 – 27.2)

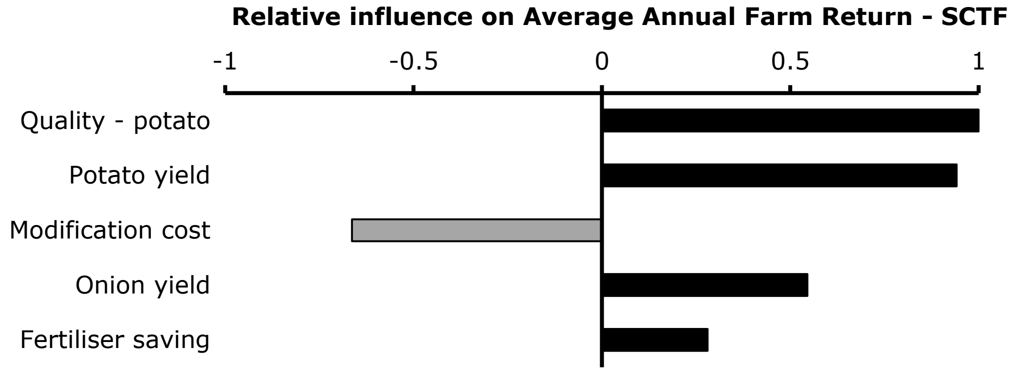

Fig. 2(a). Tornado plot showing factors which most influence the Average Annual Farm Return for a SCTF system in case study 1.

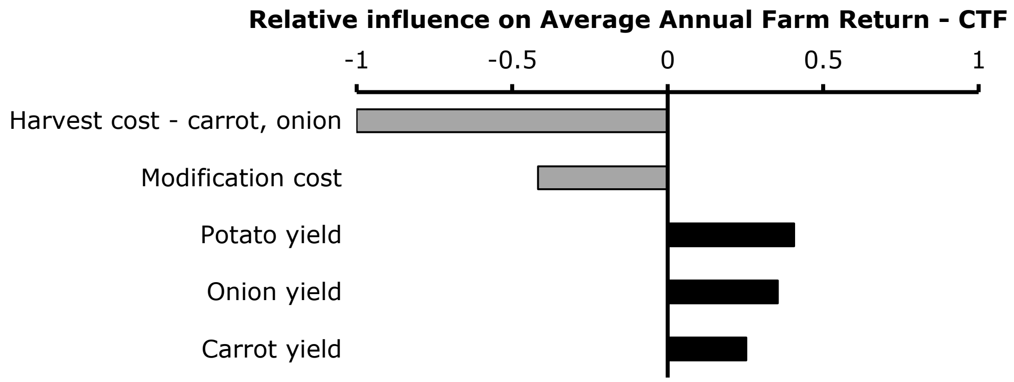

Fig. 2(b). Tornado plot showing factors which most influence the Average Annual Farm Return for a CTF system in case study 1.

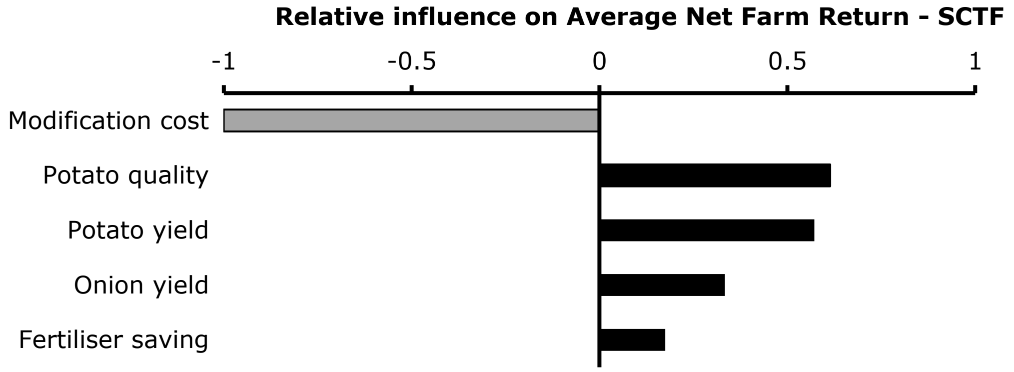

Fig. 2(c). Tornado plot showing factors which most influence the Average Net Farm Return for a SCTF system in case study 1.

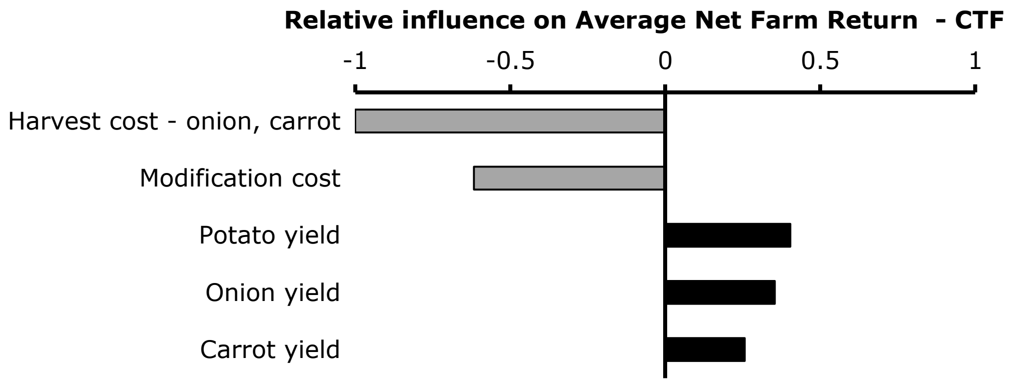

Fig. 2(d). Tornado plot showing factors which most influence the Average Net Farm Return for a CTF system in case study 1.

Table 5(a). Five most influential factors on Average Annual Farm Return for the SCTF system across all case study farms.

Case study 1	Case study 2	Case study 3	Case study 4
Potato quality	Onion yield	Potato quality	Onion yield
Potato yield	Broccoli yield	Potato yield	Onion quality
Modification cost	*Modification cost*	*Modification cost*	Pyrethrum yield
Onion yield	Onion quality	Poppy yield	Carrot yield
Fertiliser saving	Wheat yield	Fertiliser saving	Poppy yield

Table 5(b). Five most influential factors on Average Annual Farm Return for the CTF system across all case study farms.

Case study 1	Case study 2	Case study 3	Case study 4
Harvest costs	*Harvest costs*	Potato yield	*Harvest costs*
Modification cost	Onion yield	*Harvest costs*	Onion yield
Potato yield	Broccoli yield	*Modification cost*	Pyrethrum yield
Onion yield	Poppy yield	Pyrethrum yield	Carrot yield
Carrot yield	Fertiliser saving	Poppy yield	Onion quality

Table 5(c). Five most influential factors on Average Net Farm Return for the SCTF system across all case study farms.

Case study 1	Case study 2	Case study 3	Case study 4
Modification cost	*Modification cost*	Potato quality	Onion yield
Potato quality	Onion yield	*Modification cost*	*Modification cost*
Potato yield	Broccoli yield	Potato yield	Pyrethrum yield
Onion yield	Onion quality	Poppy yield	Onion quality
Fertiliser saving	Wheat yield	Fertiliser saving	Carrot yield

Table 5(d). Five most influential factors on Average Net Farm Return for the CTF system across all case study farms.

Case study 1	Case study 2	Case study 3	Case study 4
Harvest costs	*Harvest costs*	*Modification cost*	*Harvest costs*
Modification cost	Onion yield	Potato yield	Onion yield
Potato yield	*Modification cost*	*Harvest costs*	*Modification cost*
Onion yield	Broccoli yield	Pyrethrum yield	Pyrethrum yield
Carrot yield	Poppy yield	Poppy yield	Carrot yield